THE IMPORTANCE OF HEAT TREATMENT ENGINEERING

ABSTRACT

Although the major codes for fabrication, generally give clear instructions on the pre-requisites for heat treatment, the implications of carrying out such heat treatment can be significant, and is easily overlooked by the less experienced contractor.

This paper looks at the most common mechanical problems associated with heat treatment, and the necessary mechanical solutions to ensure a successful heat treatment.

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THERMAL EXPANSION

The source of many problems associated with heat treatment arises from the effects of thermal expansion. Although the principal of thermal expansion is readily understood, problems can arise as a result of thermal expansion, but these are not always so apparent.

The thermal expansion of carbon/low allow steels ranges from \(11.5 \times 10^{-6} \text{m/m°C}\) at ambient, to \(14.8 \times 10^{-6} \text{m/m°C}\) at 600°C. An easier number to work with for estimating purposes is 8mm per metre for carbon steels at 600°C.

Stainless steels have significantly higher rate of rates of expansion, approximately 30% greater than that of carbon steel; this can cause problems where stainless steel components are included in carbon steel heat treatments.

The forces generated by thermal expansion of a constrained component can be massive, and if constraints are not removed, then both distortion, and / or high residual stresses are likely following heat treatment.

The following example highlights this:

**Pipework – the effects of constrained ends**

Many codes make reference to thermal gradients, and the ‘harmful effects’ that may result, and in some cases, minimum heated bands, and insulation are prescribed to avoid such harmful effects. The harmful effects that are referred to, are a result of axial temperature gradients.

However, in addition to radial expansion, axial expansion also takes place, ie the cylinder actually gets longer during the heating cycle. The assumption is generally made, that the pipe/ cylinder is free to expand/contract. However, this may not always be the case, and the effects of constraint can be significant.

**Figure 1 Pipe thermal expansion during local heating**
The well established practice of local heat treatment of piping uses a relatively narrow band of heating to achieve the desired soak temperature at the weld. Radial expansion at soak temperature is only in the order of a few millimetres at most (for piping), and upon cooling, contraction returns the pipe to normal.

However, if the pipe is constrained, the effects are very different. Even on relatively small diameter piping, with relatively narrow heated band widths, axial free expansion is only in the order of 1-3mm. However, if the ends of the pipe are constrained, for example between large heavy wall headers, then, as the expansion cannot be accommodated, the weakest link for the expansion forces to take, is at the heated band, - this results in yielding, and larger radial expansion whilst at temperature.

**Figure 2 Heating constrained pipe**

- The mechanism is that as the region of higher temperature material has a lower modulus, and is consequently weaker, therefore, the expanding material expands into the existing natural bulge like a balloon filling up.
- The bulge creates significant local stresses and yielding, such that even after cooling, a residual bulge remains, along with high residual stresses.
HORIZONTAL VESSELS

PERMANENT SUPPORTS

SLIDING SADDLES

Almost all horizontal vessels are based upon two saddle support system; it is also standard for saddles to be mounted on concrete plinths, incorporating anchor bolts. In most cases, one saddle is fixed, and one sliding, but the sliding saddle is designed to accommodate vessel expansion in service, which may be significantly less than heat treatment temperatures. Accommodation of the design expansion / contraction is via slotted bolt holes.

For heat treatment in full of in-situ vessels, it is therefore important that the expansion can be accommodated by the sliding saddle. If the slot length is insufficient, options are limited to either extending the slots, or jacking up entire vessel so that saddle base plate is clear of anchor bolts.

Expansion can be significant, - using the above rule of thumb, for a vessel with saddles spaced at 10m apart, and thermal expansion will be in the order of 80mm.

Figure 3 – Heated Saddle

Whilst thermal expansion between saddles may be readily identified, another effect associated with heat treatment of welded saddles is not always so clear, and is an often overlooked complication to heat treatment. Not only do welded saddles represent a significant heat sink, but they are also a constraint to radial expansion, except where they are heated fully – in a furnace for example.

Considering initially the saddle alone, and heating only the wrapper plate to 600°C, and allowing conduction only down the ribs and web plate, typically, the base plate remains cold.
The net result of the thermal expansion, is that the base plate arches up at the centre and high thermal stresses are generated in the main web plate.

**Figure 4 – Deformed Saddle**

It has been found that the addition of electrical heating (via ceramic pad heaters) applied below the wrapper plate significantly reduces the magnitude of stresses in the saddle, and the level of distortion post heat treatment. This also has the benefit of compensating for the heat sink effects caused by the saddle, thus guaranteeing soak temperatures at saddle to shell welds. (There can be a knock on effect with this, for saddles in –situ, - if the saddle is low, and mounted on a concrete plinth, then it may need jacking up, and supporting on insulated beams.

**TEMPORARY SADDLES**

For new build columns, it is most common for heat treatment to be carried out in the horizontal position. This requires the use of temporary saddles supports. Aside from the need to ensure that such supports are fit for purpose, - from both saddle perspective, and vessel perspective, vessel expansion needs to be catered for.

It is not uncommon to see vessels as long as 100m, at 600°C, this equates to 800mm of expansion – a significant amount of movement.

Although as indicated above, the forces of expansion are massive, and the vessel will expand even if no specific measures are taken to allow for it. However, in doing so, there is a risk that saddles could snag and potentially tilt, or if internally fired, saddles could slide on the vessel, dislodging insulation, causing significant risk. It is therefore good practice to ensure that saddles are free to move, - ideally utilising simple rollers.
Figure 5: Saddle Rollers

This is a simple but very effective method of ensuring unrestricted expansion of vessels. However, care must be taken in allowing for significant expansion to ensure that sufficient rollers are positioned in front of the saddle.

For long vessels that necessitate a number of supporting saddles, a simple measure that can be taken, is to have the centremost support fixed, and other supports moving, - this halves the magnitude of movement at any one saddle, but remembering that expansion from the centre is in opposite directions – this is possibly quite obvious, but if set up wrongly, has the potential for disastrous results.

Figure 6 – Vessel support system
External stiffening Rings

For large diameter thin wall pressure vessels, external stiffening rings may be a part of the design. Whilst such attachments are not of concern if the vessel is heat treated in a furnace, they can be a major problem for internally heat treated vessels.

External stiffening rings can be in excess of 300mm deep, usually with an outer flange ring. Such rings present a risk from a heat sink point of view, and also thermal expansion. Although code requirements are that the attachment to shell weld reaches temperature, the effects of a cooler perimeter can be significant.

For large stiffening rings, no matter how much insulation is applied, the effects of heat loss are such that it is very difficult to achieve even 500°C at the outer flange. For a large diameter vessel, this presents significant differential thermal expansion.

For example, a 10m dia vessel, at soak temperature of 600°C, radial thermal expansion is 43mm, whereas, the outer flange of an attached ring at 500°C is 36mm. This therefore represents a constraint to expansion of the shell, though if the shell is significantly thicker, typical results are distortion of the stiffening ring.

Options for mitigating this problem are limited, - external electrical heating can be applied relatively easily, but for large diameter vessels with a number of stiffening rings, this can become impractical. One solution is to weld on 50mm short rings to the vessel shell, and then weld on the main ring after PWHT, - but this would need to be addressed at the design/ drawing stage.

Figure 7 – 360mm Stiffening Ring, temperatures at soak.

![Figure 7 - 360mm Stiffening Ring, temperatures at soak.](image)

This shows temperature of 447°C at extents of stiffening ring, even with 200mm insulation applied.
VERTICAL VESSELS

Heat treatment of vertical vessels in situ (having been in service) present a significant challenge in identifying the many factors that need to be considered before proceeding.

Vessels in service often have a significant amount of attachments of various forms that can cause restraints against expansion; it is important that a detailed survey of the vessel is undertaken to identify any attachments that may pose a risk to the heat treatment. In addition to mechanical constraints, other attachments/items in close proximity may also be affected, and require addressing, such as cable trays, instrumentation, sight glasses etc.

MECHANICAL PREPARATION

Restraints on vertical expansion: The height of vessel section being heat treated, will dictate the total vertical expansion that must be catered for. If heat treatment consists of only PWHT of a circ seam, vertical expansion may be minimal; however if a full vessel requires heat treatment, vertical expansion may be in the order of 100’s of millimetres. It is important to remember that everything attached to the vessel above the heated zone will need to move by the total calculated expansion.

ATTACHED PIPING.

Piping may remain attached providing that there is sufficient flexibility prior to any restraints. Where there is doubt, the additional loading imposed can be calculated by simple beam bending theory. If the load cannot be tolerated, then the pipe will need to be cut.

Figure 8 – Attached pipework

However, where restraints exist that cannot be removed, it is preferable to disconnect flanges if possible, but last option is to cut the line in order to provide the free expansion to take place. It is important to look at pipe supports to determine where any cut lines in piping are made, e.g. below any trunnion supports as expansion also lifts the support.
Note that there is an alternative option to cutting pipes, - this is to apply separate heating on the pipe, purely to ensure that the same thermal expansion is created. Depending upon size of heating/required expansion, this may/may not be a viable option.

**SERVICE PLATFORMS**

Service platforms are generally directly attached to the vessel – the weight of which must be accounted for in any stability calculations. Any service platforms that circumvent the vessel by a significant amount, present a restriction to radial expansion at the point of attachment. It is therefore often necessary to ensure that all platform attachments are via horizontally slotted bolt holes.

Figure 9 – Service Platforms

Note that for larger vessels, radial expansion may cause the vessel shell to expand beyond the actual platform; - in this case, it may be necessary to separate the platform into segments to allow additional space for expansion, - or of course platform removal is an alternative option.

It is not unusual to find a number of service decks adjacent to vessels that provide access to the vessel and ancillary or adjacent equipment. These decks often have connections either directly or indirectly to the vessel; any such connection is likely to be a constraint;

For example, service deck with stairs down to vessel service platform;
The stairs, attached to the deck are fixed, but the service platform needs to move vertically with the vessel during expansion. A section of the stairway may need removal to ensure free expansion.
VESSEL STABILITY

The major concern for heat treatment of vertical vessels is stability.

In order to assess stability, the primary loads imposed on the vessel at the heated area need to be considered; these are

- Vessel self weight, including all attachments, internals, insulation etc.
- Any additional loads imposed by attached piping for example.
- Wind loads

The above loads produce ‘Primary’ stresses in the vessel. It is these stresses that are of most interest, and must be within safe limits.

Also, of concern (but mostly for thinner wall sections) in columns, is the risk of local shell buckling caused by axial compression in cylindrical sections. This can be evaluated by hand calculations or analysis.

Thermal Stresses are classified as secondary stresses, and as such, are of far less concern in terms of risk to stability. However, it is not unusual for thermal stresses to be quite significant, and well in excess of yield.

WIND LOADING

Depending upon location, wind can produce a significant load on tall vertical columns, or large diameter storage tanks.

The pressure produced by wind speed, is proportional to the square of the velocity, and taking a simplistic approach, and typical vessel design wind speeds of 150km/hr, produces a pressure of 1.1kN/m². (For reference, API650 uses 1.4KN/m² in assessing overturning stability of storage tanks).

A number of building codes provide detailed methods for establishing wind loads for building design; these include detailed methods for establishing 50yr mean recurrence wind speeds, based upon specific site locations, which take account of geographical location, and site local conditions such as coastal locations; however, it is not normally necessary to revert to these, as it is reasonable to assume the design wind speed, which can be considered a pessimistic approach.

Although the safer approach is to consider design wind speeds, this can present an overly cautious approach, as such wind speeds are based upon the entire design life of the vessel, whereas the heat treatment process will be in the order of 24 hrs. Furthermore, it is highly likely that should storm force winds be forecast and foreseen, and any heat treatment work would be postponed in such circumstances.
For typical columns, the overall effect of wind loading is that the leading edge of the wind produces an overall bending moment on the column; this consequently results in tension at the windward side, which actually counteracts the compressive forces due to self weight; however, conversely, on the leeward side, the opposite effect applies, with the compressive load adding to the magnitude of the self-weight stresses.

A simplistic approach to wind loading assessment can be made by establishing total force on a projected area of the column, and use simple beam theory calculations to establish tensile and compressive bending stresses.

However, this simplistic approach, does not take account for the pressure distribution around a cylinder. Reference to BS 6399-2:1997 - Loading for buildings. Code of practice for wind loads. This document provides load factors to apply to the established wind pressure in order to establish typical pressure distributions around a cylinder.

![Figure 11 – Wind pressure distribution around a cylinder](image)

As can be seen from above, the pressure distribution around a cylinder varies significantly, including significant negative areas (suction), though the effects of this distribution need to be assessed by analysis to see results in detail.

Whilst the effects of pressure distribution are less pronounced on smaller diameter, thicker shells, the opposite is true for larger diameter, thin wall vessels such as storage tanks.
SKIRT TO SHELL WELDS

Where heat treatment involves the bottom dished head/ tan line, then the skirt / shell weld is involved. This will typically require additional electrical heating to compensate for the heat sink effect of the skirt, and also to prevent steep temperature gradients at the skirt / shell weld that would place added strain to the skirt to shell weld.

The implications of this are that the top of the skirt sees full heat treatment temperatures. However as the skirt is not part of the pressure envelope, it is usually designed with a significantly thinner material (and sometimes lower strength material). The skirt therefore is often the most highly stressed region of the vessel, as it is supporting the bulk of the overall vessel weight, but also, under wind load, the skirt is also the most highly stressed region, and this is where calculations/ analysis usually need to focus on.

VESSEL TEMPORARY SUPPORT

Where calculations indicate that additional support is required to ensure vessel stability during heat treatment, options are usually limited to either craneage, or hydraulic jacks.

Whilst either option can be engineered according to individual cases, with the load applied being evaluated from calculations and load that is considered safe for the vessel, with the balance being taken by the jacks / crane.

However, it must be recognised that as the vessel expands, the jacks / crane must be constantly monitored and adjusted in order to maintain a constant load, otherwise, expansion may be sufficient to completely negate the initial applied load. This requires the use of load cells with hydraulic jacks, or inbuilt crane load monitoring systems.

SPHERICAL STORAGE VESSELS

Spherical storage vessels present a unique but very standardised design, that often require heat treatment. The actual heat treatment process is relatively simple, usually utilising combustion based internal firing techniques.

Spherical storage tanks are supported on a number of columns that are generally attached at the equator of the vessel. The implication of this is that during the heat treatment, supporting columns are pushed out due to the radial expansion of the vessel. However, typically, the base of the supporting columns are not designed to accommodate movement, and may even be bolted via grouted bolts.

Thus, during heat treatment, without intervention, the top of the supports move outwards, but the base is fixed; this will result in bending of the columns creating bending stresses in the columns, and at the crotch connection to the spherical shell, ultimately risking the integrity of the column.
In order to remove this risk, standard practice is to provide temporary horizontal jacking mechanisms at the base of each column, and establishing a jacking plan that matches the movement of the base with that at the top of each column. This is typically carried at regular temperature intervals during the heat treatment process, such as every 50°C temperature rise, each column is jacked out by the calculated expansion for each column.

During cooling, the process must be carried out in reverse, with the jacking direction reversed such that at ambient, the column centres are as original.

**ELECTRICAL HEATING OF LARGE SURFACES**

It is sometimes necessary to heat treat very large diameter vessels, - circ seams for example.

Industry standard ceramic pad type heaters have typical power density capabilities approaching 50kW/m². This usually allows temperature in the order of 700°C to be reached even without internal insulation. With this capability, and where internal access may be limited, it may be tempting to carry out the heat treatment without internal insulation.

However, for large vessel diameters, heat loss should be considered as being to ambient, and the high levels of heat flux passing through thickness can generate high temperature differentials. For 25mm thickness, at 600°C, differentials are in the order of 25°C, but this doubles to 50°C for 50mm wall thickness.

This assumes worst case heat losses to ambient; - for smaller sizes, heat losses are reduced by cross radiant heat transfer, and internal bulk temperature build up.

Note that the application of standard thickness of insulation internally, drastically reduces heat loss, and consequently temperature differentials are only in the order of 1-2°C.

*Figure 12 – Through thickness temperature gradient*
TUBESHEETS

The heat treatment of tubesheets requires great care, especially if tubes are already installed and welded. Tubesheets typically are relatively thick, with larger tubesheets being in excess of 300mm, but the nature of tubesheet forgings is that there is usually little material provided to allow welding to the adjacent joining shells on both gas side, and shell side.

TUBESHEET to SHELL WELDS

As indicated above, tubesheet to shell welds are typically very close to the main body of the tubesheet. Although it may be feasible to reach the required temperature at the weld using only externally applied heaters, and locally applied insulation, to carry out such a heat treatment would impart huge thermal stresses in the tubesheet, and possibly distortion. This is because the unheated tubesheet centre would remain relatively cool, resulting in a significant temperature differential between centre and outer, thus creating large thermal stresses.

Note also that where tubes are attached, not only can the rear face of the tubesheet be insulated, but the tubes also act as an additional heat sink to the tubesheet face.

Therefore, in order to overcome this issue, it is important to apply heating to the tubesheet face, such that the tubesheet is raised to a similar temperature to the attachment weld during heat treatment. This ensures that the thermal expansion is uniform, thus removing the risk of induced stresses and distortion.

BAFFLE PLATES

On a similar principle to tubesheets, baffle plates can also complicate heat treatments, if they are close to or in a heated zone in a vessel. If baffle plates are bolted, then they should be removed, or otherwise, they will need to be heated and temperatures controlled accordingly.

A perhaps more simple method of visualising this, is to remember that the diametrical expansion of a cylinder, is the same as that for a beam that crosses the diameter – assuming the same temperature

In this simple example, if the beam is at the same temperature as the cylinder, then both will expand the same amount. Conversely, if the beam is cooler, then it will have less expansion, and, if attached to the cylinder, will constrain the expansion.
THIN WALL STORAGE TANKS

Due to their often very large diameters, thin wall storage tanks are generally fabricated and constructed in-situ. Designs are often based upon foundations including concrete ring walls. Ring walls are usually reinforced with rebar to ensure hoop loads in service can be supported. Anchor bolts are also commonly grouted into the ring wall prior to fabrication.

Although not pressure vessels, storage tanks often have caustic or sour service requirements. Such service has implications for Stress Corrosion Cracking, and in order to mitigate this risk, heat treatment is usually mandatory.

Figure 13 – Typical storage tank foundation/ bolting design.

In-situ heat treatment of storage tanks presents a number of problems:

- Thermal expansion is usually restricted by presence of anchor bolts
- Concrete will be damaged by exposure to high temperatures
- Any concrete rebar close to the surface of the ringwall will get hot, and expand causing further damage to the concrete
- Further complications can also arise due to:
  - Bituminous sand infills
  - Secondary HDPE membranes close to tank surface
  - PVC tubes close to tank underside for CP monitoring
Clearly, to proceed without taking action, would as a minimum be expected to cause significant damage to the concrete ring wall, and buckling of the tank base adjacent to anchor bolts. Hence, action must be taken to allow heat treatment to proceed, though options are generally limited.

There are typically two options available:

- Lift tank onto temporary dry sand base. (For larger tanks, this is usually not an option, due to the craneage capacity that would be required)
- Lift/jack up tank, to allow placement of temporary insulated support beams.

These can be major operations, and can extend site programs significantly.

The other two main areas of concern for storage tanks, are risk of buckling, and roof stability.

The two most common roof designs in tanks requiring heat treatment are domed, and coned types. The domed roof design, although less common, is inherently strong, often not requiring internal bracing; whereas almost all sizeable coned roof designs incorporate radial rafters/beams and compression ring to support the roof – such designs often require the use of temporary internal support structure to ensure stability during heat treatment.

Note - that the use of the internal firing technique, and associated combustion air blowers, generates an internal pressure within the tanks. Although pressures are generally insignificant from a tank pressure viewpoint, and typically in the order of few inches water gauge; this pressure can significantly counteract the weight of large roof areas. However, caution should be exercised in using the internal pressure as part of any stability assessment, as an electrical failure at soak temperature could be catastrophic if pressure is relied upon for roof support.

**FINITE ELEMENT ANALYSIS**

Finite element analysis is an incredibly powerful software tool that greatly aids the assessment of most heat treatment engineering problems. Various analysis options allow the user to establish temperature gradients on both static or transient basis, thermally induced stresses, static stresses caused by self-weight (Gravity), and wind loading, as well as buckling analysis – which are the most relevant analyses in relation to the subject herein, though the software has much more capability.

Although FEA software is becoming increasingly affordable, with some functionality even being shipped with higher end CAD software, including powerful user interfaces, it is all too easy for engineers to undertake analysis work, without fully understanding the complexity of the many aspects related to this work. It is imperative that any analysis has appropriate boundary conditions, elements, mesh...
size, assumptions, and applied loads. It is equally important that any results are checked, and validated before data is relied upon. It is therefore very important that any company undertaking such work is competent, and experienced in this type of work.