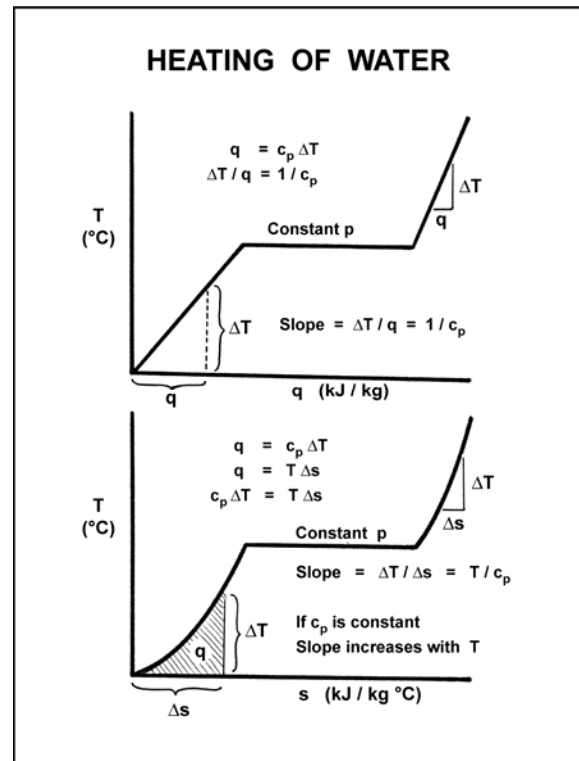
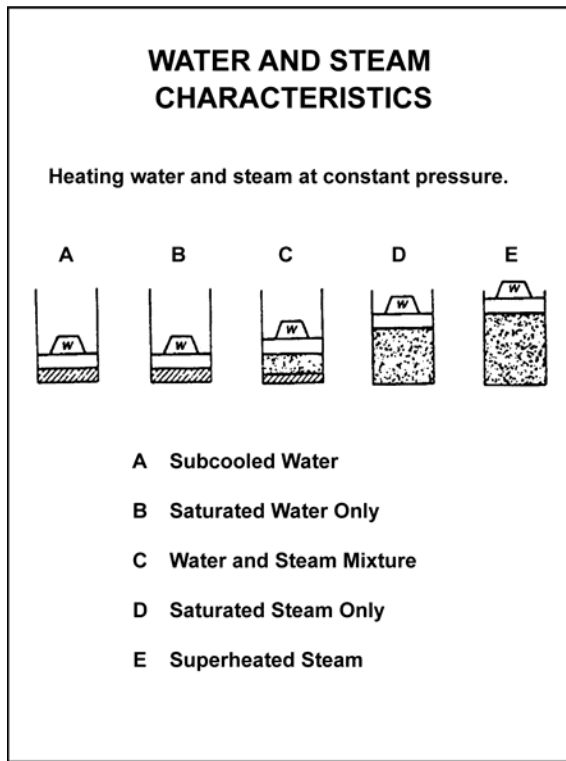


SECTION 4

STEAM TABLES AND CHARTS

WATER AND STEAM

Consider the heating of water at constant pressure. If various properties are to be measured, an experiment can be set up where water is heated in a vertical cylinder closed by a piston on which there is a weight. The weight acting down under gravity on a piston of fixed size ensures that the fluid in the cylinder is always subject to the same pressure. Initially the cylinder contains only water at ambient temperature. As this is heated the water changes into steam and certain characteristics may be noted.



Initially the water at ambient temperature is *subcooled*. As heat is added its temperature rises steadily until it reaches the saturation temperature corresponding with the pressure in the cylinder. The volume of the water hardly changes during this process. At this point the water is *saturated*. As more heat is added, steam is generated and the volume increases dramatically since the steam occupies a greater space than the water from which it was generated. The temperature however remains the same until all the water has been converted into steam. At this point the steam is *saturated*. As additional heat is added, the temperature of the steam increases but at a faster rate than when the water only was being heated. The

volume of the steam also increases. Steam at temperatures above the saturation temperature is *superheated*.

If the temperature T is plotted against the heat added q the three regions namely subcooled water, saturated mixture and superheated steam are clearly indicated. The slope of the graph in both the subcooled region and the superheated region depends on the specific heat of the water and steam respectively.

$$c_p = q / \Delta T$$

The slope however is temperature rise ΔT over heat added q . This is the inverse of specific heat c_p .

$$\text{Slope} = 1 / c_p$$

Since heat added at constant pressure is equal to the enthalpy change this plot is really a temperature-enthalpy diagram.

As has already been demonstrated, a temperature-entropy diagram is useful in showing thermodynamic cycles. The temperature-enthalpy diagram may be converted into a temperature-entropy diagram by using the two relations:

$$c_p = q / \Delta T$$

$$\Delta s = q / T$$

Combining these gives:

$$c_p \Delta T = T \Delta s$$

$$\Delta T / \Delta s = T / c_p$$

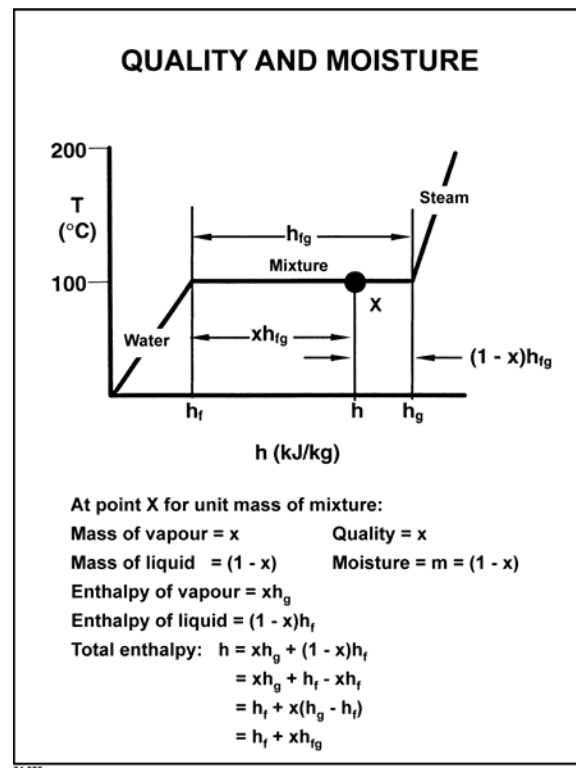
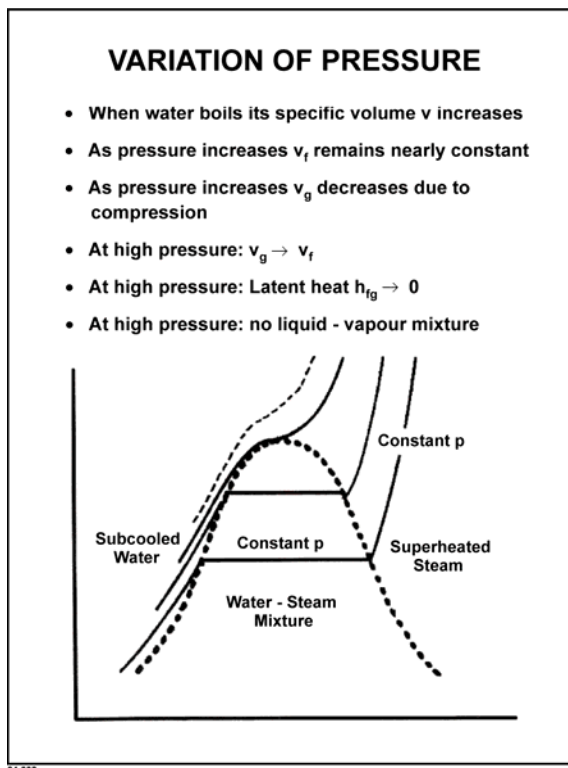
The ratio of change in temperature over change in entropy $\Delta T / \Delta s$ is the slope of the graph on a temperature-entropy diagram. If c_p is constant in one or other region of the plot the slope is proportional to temperature T and will increase as the temperature rises. The area under the curve represents the heat added q up to any point or between any points.

This plot shows just one line of a temperature-entropy chart. If the experiment is repeated under different conditions, families of lines can be developed to obtain a complete chart.

TEMPERATURE-ENTROPY CHART

Consider the heating of water at different pressures each time maintaining the selected pressure constant. A series of similar lines will be obtained with those at higher pressures being above those at lower pressures. As pressure increases however the amount of latent heat added to completely evaporate the water

decreases. This is because, at higher pressure, since the increase in volume from liquid to vapour is not as great, less energy is required to expand the fluid to its new condition. Eventually, at very high pressures, the density of the steam becomes equal to that of the water and no latent heat is required to expand the fluid. If the points at which the water and steam respectively become saturated are joined up a *saturated water line* and a *saturated steam line* are formed. These join at the *critical point* where steam and water densities are equal to form the characteristic bell shaped curve. The subcooled water region is to the left and the superheated steam region to the right of the bell curve. The saturated water-steam mixture region lies under or within the bell.



Within the saturated water-steam mixture region there are intermediate conditions. When only part of the total latent heat to evaporate the water has been added a unique point X on the particular constant pressure line is reached. At this point the mass fraction of vapour is x and the mass fraction of liquid is $(1 - x)$. Each fraction has associated with it either the enthalpy of the water at saturation conditions h_f or the enthalpy of the steam at saturation conditions h_g . The total enthalpy of the mixture is therefore:

$$h = x h_g + (1 - x) h_f$$

$$h = h_f + x (h_g - h_f)$$

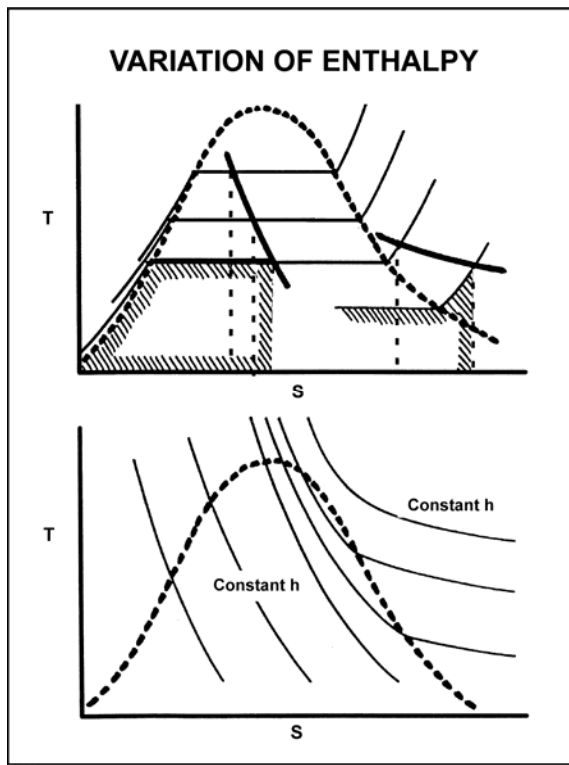
$$h = h_f + x h_{fg}$$

The value h_{fg} is equivalent to the latent heat required to convert the water into steam. Similar formulae may be derived for internal energy u and entropy s

$$u = u_f + X u_{fg}$$

$$s = s_f + X s_{fg}$$

If all these unique points X for a given mass fraction of vapour under different pressures are joined, a line of constant mass fraction or steam quality is obtained. For other unique mass fractions, other lines of *steam quality* can be drawn to create a whole family of lines. Note that these lines all meet at the critical point.



Another important family of lines is that showing constant enthalpy conditions. The change in enthalpy h is equal to the heat added q under constant pressure conditions. If given amounts of heat are added from an arbitrary zero condition for different pressure conditions, this heat q will be represented by the area under the respective constant pressure lines. These areas must all be equal for a given amount of heat added and thus a given change in enthalpy. Joining up the points on each constant pressure line at which the given amount of heat has been added will produce a line of constant enthalpy. Adding different amounts of heat will produce a family of constant enthalpy lines. Note that these have a steep slope in the saturated region but a lesser slope in the superheated region.

FLUID PROPERTIES

The following properties for liquids and gases may be determined by experiment and are plotted on thermodynamic diagrams:

Pressure	p
Temperature	T
Specific volume	v
Internal energy	u
Enthalpy	h
Entropy	s

Pressure and temperature can be measured directly. Specific volume can be obtained by measurement of the physical size of the container. Enthalpy can be obtained by measurement of the amount of heat added at constant pressure. Internal energy can be calculated from the formula for the definition of enthalpy:

$$h = u + p v$$

Entropy can be calculated from its formula in terms of temperature:

$$s = c_p \ln (T / T_o)$$

Temperature T_o is an arbitrary base temperature (273°K for water) and specific heat c_p may be obtained from the formula:

$$c_p = q / \Delta T$$

$$c_p = \Delta h / \Delta T$$

In the saturated water-steam mixture region the change in entropy is obtained as follows:

$$\Delta s = q / T$$

$$\Delta s = h_{fg} / T_{\text{saturation}}$$

All relevant parameters may thus be obtained and plotted as families of curves on a temperature-entropy diagram.

It is not always sufficiently accurate to read values from such a diagram. To overcome this problem the calculated values which would be plotted are instead presented in tabular form in a set of thermodynamic tables. These have high accuracy but, since only discrete values in a continuum are presented, interpolation is often necessary to obtain the desired values.

THERMODYNAMIC EQUATIONS

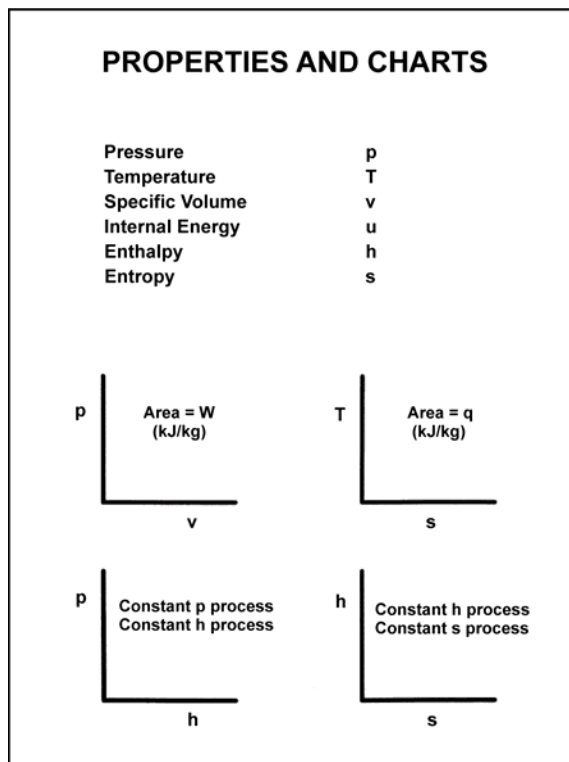
Certain steam and water properties can be determined by experiment and others subsequently by calculation from basic formulae already given. Steam does however follow to some degree the gas laws, that is, as pressure increases specific volume decreases and as temperature increases specific volume increases. Experimental determination of the properties allows the deviation from the gas laws to be ascertained. Thus using a combination of the gas laws, the equations already derived and experimental results it is possible to develop suitable semi-empirical equations which will allow the properties of water and steam to be computed. Such equations are used for developing steam tables where each tabulated value is calculated. These equations are usually polynomials with several constants. The

more complex the polynomial the more accurate the results and often as many as six constants are used in the equation.

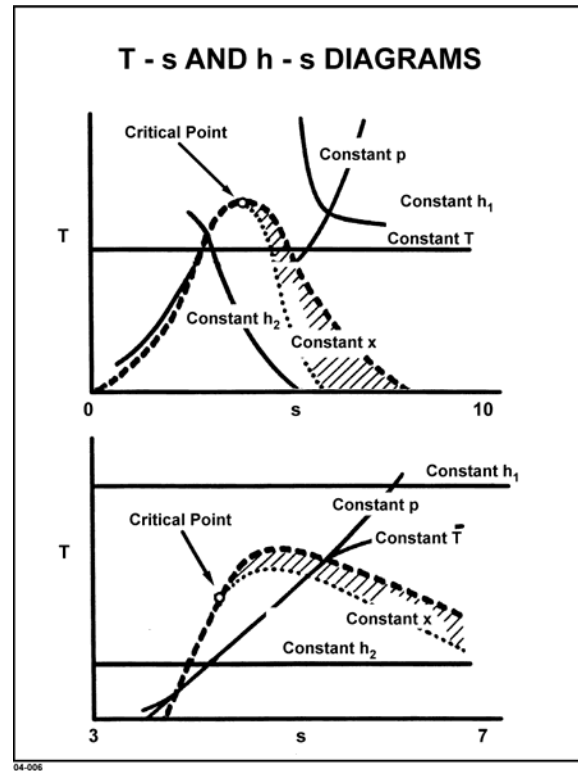
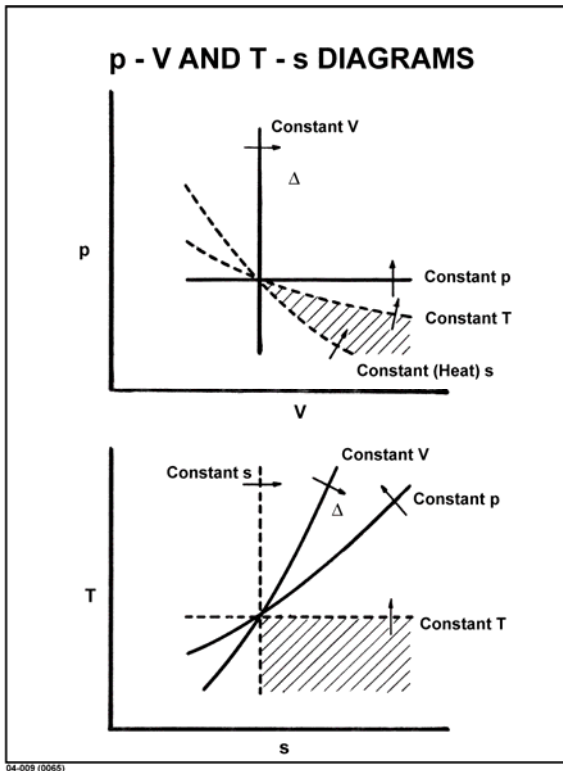
Equations of this type are also used in computer routines to find required properties. Commercially available programs are available on computer diskettes. Many of these however allow the calculation of properties from temperature and pressure and not vice-versa so are limited in their usefulness unless additional iterative routines are devised. Suitable equations for the calculation of certain properties are given in the book "Steam and Gas Tables with Computer Equations" by T.F. Irvine and P.E. Liley. This book also gives tables of values obtained from the equations so the application of any equation can be readily checked.

ENTHALPY-ENTROPY CHART

It has previously been shown that a pressure-volume diagram is useful in showing mechanical cycles and that a temperature-entropy diagram is useful in showing thermodynamic cycles. Since there are six main thermodynamic properties, as given above, any number of diagrams using two properties as axes are possible. Two other commonly used diagrams are the pressure-enthalpy diagram used for refrigeration cycles and the enthalpy-entropy diagram used for steam turbines. The choice of diagram depends primarily on what is to be shown and what processes are constant. In refrigeration cycles some processes occur at either constant pressure or constant enthalpy. These processes are simply horizontal lines or vertical lines respectively on a pressure-enthalpy diagram. For steam turbines some processes occur at either constant enthalpy or constant entropy. These processes are also simply horizontal and vertical lines respectively on an enthalpy-entropy diagram. Furthermore a change in enthalpy on such a diagram shows the work done by the turbine and a change in entropy indicates the degree of irreversibility and hence loss in the turbine.



It has been shown how a temperature-entropy diagram can be developed. All other diagrams are related in that the parameters illustrated must maintain their relationship with one another. Thus any diagram is simply a skewed version of a temperature-entropy diagram with new axes being created. To convert a temperature-entropy diagram into an enthalpy-entropy diagram the entire diagram is rotated slightly and stretched such that the constant enthalpy lines become horizontal. The saturation curve changes from a bell shaped curve into a curve with two nearly straight portions at almost right angles to one another and the critical point moves down to the left. Failure to recognise this change in shape is a common fault in Thermodynamics.



STEADY FLOW PROCESSES

With non-flow processes the working fluid is contained within a system and undergoes change from an initial to a final condition. These changes can be shown on thermodynamic diagrams. If the process maintains a certain parameter (for example pressure) constant that process simply follows that constant parameter line on the diagram.

In steady flow processes the working fluid passes through a component continuously and undergoes changes, while flowing, from an initial inlet condition to a final outlet condition. These changes can also be shown on thermodynamic diagrams.

Processes occurring at constant conditions (for example enthalpy) will also follow the appropriate constant parameter line on the diagram.

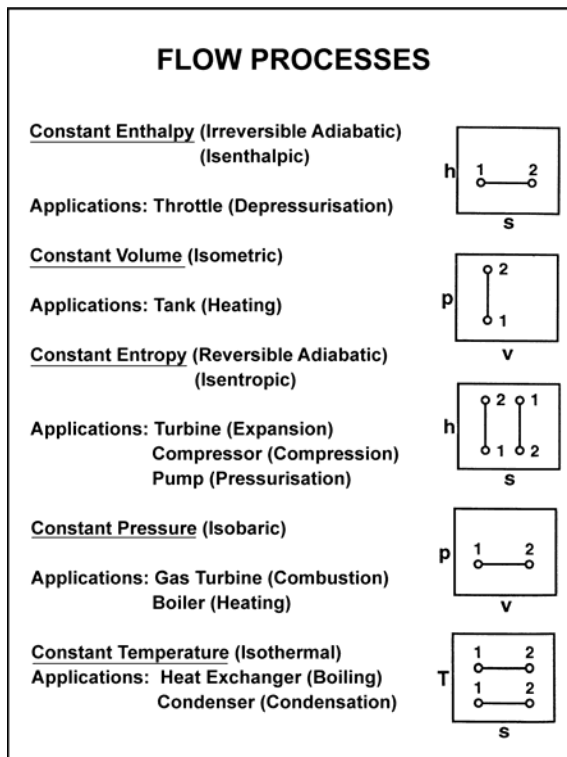
The non-flow processes previously described and listed below can all occur in steady flow devices.

- Constant Pressure
- Constant Temperature
- Constant Volume
- Constant “Heat”

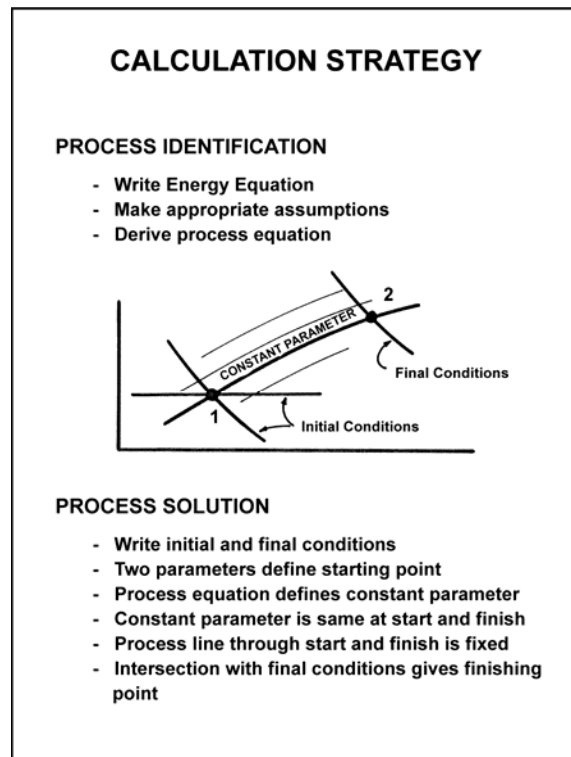
In steady flow however the constant “heat” or adiabatic process in which there is no heat transfer may be reversible or irreversible. If it has no fluid friction it is reversible adiabatic or isentropic as is the case in an ideal or frictionless turbine. If it has fluid friction it is irreversible adiabatic or isenthalpic as is the case in a throttle. There are thus five main steady flow processes:

- Constant Pressure or Isobaric
- Constant Temperature or Isothermal
- Constant Volume or Isometric
- Reversible Adiabatic or Isentropic
- Irreversible Adiabatic or Isenthalpic

Each of these processes has important engineering applications. A knowledge of the type of process allows unknown conditions to be determined from basic measurements.



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CALCULATION STRATEGY

In solving an engineering problem involving a thermodynamic process there is a particular strategy to be followed. With practice and experience some of the steps soon become intuitive or obvious but initially the full process should be followed.

Process Identification

The first stage is to identify the process. This should be done as follows:

- Write out the complete energy equation
- Make appropriate assumptions regarding minor terms
- Derive the basic process equation

Process Solution

The second stage is to solve for the unknown condition. If this is one of the final conditions after the process the following procedure should be followed:

- Write down the known initial and final conditions
- Two parameters will define the starting point
- The process equation defines the constant parameter
- The constant parameter is the same at the starting and finishing points
- The process line is drawn through the starting and finishing points
- Intersection of the process line with any final condition gives the finishing point.

This procedure may be adapted to find any unknown. If one of the initial conditions is unknown it is possible to work backwards along the process line from the known final conditions to find the unknown initial condition.