Transient Analyses In Relief Systems

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ABSTRACT

Analyses of pressure relief systems are concerned with transient process disturbances that potentially cause overpressure of piping and mechanical equipment. The transient in pressure may be beyond that allowed by the relevant design code. Process disturbances typically include blockages in piping and vessel outlets, utility failure such as air and power, and uncontrolled process reactions. The aim of transient analyses is to determine the requirements for pressure relief, such that the effect of these disturbances is minimized or controlled. The integrity of equipment is maintained thereby providing a safe operating environment for personnel. An understanding of both the hydraulic and thermodynamic response characteristics of the process involved is fundamental to these analyses. The steady state mass and energy balance is adapted to provide the basis from which the dynamic process response may be evaluated.

This paper will focus on the application of transient process analyses on the high pressure leach (or Digestion) area of alumina refineries. The impact of vessel blockages and plant power failures will be discussed with emphasis on analysis methodology for power failures.

INTRODUCTION

In the ‘Digestion’ area of an alumina refinery, ground bauxite is mixed with caustic soda solution. The resultant slurry is pumped into high pressure reaction vessels or holding tubes. Steam is injected to maintain the required reaction temperature to produce a mixture of the dissolved alumina in caustic solution and undissolved bauxite solids. The discharge from these reaction vessels or 'digesters' is cooled to atmospheric boiling temperature by passing through a series of flash vessels. The steam evolved from these pressure vessels is used to pre-heat the incoming caustic liquor or bauxite slurry in heat exchangers.

The relief system for the Digestion plant generally consists of multiple pressure relief valves connected to each pressure vessel via a dedicated header. The relief valves discharge via branch connections to a common relief line before entering an atmospheric dis-entrainment tank (refer Figure 1).

For Digestion units, the required relief capacities change considerably and generally increase with elapsed time from the onset of an emergency. For the first flash tank downstream of the reaction vessel or ‘digester’ there is an immediate relationship between the digestion feed pumps and the required relief capacity. For all remaining flash vessels, the required relief capacity is principally a function of upstream vapour pressures, the resistances of the pipework between flash vessels, and time.

In the event of a blockage downstream of the first flash vessel, an increasing slurry level will result. As the level continues to increase, the vapour space will continue to diminish until the vessel floods. This is a direct consequence of the fact that the relief valve set pressure must necessarily be above the operating vapour pressure. Not until the flash tank vapour pipework floods will the relief valve be activated.

At this point there is no more vapour generation either within the vessel or in the upstream pipework and a direct liquid connection is established between the flash tank relief valves, slurry in the digesters and through to the digestion feed pumps. The required relief capacity for the first flash tank is therefore a function of the flow delivered by the feed pumps.

For the remaining flash vessels the analysis is similar except that the relief capacity is not a function of pump duty, because there is not a liquid connection between the downstream vessel and the pump. Instead, when any downstream vessel floods, flashing between the upstream and downstream vessel will cease. A liquid connection between the flooded vessel and the vapour space in the upstream vessel will occur. The pressure in this vapour space then becomes the driving force that determines relief capacity.

In respect to flash vessel flooding, there is a direct relationship between the sizing of the underflow pipework and required relief capacity. Where the upstream vapour pressure becomes the driving force, relief capacity is driven by the resistance of the underflow pipework and the pressure difference between the upstream and downstream tank. The absence of vapour generation suppresses high volume and high resistance two phase flow, and the inter-stage pipework is capable of conveying more mass flow than during normal operations.

During a power failure the flow of spent liquor (or slurry) will cease through the spent liquor heaters resulting in a loss of condensing capacity. As a result, vapour extraction from the flash vessels will also cease. With an existing pressure gradient at the moment of power failure, slurry flow from tank to tank will continue. This pressure gradient is no longer a function of the heater performance (i.e. rates of condensation) but is governed by the flow resistances of the underflow pipework.

The analysis of the transient events described above is complex, particularly in respect of a power failure. The number of configurations are dependent on the slurry inventory present in each individual flash tank at the time of the power cut, and the number of vessels in service. Each set of initial conditions will provide a different set of answers.

To determine the required relief capacity to cover all variations is impractical. Realistic emergency scenarios must therefore be individually examined to determine required relief valve capacities. Such scenarios usually assume a single incident, failure or error occurring at time zero. Events are not compounded unless one incident, failure or error cascades into another failure.

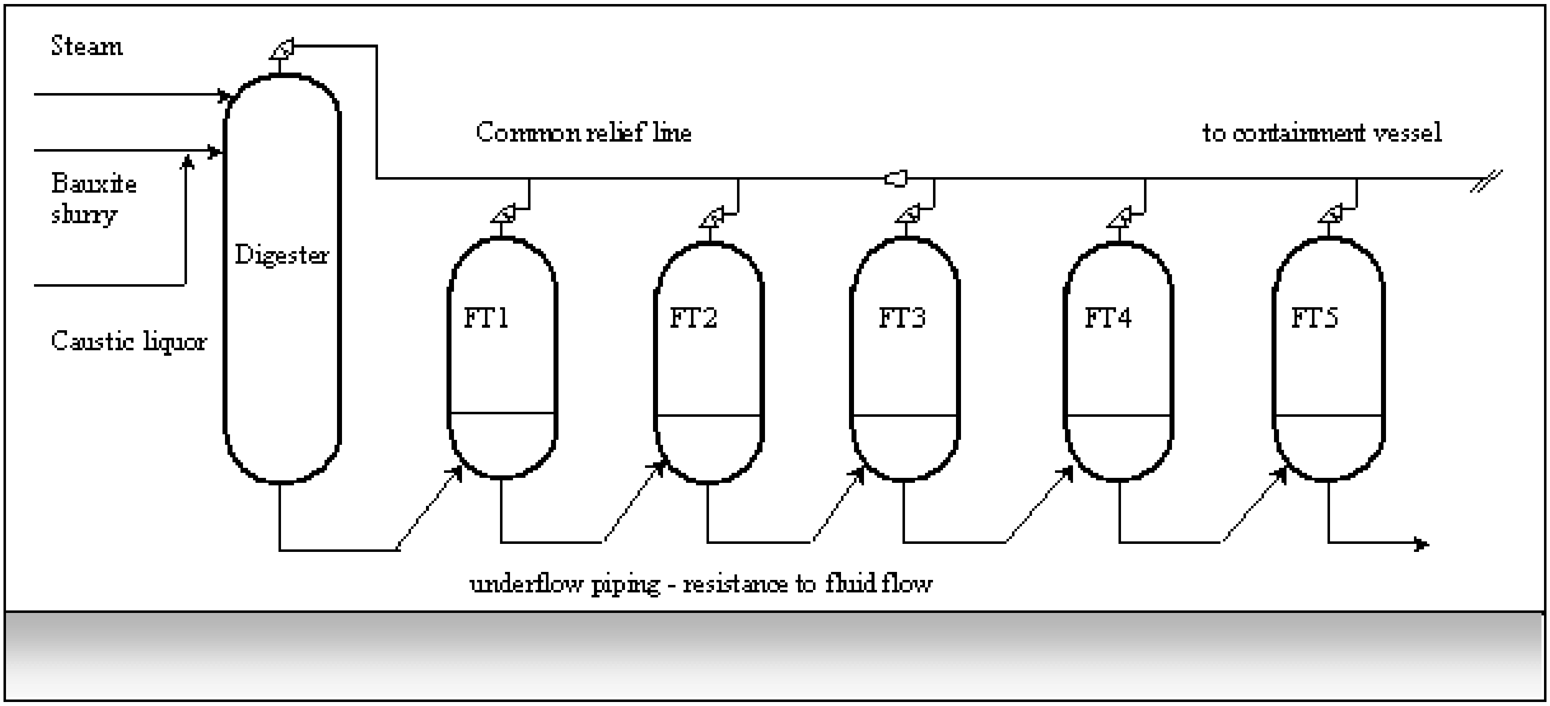

Figure 1: Digestion Flash Train

POWER FAILURE ANALYSIS METHODOLOGY

The generalized methodology for analysis of a power failure is set out below.

Analysis requires simulation of the thermodynamic and hydraulic response of the system. The methodology allows a quasi-dynamic assessment of the effects of a power outage based on calculations over finite time integrals. The power failure analyses are generally conducted over a 15 minute time frame to assess required relief capacities. This time period is taken as a suitable operator response time from the onset of the transient condition for corrective action to be taken, based on American Petroleum Institute Recommended Practice 521.

Generalized Power Failure Analysis Methodology

1. The initial solids, liquor and vapour masses in each vessel are calculated from the vessel levels at $t=0$.
   For vessel 'n' :

   Solids = $M_{s(n,t=0)}$; *Liquor* = $M_{l(n,t=0)}$; *Vapour* = $M_{v(n,t=0)}$

2. From the initial solids, liquor and vapour mass, the energy in each vessel may be determined at $t=0$.

   $$E_{(n,t=0)} = M_{s(n,t=0)} . \overline{C}_{ps} . T_{s(n,t=0)} + M_{l(n,t=0)} . \overline{C}_{pl} . T_{l(n,t=0)} + M_{v(n,t=0)} . \hat{H}_{v(n,t=0)} \qquad (1)$$

3. Two phase flow calculations are performed using Kaiser Engineers' Two Phase Slip Model program to calculate the slurry flow from the upstream vessel to the downstream vessel at the onset of the power failure. For the initial calculations, a particular tank level is assumed with flash stage vapour pressures taken from normal process operation. These vapour pressures are normally dictated by condensing capacity of the corresponding heater stage.

4. Based on the liquid and solids flows accumulated in each vessel), new vessel levels may be determined over the selected time interval of analysis (15 -30s time periods).

5. A total energy balance (neglecting frictional losses) may then be performed on each vessel, based

on the initial energy in the vessel and the incoming and outgoing slurry (energy) flows.

$$E_{(x,t=1)} = E_{(x,t=0)} + E_{(x-1,t=1)} - E_{(x,t=1)}$$
$$E_{(x-1,t=1)} = M_{s(x-1,t=1)}.\overline{C}_{ps}.T_{s(x-1,t=0)} + M_{l(x-1,t=1)}.\overline{C}_{pl}.T_{l(x-1,t=0)}$$
$$E_{(x,t=1)} = M_{s(x,t=1)}.\overline{C}_{ps}.T_{s(x,t=0)} + M_{l(x,t=1)}.C_{pl}.T_{l(x,t=0)}$$

(2)

6. The new liquid/vapour mass may be determined from:

$$(M_l + M_v)_{(x,t=1)} = M_{l(x,t=0)} + M_{v(x,t=0)} + M_{l(x-1,t=1)} - M_{l(x,t=1)}$$

(3)

7. The vapour liquid split may then be determined from thermodynamic equilibrium considerations. From an initial estimate of the new vapour pressure and temperature, the thermodynamic properties $\hat{H}_v$ and $\bar{v}$ may be determined.

From the new slurry level the vapour volume may be estimated. From the vapour specific volume, the
new liquid mass can be calculated. The temperature and vapour pressure may be solved iteratively until the total energy determined from thermodynamic properties equates to that determined in equation (2) above.

This generalized procedure is used for each vessel over each time interval for the 15 minute period of analysis.

The results from this analysis are generally plotted as trends of flash tank levels and vapour pressure. Typical output from these calculations is shown below.

Of critical importance to the determination of required relief capacity is the slurry inventory accumulated (positive or negative) in each vessel. The flooding of a flash tank with slurry will impose the requirement for flashing liquid relief through the relief valves as opposed to vapour relief only.

The maximum requirement for relief capacity for any vessel generally results from consideration of vessel blockages in the absence of a coincident event (such as a vessel blockage at the same time as a power failure).

SAMPLE RESULTS – POWER FAILURE ANALYSIS

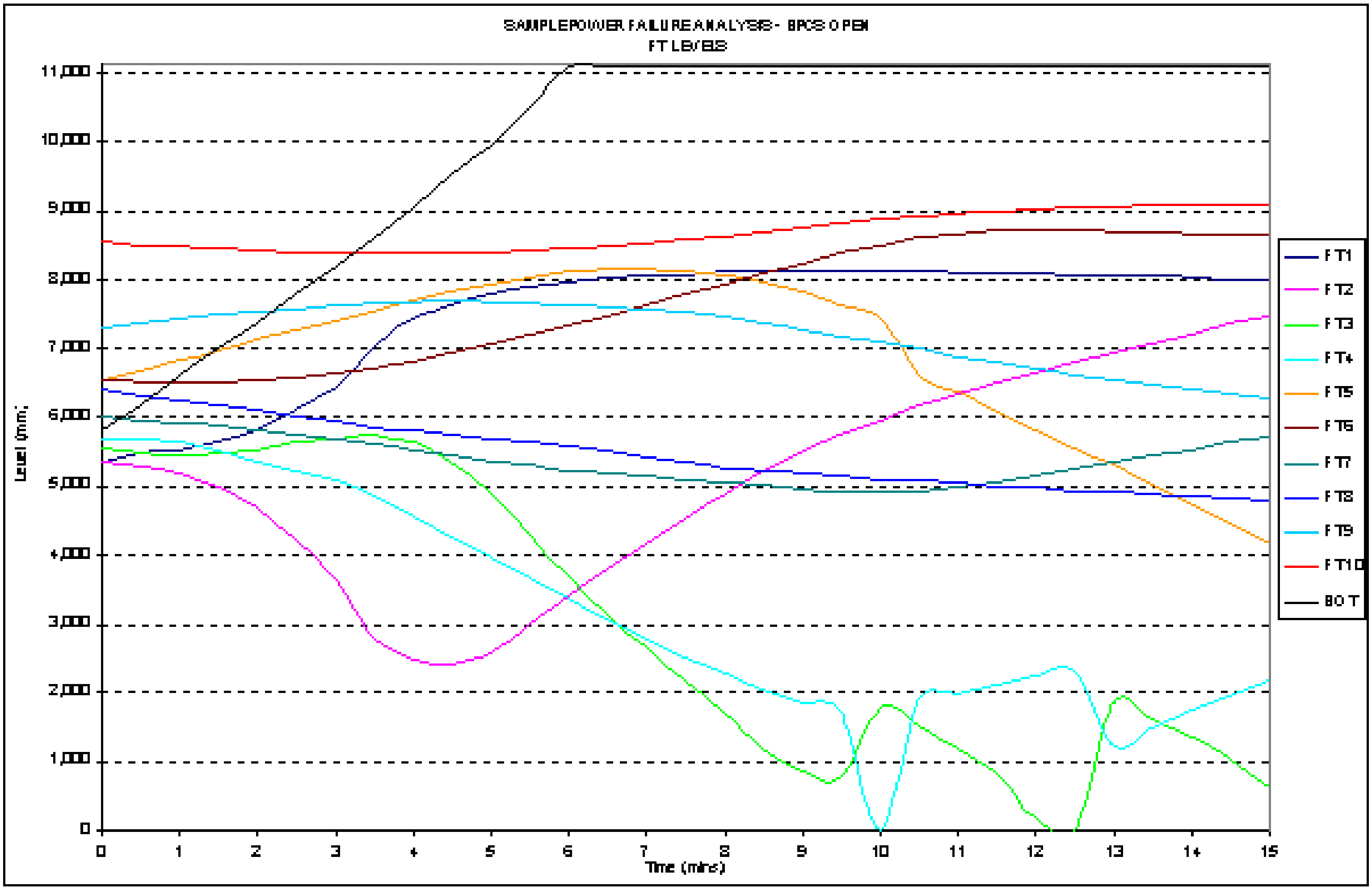

Figure 2: Slurry level in flash tanks.

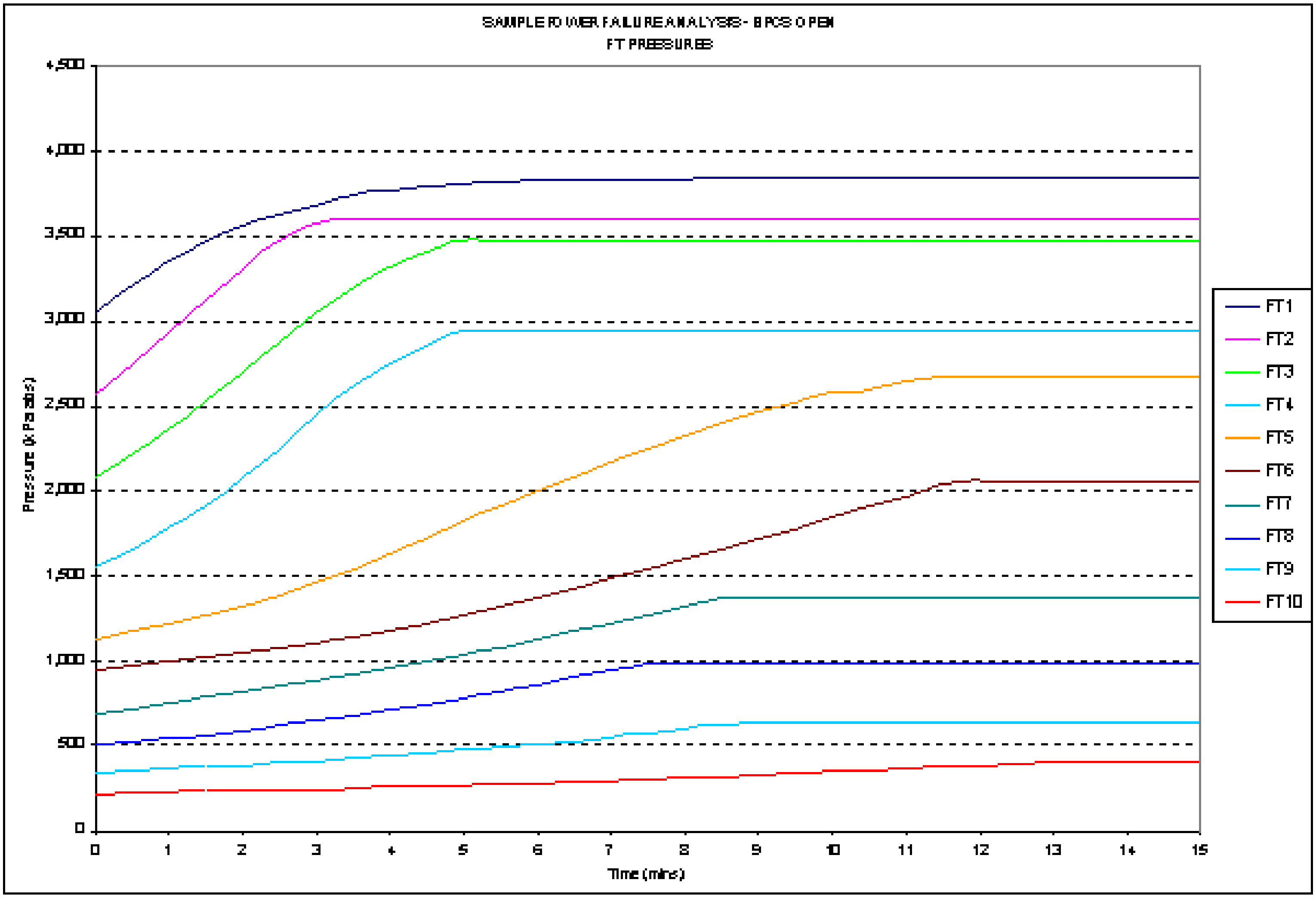

Figure 3: Pressure Profiles.

DISCUSSION OF RESULTS

The sample results above illustrates a power failure analysis, with live steam to the digesters on and back pressure control valves between the digester vessel and the flash train failing open.

Following the power failure, the flash tank pressures provide a driving force for the flow of flashing slurry between vessels. The transient flows are determined by the continuously changing pressure differentials between flash vessels balanced against the hydraulic resistance, unless critical flow conditions prevail in the underflow pipework.

The medium and low pressure vessels are subject to increasing liquor temperatures and vapour pressures as the high temperature slurry continues its passage to the downstream vessels. The flash train vapour pressures increase as a family of curves, with the highest rates of pressure rise evident in the high pressure flash vessels. The vessel vapour pressures continue to rise until the set pressure of individual relief valves is reached. All flash vessels were predicted to reach the ‘set pressure’ of their relief valves by the end of the 15 minute period in the above analysis.

Back pressure control valves between the ‘digester’ and flash train are assumed to fail open at the moment of power failure. The flash vessels continue to be fed by slurry inventory from the upstream ‘Digesters’ for the 15 minute period of analysis, at which point inventory in the digesters is nearly exhausted. For this analysis, flash tanks were predicted not to flood with slurry (other than the atmospheric ‘Blow Off Tank’). This outcome suggests vapour relief from each vessel to the common relief line would occur.

The required vapour relief rates can be estimated based on the vapour accumulation rates into each vessel at the relieving conditions.

Evident from the analysis is the importance of allowing, or having sufficient capacity to allow the Blow Off Tank (atmospheric flash tank) to continue to overflow with slurry from the upstream vessels, during the transient period. The required overflow flow rates can be estimated from the analysis by examining the maximum inter-stage slurry flow from the last low pressure flash tank to the Blow Off Tank.

As discussed above, at the end of the 15 minute period of analysis slurry inventory in the digesters appears almost exhausted. Live steam addition continuing to the digester during the power outage represents the most critical condition. When slurry inventory in the digesters has been exhausted, the potential exists for live steam at the digester relieving pressure to flow through the downstream piping and into the first flash vessel. If the slurry level in this vessel is above the exit point of the inlet piping, the vessel pressure may instantaneously peak at the digester pressure. This pressure may well exceed the accumulation permitted by the relevant code. Isolation of live steam during such transient conditions is therefore recommended.

The 15 minute period of analysis is based on an assumed plant operator response time of 15 minutes, to take corrective action following the onset of the transient condition. This assumption does not suggest the return to normal process operation should immediately follow as such actions may exacerbate the transient condition. Adequate time following the corrective action must be allowed to enable the plant to return to normal levels of pressure, temperature and flow.

CONCLUSIONS

Relief system analyses have been conducted by Kaiser Engineers for multiple Digestion units in alumina refineries incorporating both ‘Digester’ vessels, and ‘Tube digestion’ units. Analyses for back pressure control stations either remaining open and failing closed, and for coincident vessel blockages have also been investigated.

In addition to providing a quantitative assessment of the required liquid and/or vapour relief rates, these analyses provide the basis for determining the optimal operation of the digester piping during transient events .

The power failure analyses also indicate the optimal failure mode of control valves where they are throughout a flash train underflow piping.

NOMENCLATURE

M	mass (kg)
$\overline{C}_p$	mean heat capacity (kJ/kg.°C)
T	temperature (°C)
E	energy (J)
$\hat{H}$	enthalpy (kJ/kg)
$\bar{v}$	specific volume (m^3/kg)

Subscripts

s	solids
l	liquid
v	vapour
n	stage
t	time

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