Steam Cycle calculation function calculates five cycle points: of a steam cycle having compression and clearance. The output of a cycle calculations is a 7x 6 array.

The first column contains cycle parameters. The second column through the sixth contain the cycle property points.

1. The inlet point properties is computed directly from inlet properties.
2. The cutoff point properties as mixture residual and inlet steam properties.
3. The end of expansion point properties.
4. The exhaust point properties.
5. The compressed residual point properties.

Each point is a column in the array and the column's rows containe the following properties.

0 ***pressure***
1 ***temperature***
2 ***specific volume***
3 ***specific internal energy***
4 ***specific enthalpy***
5 ***specific entropy***
6 ***quality***

As an example if M is a cycle array. Then $M_{0,1}$ would be the inlet pressure. $M_{4,4}$ would be the exhaust ***specific enthalp***

$M_{\text{property},\text{point}}$ returns the property at a specific point.

The cycle properties returned in the first column are:

0 ***scaling factor***
1 ***clearance***
2 ***cutoff, as percent of displacement***
3 ***exhaust close, as percent of displacement when valve closes***
4 ***makeup steam part, in a compound cycle this parameter is makeup steam part***
5 ***residual steam part***
6 ***fresh inlet steam part***

$\text{Mcy} := \text{Rankine\_p}(\text{ST\_ptdata}(500, 800, 1, 1), 100, 14.7, 0.10, 300)$

$$\text{Mcy} = \begin{pmatrix} 1 & 500 & 500 & 100 & 14.7 & 300 \\ 0.1 & 800 & 870.956 & 460.579 & 440.638 & 1296.573 \\ 0.216 & 1.44 & 1.533 & 5.334 & 36.331 & 3.465 \\ 0.948 & 1279.481 & 1309.102 & 1160.453 & 1160.34 & 1493.74 \\ 0 & 1412.687 & 1450.952 & 1259.167 & 1259.167 & 1686.11 \\ 0.14 & 1.658 & 1.687 & 1.687 & 1.896 & 1.896 \\ 0.86 & 1 & 1 & 1 & 1 & 1 \end{pmatrix}$$

The above shows the calculation of a cycle. The result being assigned to Mcy ":=" op and then displayed "=" op. These can be retrieved in the same way as the steam property points. $\text{Mcy}_{5,0} = 0.1399$ returns the ***residual steam part***. One may use

$\text{Mcy}_{\boldsymbol{rm},\boldsymbol{PA}} = 0.1399$ as well. Readability indices are explained later. If you are using this package I must assume that you know what the steam properties are and how to use them. Some of the cycle point properties need some explination. ***expansion ratio*** is the true expansion ratio: the ratio of specific volume at the end of expansion to the specific volume at the cutoff point. ***clearance*** is one of the input parameters to the cycle function that is used by other function that operate on the cycle matrix. ***clearance*** is also calculated by cycle functions that take power as an input. ***cutoff*** has it's usual meaning. ***exhaust close*** is the point of exhaust closure. ***clearance***, ***cutoff***, and ***exhaust close*** are always relative to displacement.

The last three cycle properties are ***makeup steam part***, ***residual steam part***, and ***fresh inlet steam part*** are unique features of the compression cycle. The standard way of doing cycle analysis is based on a unit mass being passed through the cycle. A unit mass could be 1 pound of steam or 1 kilogram or what ever mass units one chooses to work with. The compression cycle is no different. However the unit mass here, is the total combined mass of the fresh steam part and the residual part that remains in the cylander from the last cycle. Only the ***fresh inlet steam part*** is actually going through the cycle. And in the case of a compound expansion cycle. The fresh inlet steam can be a mixture of the intermediat stage steam from the previous stage and makeup steam that has been added into the interstage reciever from the high pressure inlet to the engine. In a simple expansion engine the ***makeup steam part*** will always be 0.

A cycle calculated on a unit mass makes the steam's specific properties scalable to engine displacement. The major thing in these calculations is that that 1 pound of steam is made up of two parts. The ***fresh inlet steam part*** and the ***residual steam part*** (recycled steam). And that only the ***fresh inlet steam part*** of the pound of steam in the cycle is going through the cycle. The other ***residual steam part*** is recycled steam. That becomes very important to rember when calculating efficiency or work out per pound of steam going through the cycle. ***makeup steam part*** is a multistage cycle calculations parameter of Rankine_h. It is the throttled down HP stage steam. In one type of analysis make up steam is required to get the specified expansion. Rankine_h is a special cycle for for this case.

The cycle function use ASTEM for Mathcad-Pro (ASTEMMCP)

ASTEM is an add-on dynamic link library (DLL) for obtaining thermodynamic properties of water and steam based on the 1967 IFC Formulation for Industrial Use, ASTEM for Mathcad-Pro (ASTEMMCP) is Copyrighted 1998 Edward D. Throm Mr. Ed's Software.

The basic compression cycle is done in an expander. An expander is simple device to obtain mechinical work from the heat energy contained in the steam. There are many types of expanders. Here we will only be dealing with positive displacement expanders. "Positive Displacement" Now that is in intersting term. What is a positive displacement expander. As best as I can define it. A positive displacement expander is one that fully containes the working fluid during expansion and the work output is directly a result of the change in contained volume. The piston engine is a positive displacement engine. A wankel is anothe example of a positive displacement engine. Turbines are not positive displacement engines.

The cycle is divided into two strokes. Stroke comes from piston engine termonolgy. In the general sense it applies to the change of volume of the expander. The expander goes from min volume to max volume and back again. A stroke is a volume change from min to max or from max to min. In a piston engine these volume changes corospond to piston travel, a piston stroke from TDC to BDC or BDC to TDC . The cycle begines when the expander is at minimal volume TDC. Steam is admited while the expander volume increasses. At some point the steam being admited is cutoff and the steam with in the expander expands as the expander continues to increase in volume until the max volume of the expander is reached BDC. The volume change reverses and the exhaust port is opened. At some point as the volume is decreassing the exhaust port is closed and as the volume continues decreasing the steam is compressed into a smaller and smaller volume until the expander reaches it's min volume and the cycle begins again. The cycle is made up of several processes. During admission, work is being down by a constant pressure process. At cutoff we begin an isentropic expansion process that continues till the expander reaches max volume (or the exhaust port opens). When the exhaust opens the pressure equilizes with the external exhaust pressure. The steam remaining undergoes a pressure drop to that exhaust pressure. during the exhaust part of the stroke the steam if forced out of the cylander at constant pressure. work is being done forceing exhaust from the engine in a constant pressure process. When the exhaust is closed the remaining steam is compressed into the min volume space in a constant entropy process. During admission the residual compressed steam is mixed with the fresh inlet steam. The mixing process is a balanced enthalpy process. The enthalpy of the two parts are s3umed and the new state calculated at inlet pressure becomes the cutoff state point. The total mass m at cutoff is the sum of the input mass i and the residual mass r. m = i + r. Sense m = 1 unit mass them i + r = 1. The specific enthalpy of the mixture at cutoff point h_c is is calculated as:

$h_c := \mathrm{Mcy}_{\boldsymbol{im,PA}} \cdot \mathrm{Mcy}_{\boldsymbol{h,in}} + \mathrm{Mcy}_{\boldsymbol{rm,PA}} \cdot \mathrm{Mcy}_{\boldsymbol{h,co}}$ $h_c = 1450.9520$ $\mathrm{Mcy}_{\boldsymbol{h,cu}} = 1450.9520$

For greater readability of a cycle array access the following maybe used. Note their use in accessing cycle values from the Mcy cycle calculated above.

$\boldsymbol{PA} \equiv 0$ Parameter column index

Cycle paramater column row indices:

$\boldsymbol{sc} \equiv 0$ Stage Scaling. $\mathrm{Mcy}_{\boldsymbol{sc},\boldsymbol{PA}} = 1.000$

$\boldsymbol{Cl} \equiv 1$ Clearance. $\mathrm{Mcy}_{\boldsymbol{Cl},\boldsymbol{PA}} = 0.100$

$\boldsymbol{cu} \equiv 2$ Cutoff. $\mathrm{Mcy}_{\boldsymbol{cu},\boldsymbol{PA}} = 0.2161$

$\boldsymbol{xc} \equiv 3$ Exhaust close. $\mathrm{Mcy}_{\boldsymbol{xc},\boldsymbol{PA}} = 0.9484$

$\boldsymbol{hm} \equiv 4$Makeup mass. $\mathrm{Mcy}_{\boldsymbol{hm},\boldsymbol{PA}} = 0.0000$

$\boldsymbol{rm} \equiv 5$Residual mass. $\mathrm{Mcy}_{\boldsymbol{rm},\boldsymbol{PA}} = 0.1399$

$\boldsymbol{im} \equiv 6$Inlet mass. $\mathrm{Mcy}_{\boldsymbol{im},\boldsymbol{PA}} = 0.8601$

$\boldsymbol{in} \equiv 1$ Inlet properties column index.

$\boldsymbol{cu} \equiv 2$ Cutoff properties column index

$\boldsymbol{ex} \equiv 3$ End of expansion properties column index

$\boldsymbol{xh} \equiv 4$ Exhaust properties column index

$\boldsymbol{co} \equiv 5$ Compression properties column index.

$$\mathrm{Mcy}^{\langle \boldsymbol{cu} \rangle} = \begin{pmatrix} 500.0000 \\ 870.9564 \\ 1.5331 \\ 1309.1023 \\ 1450.9520 \\ 1.6874 \\ 1.0000 \end{pmatrix}$$

Cycle steam property point row indices:

$\boldsymbol{p} \equiv 0$ Pressure. $\mathrm{Mcy}_{\boldsymbol{p},\boldsymbol{cu}} = 500.0000$

$\boldsymbol{t} \equiv 1$ Temperature. $\mathrm{Mcy}_{\boldsymbol{t},\boldsymbol{cu}} = 870.9564$

$\boldsymbol{v} \equiv 2$ Specific volume $\mathrm{Mcy}_{\boldsymbol{v},\boldsymbol{cu}} = 1.5331$

$\boldsymbol{i} \equiv 3$ Specific internal energy $\mathrm{Mcy}_{\boldsymbol{i},\boldsymbol{cu}} = 1309.1023$

$\boldsymbol{h} \equiv 4$ Specific enthalpy $\mathrm{Mcy}_{\boldsymbol{h},\boldsymbol{cu}} = 1450.9520$

$\boldsymbol{s} \equiv 5$ Specific entropy $\mathrm{Mcy}_{\boldsymbol{s},\boldsymbol{cu}} = 1.6874$

$\boldsymbol{Q} \equiv 6$ Qualty $\mathrm{Mcy}_{\boldsymbol{Q},\boldsymbol{cu}} = 1.0000$

Some other constants used in these cycle calculations:

$\boldsymbol{J} \equiv 778.169262266$ Foot-pounds(ftlb) per BTU

$\boldsymbol{sqin} \equiv 144$ Square inches per square foot

Note that the functions and indecies are defined with the global assignment operator '▮ ≡ ▮". Global assignment forces MathCad to evaluate these asignments first. This allows us to use thoes functions and values with the normal '▮ := ▮" assignment ahead of thier defination. MathCad normally evaluates left to right across the page and then down through the document. You must define a variable ahead of using it. But MathCad makes two passes. The first pass processes the global assignments. And the second pass then does the normal assignments. That is the only reasion that I am able to use Rankine_p above to calculate Mcy.

The flag ValveProcess is used to effect the way the exhaust(residual steam) enthalpy is calculated. This is a very important value as it effects the compressed steam point. There have been three ways sugested that this value should be calculated. As a throttling process the exhaust enthalpy would be equal to the end of expansion enthalpy. In many theodynamic books I have read thay say the the flow through valves is a throttling process. However there is also the theodynamics law of conservation of energy that when applied to the exhaust enthalpy one would expect all of heat not converted into work to be rejected in that exhaust. And a third sugested by Ted Pritchard is that the enthalpy should be the same as a full expansion to exhaust pressure. You have a choce of these three options here.

The basic Rankine compression cycle function:

This finction Rankine_p takes parameters:

Inlet property vector	Pti	End of expansion pressure	Pe
Exhaustr pressure	Px	Clearance	Cl
Compression pressure	Pc		

```
$Rankine\_p(Pti, Pe, Px, Cl, Pc) \equiv$
    ST_limit(7)
    $Ptu \leftarrow Pti$
    while 1
        $Hu \leftarrow Ptu_{h}$
        $Pte \leftarrow ST\_ptdata(Pe, Ptu_{s}, \boldsymbol{s}, 1)$
        $Hx \leftarrow Pte_{h}$ if $\boldsymbol{ValveProcess} = 2$
        otherwise
            $Ptfe \leftarrow ST\_ptdata(Px, Ptu_{s}, \boldsymbol{s}, 1)$
            $Hx \leftarrow Ptfe_{h}$ if $\boldsymbol{ValveProcess} = 0$
            $Hx \leftarrow Ptfe_{h} + \left[Pte_{i} - Ptfe_{i} - Px \cdot (Ptfe_{v} - Pte_{v}) \cdot \frac{\boldsymbol{sqin}}{\boldsymbol{J}}\right]$ otherwise
        $Ptx \leftarrow ST\_ptdata(Px, Hx, \boldsymbol{h}, 1)$
        $Ptc \leftarrow ST\_ptdata(Pc, Ptx_{s}, \boldsymbol{s}, 1)$
        $res \leftarrow \frac{Cl}{1 + Cl} \cdot \frac{Pte_{v}}{Ptc_{v}}$
        $Ptu \leftarrow ST\_ptdata\left[Pti_{p}, res \cdot Ptc_{h} + (1 - res) \cdot Pti_{h}, \boldsymbol{h}, 1\right]$
        break if $\left|Hu - Ptu_{h}\right| < 0.0001$
    $r \leftarrow \frac{Pte_{v}}{Ptu_{v}}$
    $Pr \leftarrow \begin{pmatrix} 1 \\ Cl \\ \frac{1 + Cl}{r} - Cl \\ \frac{Ptx_{v}}{Ptc_{v}} \cdot Cl - Cl \\ 0 \\ res \\ 1 - res \end{pmatrix}$
    augment(augment(augment(augment(augment(Pr, Pti), Ptu), Pte), Ptx), Ptc)
```

Generate the steam property point for the inlet steam Cutoff steam initially is the same as the inlet   When cutoff enthalpy cesses to change by more then 0.0001 we will stop.Calculate the expansion point.   Use constant enthalpy throttling process or calculate exhaust enthalpy to balance energy conversion.

2 is a throttling process residual enthalpy = end of expansion enthalpy

Adjust full expansion enthalpy by the work that would have been done by that further expansion Or use full expansion enthalpy.

Calculate exhaust properties.
Dito for compression.

The residual steam is exhaust steam in the cylander at exhaust close. See the calculation res to the left. Steam at BDC is found by the volumetric ratio.

Now we calculate the residual compressed and inlet steam state to arive at a new cutoff point. We terminate this loop when there very little change in cutoff enthalpy from the previous loop.

Upon having a stable cycle. Calculate expansion ratio, cutoff and exhaust valve close

Generate the parameter matrix and combine with the property pointes to get the cycle array

Compound first stage Rankine compression cycle function:

```
Rankine_HP(Pti, Pe, Px, Cl, Pc, v0) ≡
    ST_limit(7)
    Ptu ← Pti
    while 1
        Hu ← $Ptu_h$
        Pte ← ST_ptdata($(Pe, Ptu_s, s, 1)$)
        Hx ← $Pte_h$  if ValveProcess = 2
        otherwise
            Ptfe ← ST_ptdata($(Px, Ptu_s, s, 1)$)
            Hx ← $Ptfe_h$  if ValveProcess = 0
            Hx ← $Ptfe_h + \left[Pte_i - Ptfe_i - Px\cdot(Ptfe_v - Pte_v)\cdot\frac{sqin}{J}\right]$  otherwise
        Ptx ← ST_ptdata(Px, Hx, h, 1)
        Ptc ← ST_ptdata($(Pc, Ptx_s, s, 1)$)
        res ← $\frac{Cl}{1 + Cl}\cdot\frac{Pte_v}{Ptc_v}$
        Ptu ← ST_ptdata$\left[Pti_p, res\cdot Ptc_h + (1 - res)\cdot Pti_h, h, 1\right]$
        break  if $|Hu - Ptu_h| < 0.0001$
    r ← $\frac{Pte_v}{Ptu_v}$
    Pr ← $\begin{pmatrix} \frac{v0}{Ptx_v} \\ Cl \\ \frac{1 + Cl}{r} - Cl \\ \frac{Ptx_v}{Ptc_v}\cdot Cl - Cl \\ 0 \\ res \\ 1 - res \end{pmatrix}$
    augment(augment(augment(augment(augment(Pr, Pti), Ptu), Pte), Ptx), Ptc)
```

Generate the steam property point for the inlet steam Cutoff steam initially is the same as the inlet When cutoff enthalpy cesses to change by more then 0.0001 we will stop.Calculate the expansion point. Use constant enthalpy throttling process or calculate exhaust enthalpy to balance energy conversion.

2 is a throttling process residual enthalpy = end of expansion enthalpy

Adjust full expansion enthalpy by the work that would have been done by that further expansion Or use full expansion enthalpy.

Calculate exhaust properties.
Dito for compression.

The residual steam is exhaust steam in the cylander at exhaust close. See the calculation of Xc below. Steam at BDC is found by the volumetric ratio.

Now we calculate the residual compressed and inlet steam state to arive at a new cutoff point. We terminate this loop when there very little change in cutoff enthalpy from the previous loop.

Upon having a stable cycle. Calculate expansion ratio, cutoff and exhaust valve close

Generate the parameter matrix and combine with the property pointes to get the cycle array

Multistage Rankien cycle function Rankine_S:

This function does a compresion cycle and balances the mass consumption with the previous stage mass usage. Hcy Icy are cycle arrays. Hcy is the source of makeup steam and Icy is the previous stages cycle. The end of expansion pressure Pe and exhaust pressure Px along with clearance Cl make up the cycles input point parameters. v_0 and mi are makeup steam balancing parameters.

Generate the steam property point for the inlet steam Cutoff steam initially is the same as the inlet When cutoff enthalpy cesses to change by more then 0.0001 we will stop.Calculate the expansion point. Use constant enthalpy throttling process or calculate exhaust enthalpy to balance energy conversion.

```
$Rankine\_S(Ptm, Pti, Pe, Px, Cl, mi, v0) \equiv$
    $ST\_limit(7)$
    $Ptu \leftarrow Pti$
    $mm \leftarrow 0$
    while 1
        $Hu \leftarrow Ptu_{\boldsymbol{h}}$
        $Pte \leftarrow ST\_ptdata\left(Pe, Ptu_{\boldsymbol{s}}, \boldsymbol{s}, 1\right)$
        $Hx \leftarrow Pte_{\boldsymbol{h}}$  if  $\boldsymbol{ValveProcess} = 2$
        otherwise
            $Ptfe \leftarrow ST\_ptdata\left(Px, Ptu_{\boldsymbol{s}}, \boldsymbol{s}, 1\right)$
            $Hx \leftarrow Ptfe_{\boldsymbol{h}}$  if  $\boldsymbol{ValveProcess} = 0$
            $Hx \leftarrow Ptfe_{\boldsymbol{h}} + Pte_{\boldsymbol{i}} - Ptfe_{\boldsymbol{i}} - Px\cdot\left(Ptfe_{\boldsymbol{v}} - Pte_{\boldsymbol{v}}\right)\cdot\frac{\boldsymbol{sqin}}{\boldsymbol{J}}$  otherwise
        $Ptx \leftarrow ST\_ptdata\left(Px, Hx, \boldsymbol{h}, 1\right)$
        $Ptc \leftarrow ST\_ptdata\left(Pti_{\boldsymbol{p}}, Ptx_{\boldsymbol{s}}, \boldsymbol{s}, 1\right)$
        $res \leftarrow \frac{Cl}{1 + Cl}\cdot\frac{Pte_{\boldsymbol{v}}}{Ptc_{\boldsymbol{v}}}$
        if  $sc \neq 0$
            $mm \leftarrow (1 - res)\cdot sc - mi$
            $mm \leftarrow 0.0$  if  $mm < 0.0$
            $Pti \leftarrow ST\_ptdata\left(Pti_{\boldsymbol{p}}, \frac{mm\cdot Ptm_{\boldsymbol{h}} + mi\cdot Pti_{\boldsymbol{h}}}{mm + mi}, \boldsymbol{h}, 1\right)$
        $Ptu \leftarrow ST\_ptdata\left[Pti_{\boldsymbol{p}}, \left[res\cdot Ptc_{\boldsymbol{h}} + (1 - res)\cdot Pti_{\boldsymbol{h}}\right], \boldsymbol{h}, 1\right]$
        break  if  $\left|Hu - Ptu_{\boldsymbol{h}}\right| < 0.0001$
    $r \leftarrow \frac{Pte_{\boldsymbol{v}}}{Ptu_{\boldsymbol{v}}}$
    $Pr \leftarrow \begin{bmatrix} r \\ Cl \\ \frac{1 + Cl}{r} - Cl \\ Cl\cdot\left(\frac{Ptx_{\boldsymbol{v}}}{Ptc_{\boldsymbol{v}}} - 1\right) \\ \frac{mm}{sc} \\ res \\ 1 - res \end{bmatrix}$
    $augment(augment(augment(augment(augment(Pr, Pti), Ptu), Pte), Ptx), Ptc)$
```

Adjust full expansion enthalpy by the work that would have been done by that further expansion

Calculate exhaust properties.

Dito for compression.

The residual steam is exhaust steam in the cylander at exhaust close. See the calculation of Xc below. Steam at BDC is found by the volumetric ratio

Now we calculate the residual compressed and inlet steam state to arive at a new cutoff point. We terminate this loop when there very little change in cutoff enthalpy from the previous loop.

Upon having a stable cycle. Calculate expansion ratio, cutoff and exhaust valve close

Generate the parameter matrix and combine with the property pointes to get the cycle array

This function calculates a Rankine compression cycle. It differs from Rankine_p only that it takes a fixed cutoff. It solves for the end of expansion pressure. Otherwise it is much the same as Rankine_p

```
Rankine_c(Pti, Cu, Px, Cl, Pc) ≡
    ST_limit(7)
    $Ptu \leftarrow Pti$
    $r \leftarrow \frac{Cl + 1}{Cl + Cu}$        Initially cutoff same as inlet. Ptu will be solved for to a stable enthalpy.
    while 1                                        Calculate true expansion ration including clearance and cutoff.
        $Hu \leftarrow Ptu_{h}$                    We will quite inerating when the enthalpy at cutoff stablizes to 4 decmal places
        $pe \leftarrow \frac{Ptu_{0}}{r \cdot Ptu_{s}}$      Need an initial end of expansion pressure for root to work with
        $pe \leftarrow root\left(ST\_ptdata\left(pe, Ptu_{v} \cdot r, v, 1\right)_{s} - Ptu_{s}, pe\right)$
        $Pte \leftarrow ST\_ptdata\left(pe, Ptu_{s}, s, 1\right)$      Solve for the ending isentropic expansion pressure. Use the specific volume at cutoff times the expansion ratio r.
        $Hx \leftarrow Pte_{h}$  if  $ValveProcess = 2$
        otherwise                                  Need to figure the exhaust enthalpy. The method used can be constant enthalpy from expansion point or energy balanced exhaust enthalpy.
            $Ptfe \leftarrow ST\_ptdata\left(Px, Ptu_{s}, s, 1\right)$
            $Hx \leftarrow Ptfe_{h}$  if  $ValveProcess = 0$
            $Hx \leftarrow Ptfe_{h} + Pte_{i} - Ptfe_{i} - Px \cdot \left(Ptfe_{v} - Pte_{v}\right) \cdot \frac{sqin}{J}$  otherwise
        $Ptx \leftarrow ST\_ptdata\left(Px, Hx, h, 1\right)$      Calculate exhaust state from exhaust enhalpy.
        $Ptc \leftarrow ST\_tpdata\left(1472, Ptx_{s}, s, 1\right)$      Can not compress to temperatures above 1472. IFC-67 limit.
        $Ptc \leftarrow ST\_ptdata\left(Pc, Ptx_{s}, s, 1\right)$  if  $Pc \le Ptc_{0}$
        $res \leftarrow \frac{Cl}{1 + Cl} \cdot \frac{Pte_{v}}{Ptc_{v}}$      Calculate residual steam part.
                                                   Calculate residual-inlet mix properties
        $Ptu \leftarrow ST\_ptdata\left[Pti_{p}, res \cdot Ptc_{h} + (1 - res) \cdot Pti_{h}, h, 1\right]$
        break  if  $\left|Hu - Ptu_{h}\right| < 0.0001$
    $Pr \leftarrow \begin{bmatrix} 1 \\ Cl \\ \frac{1 + Cl}{r} - Cl \\ Cl \cdot \left(\frac{Ptx_{v}}{Ptc_{v}} - 1\right) \\ 0 \\ res \\ 1 - res \end{bmatrix}$
        Expansion ratio
        clearance
        cutoff
        exhaust close
        make up steam part.
        residual steam part
        fresh inlet steam part
    augment(augment(augment(augment(augment(Pr, Pti), Ptu), Pte), Ptx), Ptc)
```

```
$\text{Rankine\_X}(Pti, Pe, Px, X, Pc) \equiv$
    ST_limit(7)
    Ptu ← Pti
    while 1
```

Generate the steam property point for the inlet steam Cutoff steam initially is the same as the inlet When cutoff enthalpy cesses to change by more then 0.0001 we will stop.Calculate the expansion point. Use constant enthalpy throttling process or calculate exhaust enthalpy to balance energy conversion.

```
        Hu ← $Ptu_{\boldsymbol{h}}$
        Pte ← ST_ptdata$(Pe, Ptu_{\boldsymbol{s}}, \boldsymbol{s}, 1)$
        Hx ← $Pte_{\boldsymbol{h}}$  if  $\boldsymbol{ValveProcess} = 2$
```

2 is a throttling process residual enthalpy = end of expansion enthalpy

```
        otherwise
            Ptfe ← ST_ptdata$(Px, Ptu_{\boldsymbol{s}}, \boldsymbol{s}, 1)$
            Hx ← $Ptfe_{\boldsymbol{h}}$  if  $\boldsymbol{ValveProcess} = 0$
            Hx ← $Ptfe_{\boldsymbol{h}} + \left[Pte_{\boldsymbol{i}} - Ptfe_{\boldsymbol{i}} - Px\cdot\left(Ptfe_{\boldsymbol{v}} - Pte_{\boldsymbol{v}}\right)\cdot\frac{\boldsymbol{sqin}}{\boldsymbol{J}}\right]$  otherwise
```

Adjust full expansion enthalpy by the work that would have been done by that further expansion Or use full expansion enthalpy.

```
        Ptx ← ST_ptdata$(Px, Hx, \boldsymbol{h}, 1)$
        Ptc ← ST_ptdata$(Pc, Ptx_{\boldsymbol{s}}, \boldsymbol{s}, 1)$
```

Calculate exhaust properties. Dito for compression.

```
        Ptu ← ST_ptdata$\left[Pti_{\boldsymbol{p}}, (1 - X)\cdot Ptc_{\boldsymbol{h}} + X\cdot Pti_{\boldsymbol{h}}, \boldsymbol{h}, 1\right]$
        break  if  $\left|Hu - Ptu_{\boldsymbol{h}}\right| < 0.0001$
```

Now we calculate the residual compressed and inlet steam state to arive at a new cutoff point. We terminate this loop when there very little change in cutoff enthalpy from the previous loop.

```
    r ← $\frac{Pte_{\boldsymbol{v}}}{Ptu_{\boldsymbol{v}}}$
```

Upon having a stable cycle. Calculate expansion ratio, cutoff and exhaust valve close

```
    Cl ← $\frac{1}{r\cdot\left(\frac{X}{1 - X}\right) + r - 1}$
    res ← $\frac{Cl}{1 + Cl}\cdot\frac{Pte_{\boldsymbol{v}}}{Ptc_{\boldsymbol{v}}}$
    Pr ← $\begin{pmatrix} 1 \\ Cl \\ Cl\cdot\frac{X}{1 - X} \\ \frac{Ptx_{\boldsymbol{v}}}{Ptc_{\boldsymbol{v}}}\cdot Cl - Cl \\ 0 \\ res \\ 1 - res \end{pmatrix}$
    augment(augment(augment(augment(augment(Pr, Pti), Ptu), Pte), Ptx), Ptc)
```

Constant pressure inlet work

inlet pressure minus exhaust pressure times the volume change during inlet.

$$\mathrm{CyCuW}(Cy) \equiv \left| \begin{array}{l} \text{return } \left(Cy_{p,cu} - Cy_{p,xh}\right) \cdot Cy_{v,cu} \cdot \dfrac{Cy_{cu,PA} \cdot Cy_{sc,PA}}{Cy_{cu,PA} + Cy_{Cl,PA}} \cdot \dfrac{sqin}{J} \quad \text{if } \mathrm{IsScalar}\left(Cy_{0,0}\right) \\ \displaystyle\sum_{i=0}^{\mathrm{rows}(Cy)-1} \left[\left(Cy_i\right)_{p,cu} - \left(Cy_i\right)_{p,xh}\right] \cdot \left(Cy_i\right)_{v,cu} \cdot \dfrac{\left(Cy_i\right)_{cu,PA} \cdot \left(Cy_i\right)_{sc,PA}}{\left(Cy_i\right)_{cu,PA} + \left(Cy_i\right)_{Cl,PA}} \cdot \dfrac{sqin}{J} \end{array} \right.$$

Expansion work

Internal energy difference between cutoff and end of expansion minus the constant pressure work below the exhaust pressure line.

$$\mathrm{CyExpW}(Cy) \equiv \left| \begin{array}{l} \text{return } Cy_{i,cu} - Cy_{i,ex} - Cy_{p,xh} \cdot \left(Cy_{v,ex} - Cy_{v,cu}\right) \cdot Cy_{sc,PA} \cdot \dfrac{sqin}{J} \quad \text{if } \mathrm{IsScalar}\left(Cy_{0,0}\right) \\ \displaystyle\sum_{i=0}^{\mathrm{rows}(Cy)-1} \left[\left(Cy_i\right)_{i,cu} - \left(Cy_i\right)_{i,ex} - \left(Cy_i\right)_{p,xh} \cdot \left[\left(Cy_i\right)_{v,ex} - \left(Cy_i\right)_{v,cu}\right] \cdot \left(Cy_i\right)_{sc,PA} \cdot \dfrac{sqin}{J}\right] \end{array} \right.$$

Compression work

Internal energy change during compression minus the constant pressure work below the exhaust pressure line.
Note. Compression work is only on the residual part of the steam $Cy_{5,0}$

$$\mathrm{CyComW}(Cy) \equiv \left| \begin{array}{l} \text{return } \left[\left(Cy_{i,co} - Cy_{i,xh}\right) + Cy_{p,xh} \cdot \left(Cy_{v,co} - Cy_{v,xh}\right) \cdot \dfrac{sqin}{J}\right] \cdot Cy_{sc,PA} \cdot Cy_{rm,PA} \quad \text{if } \mathrm{IsScalar}\left(Cy_{0,0}\right) \\ \displaystyle\sum_{i=0}^{\mathrm{rows}(Cy)-1} \left[\left(Cy_i\right)_{i,co} - \left(Cy_i\right)_{i,xh} + \left(Cy_i\right)_{p,xh} \cdot \left[\left(Cy_i\right)_{v,co} - \left(Cy_i\right)_{v,xh}\right] \cdot \dfrac{sqin}{J}\right] \cdot \left(Cy_i\right)_{sc,PA} \cdot \left(Cy_i\right)_{rm,PA} \end{array} \right.$$

PumpWork

Pump work is calculated as compression work to compress water to boiler pressure and constant pressure work forcing it into the boiler. $pump_t = 0.8490$ Is the nominal condenser temperature drop below saturation temperature at exhaust pressure.

```
$PumpWork(Cy) \equiv$
    if $IsScalar(Cy_{0,0})$
        $satliquid \leftarrow ST\_ptdata(Cy_{p,xh}, 0, -1, 1)$          Exhaust steam cooled to saturated liquid state.
        $P \leftarrow Cy_{p,in}$                                         Boiler pressure
        $mass \leftarrow Cy_{im,PA}$                                     Mass input part
    otherwise
        $laststage \leftarrow rows(Cy) - 1$                              Last stage index
        $satliquid \leftarrow ST\_ptdata[(Cy_{laststage})_{p,xh}, 0, -1, 1]$   Exhaust steam cooled to saturated liquid state.
        $P \leftarrow (Cy_0)_{p,in}$                                     Boiler pressure
        $mass \leftarrow (Cy_{laststage})_{im,PA} \cdot (Cy_{laststage})_{sc,PA}$   Mass input part
    $pumpinlet \leftarrow ST\_ptdata(satliquid_p, satliquid_t \cdot pump_t, 1, 1)$   Pump inlet state
    $pumpoutlet \leftarrow ST\_ptdata(P, pumpinlet_s, 1)$               Pump outlet state
    $\left[\frac{(P - pumpinlet_p) \cdot pumpoutlet_v \cdot sqin}{J} + (pumpoutlet_i - pumpinlet_i)\right] \cdot mass$   PumpWork = Transport + compression work
```

CycleWO

The total output work from this cycle.

$$\mathrm{CycleWO}(Cy) \equiv \left|\begin{array}{ll} (\mathrm{CyCuW}(Cy) + \mathrm{CyExpW}(Cy)) - \mathrm{CyComW}(Cy) - \mathrm{PumpWork}(Cy) & \text{if } \mathrm{IsScalar}\left(Cy_{0,0}\right) \\ \displaystyle\sum_{i=0}^{\mathrm{rows}(Cy)-1} \left(\mathrm{CyCuW}\left(Cy_i\right) + \mathrm{CyExpW}\left(Cy_i\right) - \mathrm{CyComW}\left(Cy_i\right)\right) - \mathrm{PumpWork}(Cy) & \text{otherwise} \end{array}\right.$$

CycleWOv

Scaled to fixed expansion volume v.

$$\mathrm{CycleWOv}(Cy, v) \equiv \frac{v \cdot \left|\begin{array}{ll} (\mathrm{CyCuW}(Cy) + \mathrm{CyExpW}(Cy)) - \mathrm{CyComW}(Cy) - \mathrm{PumpWork}(Cy) & \text{if } \mathrm{IsScalar}\left(Cy_{0,0}\right) \\ \displaystyle\sum_{i=0}^{\mathrm{rows}(Cy)-1} \left(\mathrm{CyCuW}\left(Cy_i\right) + \mathrm{CyExpW}\left(Cy_i\right) - \mathrm{CyComW}\left(Cy_i\right)\right) - \mathrm{PumpWork}(Cy) & \text{otherwise} \end{array}\right.}{\left|\begin{array}{ll} \displaystyle\sum_{i=0}^{\mathrm{rows}(Cy)-1} \left(Cy_i\right)_{\boldsymbol{v,ex}} \cdot \left(Cy_i\right)_{\boldsymbol{sc,PA}} & \text{if } \mathrm{IsArray}\left(Cy_{0,0}\right) \\ Cy_{\boldsymbol{v,ex}} & \text{otherwise} \end{array}\right.}$$

CycleWork

This function gives us the work per pound of steam going through the cycle. Note how it is the total work produced by the cycle calculated using the above partial work function but is divided by the fresh inlet steam part.

$$\mathrm{CycleWork}(Cy) \equiv \frac{\left|\begin{array}{ll} (\mathrm{CyCuW}(Cy) + \mathrm{CyExpW}(Cy)) - \mathrm{CyComW}(Cy) - \mathrm{PumpWork}(Cy) & \text{if } \mathrm{IsScalar}\left(Cy_{0,0}\right) \\ \displaystyle\sum_{i=0}^{\mathrm{rows}(Cy)-1} \left(\mathrm{CyCuW}\left(Cy_i\right) + \mathrm{CyExpW}\left(Cy_i\right) - \mathrm{CyComW}\left(Cy_i\right)\right) - \mathrm{PumpWork}(Cy) & \text{otherwise} \end{array}\right.}{\left|\begin{array}{ll} \left(Cy_{\mathrm{rows}(Cy)-1}\right)_{\boldsymbol{im,PA}} \cdot \left(Cy_{\mathrm{rows}(Cy)-1}\right)_{\boldsymbol{sc,PA}} & \text{if } \mathrm{IsArray}\left(Cy_{0,0}\right) \\ Cy_{\boldsymbol{im,PA}} & \text{otherwise} \end{array}\right.}$$

CycleEff

Efficiency of the cycle

$$\mathrm{CycleEff}(Cy) \equiv \left|\begin{array}{l} \text{if } \mathrm{IsScalar}\left(Cy_{0,0}\right) \\ \quad \left|\begin{array}{l} \mathrm{feedtemp} \leftarrow \mathrm{ST\_ptdata}\left(Cy_{\boldsymbol{p,xh}}, 0, -1, 1\right)_{\boldsymbol{t}} \cdot \boldsymbol{pump_t} \\ \dfrac{(\mathrm{CyCuW}(Cy) + \mathrm{CyExpW}(Cy)) - \mathrm{CyComW}(Cy) - \mathrm{PumpWork}(Cy)}{Cy_{\boldsymbol{im,PA}} \cdot \left(Cy_{\boldsymbol{h,in}} - \mathrm{ST\_ptdata}\left(Cy_{\boldsymbol{p,xh}}, \mathrm{feedtemp}, 1, 1\right)_{\boldsymbol{h}}\right)} \end{array}\right. \\ \text{otherwise} \\ \quad \left|\begin{array}{l} \mathrm{last} \leftarrow \mathrm{rows}(Cy) - 1 \\ \mathrm{feedtemp} \leftarrow \mathrm{ST\_ptdata}\left[\left(Cy_{\mathrm{last}}\right)_{\boldsymbol{p,xh}}, 0, -1, 1\right]_{\boldsymbol{t}} \cdot \boldsymbol{pump_t} \\ \dfrac{\displaystyle\sum_{i=0}^{\mathrm{rows}(Cy)-1} \left(\mathrm{CyCuW}\left(Cy_i\right) + \mathrm{CyExpW}\left(Cy_i\right) - \mathrm{CyComW}\left(Cy_i\right)\right) - \mathrm{PumpWork}(Cy)}{\left(Cy_{\mathrm{last}}\right)_{\boldsymbol{im,PA}} \cdot \left[\left(Cy_0\right)_{\boldsymbol{h,in}} - \mathrm{ST\_ptdata}\left[\left(Cy_{\mathrm{last}}\right)_{\boldsymbol{p,xh}}, \mathrm{feedtemp}, 1, 1\right]_{\boldsymbol{h}}\right]} \end{array}\right. \end{array}\right.$$

The following function is used to generate a cycle plot array. Row 0 containes piston position.

```
$ChCy(Cy, pr, vo) :=$
    $n \leftarrow rows(pr) \cdot cols(pr) - 1$
    for $k \in 0..n$ if $n \geq 0$
        $pr_k \leftarrow pr_k$
    otherwise
        $pr_0 \leftarrow pr$
        $n \leftarrow 0$
    $im \leftarrow 0$
    $im \leftarrow root\left[ST\_ptdata\left(Cy_{\boldsymbol{p},\boldsymbol{in}}, \frac{Cy_{\boldsymbol{h},\boldsymbol{in}} \cdot im + Cy_{\boldsymbol{h},\boldsymbol{co}} \cdot Cy_{\boldsymbol{rm},\boldsymbol{PA}}}{im + Cy_{\boldsymbol{rm},\boldsymbol{PA}}}, \boldsymbol{h}, 1\right)_{\boldsymbol{v}} \cdot \left(im + Cy_{\boldsymbol{rm},\boldsymbol{PA}}\right) - Cy_{\boldsymbol{v},\boldsymbol{co}} \cdot Cy_{\boldsymbol{rm},\boldsymbol{PA}}, im$
    $Ptim \leftarrow ST\_ptdata\left(Cy_{\boldsymbol{p},\boldsymbol{in}}, \frac{Cy_{\boldsymbol{h},\boldsymbol{in}} \cdot im + Cy_{\boldsymbol{h},\boldsymbol{co}} \cdot Cy_{\boldsymbol{rm},\boldsymbol{PA}}}{im + Cy_{\boldsymbol{rm},\boldsymbol{PA}}}, \boldsymbol{h}, 1\right)$
    for $k \in 0..n$
        $P_{k+1,0} \leftarrow Ptim_{(pr_k)}$
        $P_{k+1,100} \leftarrow Cy_{pr_k, \boldsymbol{xh}}$
        $P_{k+1,200} \leftarrow Ptim_{(pr_k)}$
    $P_{0,0} \leftarrow vo \cdot \frac{Cy_{\boldsymbol{Cl},\boldsymbol{PA}}}{Cy_{\boldsymbol{Cl},\boldsymbol{PA}} + 1}$
    $P_{0,100} \leftarrow vo$
    $P_{0,200} \leftarrow vo \cdot \frac{Cy_{\boldsymbol{Cl},\boldsymbol{PA}}}{Cy_{\boldsymbol{Cl},\boldsymbol{PA}} + 1}$
    $pse \leftarrow \frac{1 - Cy_{\boldsymbol{cu},\boldsymbol{PA}}}{98}$
    $psc \leftarrow \frac{Cy_{\boldsymbol{xc},\boldsymbol{PA}}}{98}$
    $vse \leftarrow \frac{Cy_{\boldsymbol{v},\boldsymbol{ex}} - Cy_{\boldsymbol{v},\boldsymbol{cu}}}{98}$
    $vsc \leftarrow \frac{Cy_{\boldsymbol{v},\boldsymbol{xh}} - Cy_{\boldsymbol{v},\boldsymbol{co}}}{98}$
    for $j \in 1..99$
        $P_{0,j} \leftarrow vo \cdot \frac{Cy_{\boldsymbol{Cl},\boldsymbol{PA}} + Cy_{\boldsymbol{cu},\boldsymbol{PA}} + pse \cdot (j - 1)}{Cy_{\boldsymbol{Cl},\boldsymbol{PA}} + 1}$
        $P_{0,j+100} \leftarrow vo \cdot \frac{Cy_{\boldsymbol{Cl},\boldsymbol{PA}} + Cy_{\boldsymbol{xc},\boldsymbol{PA}} - psc \cdot (j - 1)}{Cy_{\boldsymbol{Cl},\boldsymbol{PA}} + 1}$
        $pe \leftarrow \frac{Cy_{\boldsymbol{p},\boldsymbol{cu}}}{\left[Cy_{\boldsymbol{v},\boldsymbol{cu}} + vse \cdot (j - 1)\right.}$
```

```
        $\left\lfloor \dfrac{}{Cy_{2,2}} \cdot Cy_{\boldsymbol{s},\boldsymbol{cu}} \right\rfloor$
        $pe \leftarrow \mathrm{root}\left[\mathrm{ST\_ptdata}\left[pe, Cy_{\boldsymbol{v},\boldsymbol{cu}} + vse\cdot(j-1), \boldsymbol{v}, 1\right]_{\boldsymbol{s}} - Cy_{\boldsymbol{s},\boldsymbol{cu}}, pe\right]$
        $Pte \leftarrow \mathrm{ST\_ptdata}\left(pe, Cy_{\boldsymbol{s},\boldsymbol{cu}}, 5, 1\right)$
        $pc \leftarrow \dfrac{Cy_{\boldsymbol{p},\boldsymbol{xh}}}{\left[\dfrac{Cy_{\boldsymbol{v},\boldsymbol{xh}} - vsc\cdot(j-1)}{Cy_{\boldsymbol{v},\boldsymbol{4}}} \cdot Cy_{\boldsymbol{s},\boldsymbol{xh}}\right]}$
        $pc \leftarrow \mathrm{root}\left[\mathrm{ST\_ptdata}\left[pc, Cy_{\boldsymbol{v},\boldsymbol{xh}} - vsc\cdot(j-1), \boldsymbol{v}, 1\right]_{\boldsymbol{s}} - Cy_{\boldsymbol{s},\boldsymbol{xh}}, pc\right]$
        $Ptc \leftarrow \mathrm{ST\_ptdata}\left(pc, Cy_{\boldsymbol{s},\boldsymbol{xh}}, 5, 1\right)$
        for $k \in 0..n$
            $P_{k+1,j} \leftarrow Pte_{\left(pr_k\right)}$
            $P_{k+1,j+100} \leftarrow Ptc_{pr_k}$
    P
```

```
isentropic_r(Ptc, r) :=
    $pe \leftarrow \dfrac{Ptc_0}{r\cdot Ptc_5}$
    $pe \leftarrow \mathrm{root}\left(\mathrm{ST\_ptdata}\left(pe, Ptc_2\cdot r, 2, 1\right)_5 - Ptc_5, pe\right)$
    $\mathrm{ST\_ptdata}\left(pe, Ptc_5, 5, 1\right)$
```