PRACTICAL GUIDELINES FOR REDUCING STRESSES AND LOADS IMPOSED BY THERMAL EXPANSION OF STEAM PIPING

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Abstract

The effects of thermal expansion of live and exhaust steam piping, and the imposed load limits on turbine branches and stress in piping with reference to the codes of practice are presented.

The procedures to implement and optimise piping design and layout are examined, and the definition and application of loops, restraints, supports, spring hangers, and cold pulls to minimise these thermal effects without the use of expansion bellows are described.

Recommendations on modelling, piping installation and interpretation of stress analysis results are made.

Introduction

There are many instances in sugar factories where the design, installation, and maintenance of high pressure steam and exhaust piping is neglected. The steam piping codes of practice are as stringent as those for a boiler and steam piping deserves the same care and attention as that of a boiler. The expansion of a pipe system subjected to temperature changes creates forces, moments and stresses that must be catered for so that the system is safe to man and machine.

Recent design analyses of both old and new steam and exhaust ranges at Tongaat-Hulett Mills have revealed many serious deficiencies in these systems. The evolutionary nature of sugar mills is one of the major causes of these problems. Turbines and vessels are added to the plant and, whereas the new system itself is adequately designed, the effects on and from the existing systems are often ignored.

The common solution for absorbing thermal movements has been the use of expansion compensators or bellows, but there have recently been failures in some of these high pressure units, which have caused considerable down time as well as costs for replacements or modifications. It has been demonstrated that the correct application of the appropriate devices and methods has provided solutions to thermal expansion problems without resorting to the use of bellows.

Limitations of Piping and Plant

The limits of pipe stress and loads applied by the thermal growth of the piping to turbines, pumps, boilers and vessels dictate the need for care and skill in the design of the system.

The most common high pressure (HP) steam generated in the sugar industry is 3.1 MPa(g) at 380 to 400°C. The piping available in South Africa for this duty is carbon steel pipe to ASTM A 106 grade B, which has an expansion coefficient of $1.2 \times 10^{-6}$°C temperature change. This is equivalent to a growth of 4.5 mm for every metre of pipe length for a temperature rise of 380°C.

Turbine exhaust pressures are commonly 100 kPa(g) which has a saturated temperature of 120°C, giving 1.3 mm/metre of pipe length of growth. However if a turbine runs on low load, for example if its alternator is not producing power during startup, the steam does little work and the exhaust temperature can rise up to 340°C resulting in a growth of 4.2 mm/metre.

The code ANSI B31.1 governing the design of steam piping limits the maximum resultant combined stress in the piping to 150 MPa at 400°C. This stress takes into account internal pressure, bending, torsion and shear.

Stress intensification factors are applied to bends and tees. This stress also provides for a fatigue life of 7000 cycles.

Allowable forces and moments on turbines, pumps and boilers are usually available from the manufacturers of new equipment but with old plant this is not always the case. Guidelines for the determination of allowable forces and moments on steam turbines is given in the NEMA Standard SM23, and in the API Standard 610 for centrifugal pumps.

The limits specified by manufacturers and the NEMA and API standards refer to the resultant forces and moments on machine flanges.

Forces and moments at any point in a system are related to the 3 co-ordinate axes i.e. 3 forces and 3 moments are applied simultaneously, the resultants being given by the root mean square values as follows:

\[
\text{Resultant Force} = \sqrt{F_x^2 + F_y^2 + F_z^2}
\]

\[
\text{Resultant Moment} = \sqrt{M_x^2 + M_y^2 + M_z^2}
\]
Design of a Flexible Piping System

The objective of the pipe system designer is to provide sufficient flexibility in the system, so that the combined effects of the piping's own mass and those induced from thermal expansion are contained within the limits of the standards.

Before looking at the procedure for designing the system one needs to know the essential devices, methods of application and procedures that are used. The challenge is then to examine the pipe layout and select from this "set of tools" the items needed to fit into the system to overcome the problems that have been identified.

Listed below is a glossary of terms describing these "tools".

Isometric layout

The starting point of the analysis is a dimensioned isometric layout of the pipe system which should include all of the existing piping features that could affect the new system. This could mean starting at the boiler outlet for a HP system.

Restraints

A device which prevents, resists or limits the free thermal movement of the pipe. Restraints can be either directional, rotational or a combination of both.

Anchors

A rigid restraint which provides substantially full fixety, ie encastre or "built in", ideally allowing neither movements nor bending moments to pass through them.

True anchors are usually difficult to achieve. A seemingly solid gussetted bracket welded to a house column does not qualify as an anchor if the column does not have the strength to resist the loads applied to it.

Expansion Loop

A purpose designed device which absorbs thermal growth; usually used in combination with restraints and cold pulls.

Neutral Planes of Movement

This refers to the planes on the 3 axes of a turbo machine or pump from where expansion of the machine starts eg the fixed end of a turbine casing. This information is normally provided by the equipment manufacturer. If not available from this source, the fixed points of the machine must be determined by inspection and an estimation of the turbine growths calculated.

A pipe restraint positioned in line with a neutral plane prevents differential expansion forces between the pipe and the machine.

Cold pull

This is used to pre-load the piping system in the cold condition in the opposite direction to the expansion, so that the effects of expansion are reduced. Cold pull is usually 50% of the expansion of the pipe run under consideration.

Spring Hangers

Used to support a piping system that is subjected to vertical thermal movements. Commercially available single coil spring units are suitable for most applications. Supplier's catalogues adequately cover the selection of these springs. According to Hooke's law, the spring's supporting capacity will vary in direct proportion to the amount of displacement the spring undergoes due to thermal movement. This variation between cold and hot should be between 25 and 50% of the hot loaded condition.

Solid Vertical Support

In places where vertical thermal movement does not create undesirable effects, or where vertical movement is intentionally prevented or directed, solid supports in the form of rollers, rods or slippers are used.

It is important that free horizontal movement of the pipe is not impeded unless horizontal restraint is desired. Slippers and rollers must be well designed and lubricated.

Measurement of actual movement

It is very useful to know the movement of an existing pipe at the point at which a tie-in to a new machine is intended. This movement is not always predictable, and a physical check can be made by fixing pointers to a non-movable structure and measuring the movement of the pipe between cold and hot.

This will require a planned shutdown of the plant for the lines to cool. It is unlikely that the piping will reach ambient temperature during a short shutdown, so the hot and "warm" temperature of the piping should be taken at the time of measurement. The results can be extrapolated to relate to ambient and hot conditions.

Procedure

A careful study of the site must be made and particular note taken of existing supports, restraints, pipe movements, structures that could be used for new supports, and possible routing options for proposed new pipe lines.

It is most important that the correct physical aspects are obtained from the site. For example, the analysis results will be significantly affected if an anchor is assumed when in fact it is a restraint.

The first isometric produced is unlikely to provide the final solution. The drawing should be studied and the magnitude and direction of movements determined. Positions of new restraints, supports, loops etc. can then be chosen to best absorb and direct forces and movements away from the plant item. Close attention must be given to adequately supporting the piping with its valves and fittings for both cold and hot conditions.

The stress analysis of the system should then be undertaken. The results will indicate if there are any overstressed or overloaded conditions. By studying the analysis results, appropriate modifications or additions to the system are chosen to compensate for limits that have been exceeded.

This procedure might require repeating several times with changes to the pipe run configuration, and the addition of restraints or loops. The effects on the existing piping and machines must be considered when making these changes.

Examples of improved systems

The possible combinations and configurations of piping layouts are infinite. Examples of two installation modifications are described.

1. Felixton: Figure 8 shows the before and after layouts of the 500 mm diameter high pressure steam range at Felixton. Repeated failure of the angular compensators prompted the Mill and the Tongaat-Hulett Technical Management Department (TMD) to examine ways of eliminating these weak links in the system.
**FIGURE 2** Typical isometric layout of a steam line to a turbine (Mount Edgecombe Mill).

**FIGURE 3** Examples of restraints.
FIGURE 4 Typical expansion loops.

FIGURE 5 Use of turbine neutral planes for restraint position selection.
FIGURE 6 Application of cold pull.

FIGURE 7 Examination of 1st analysis results and system modifications to reduce excessive moments and forces.
Reactions & system stresses. Hot condition.

<table>
<thead>
<tr>
<th>Point</th>
<th>Moments in Nm</th>
<th>Forces in Newtons</th>
<th>Stress MPA</th>
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<tr>
<td></td>
<td>Me My Mz</td>
<td>Fx FY Fz</td>
<td></td>
</tr>
<tr>
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<td>92</td>
<td>1359 -946 -372</td>
<td>-133 -5600 969</td>
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System deflections. Hot condition.

<table>
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<th>Translations in mm</th>
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<td>X Y Z</td>
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<tr>
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<td>-10.4 6.9 15.5</td>
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<tr>
<td>95</td>
<td>0.0001 0.0008 0.0002</td>
<td>-9.3 -0.8 18.8</td>
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FIGURE 8 Modification to 3100 Kpa steam main at Felixton Mill.

FIGURE 9 Sample analysis reports.
The provision of the vertical loop and the application of cold pulls was sufficient to absorb the 260 mm of growth between the restraints at the boilers and take-off to the power station.

The cost to replace the bellows units would be R45 000, and to provide a permanent solution by installing the loop is estimated at R100 000. The cost difference would have been marginal if the loop instead of bellows had been installed at the outset.

2. Mount Edgecombe: Figure 2 shows the layout of steam piping to a new turbo-alternator. The growth of the line from the existing restraint is absorbed by the expansion loop and the restraint opposite the turbine neutral plane prevents differential expansion of the horizontal loop in the negative X direction. Vertical expansion is taken up in spring hangers.

Models
Movements in a 3-dimensional layout are difficult to visualise. A simple and effective method of assessing complex thermal movements and to remove doubt as to how cold pull should be applied, is to make a scale model of the pipe branch from light gauge wire or plastic tube. The model can be manipulated to simulate expansion and a close approximation of the pipes' behaviour can be made.

Installation
Few contractors appreciate or understand the importance of cold pull, supporting of piping and prevention of initial loads onto turbines. Close supervision of these procedures is advised.

The acid test to determine the success of the installation at the turbine is to remove the bolts from the turbine flange after completion of the piping. The flanges should then just touch and be square to each other. If applicable, cold pull displacements can be measured at these flanges also. The initial flange loading can be adjusted to be effectively zero by means of the spring hangers closest to the machine.

A reasonable indication of the stiffness of the piping and forces imposed at turbine flanges can be obtained by levering with a crowbar between the flanges.

Analysis results
It is not intended to cover the actual stress analysis of a piping system in this paper. The complexity of a 3-plane system lends itself to computer analysis and many commercial software packages are available for this purpose. Alternatively these packages can be hired or a specialist consultant can undertake this work at reasonable fees. Software costs between R15 000 and R25 000 and a consultant's fee would depend on the size of the analysis and the number of analysis runs required.

The new era analysis packages offer an enormous amount of information. The most significant items are:
- Validation of input data
- Movement and rotation report
- Force and Moment report
- Stress report
- Summary of support, restraint, anchor and turbine forces
- Summary of maximum system values.

These packages contain libraries of certain spring hangers and bellows and will automatically select these items if requested. Also they can check that turbine flange forces are in compliance with the NEMA SM23 standard. Some packages will even draw the isometric, indicate deflected shape and produce an animated graphic display of vibration.

Bellows
There are instances where it is not economic to avoid the use of bellows. Failures on bellows at Darnall and Felixton were on HP systems where the Chromemoly and Incalloy bellows were installed in horizontal positions. Pin holes and fractures occurred on the bottom of the convolutions. At the time of writing, tests to determine the cause of the failures were still being evaluated. However it is significant that, to our knowledge, there has not been a failure of a bellows unit installed in the vertical position nor a bellows on exhaust steam duty in either position. This suggests that corrosive deposits and temperature may both have contributed to the failures.

Bellows must be used with caution and conservatively selected such that they are not deflect a their full limit. Suppliers of bellows and catalogue information can provide the guidelines for the selection and application of units.

Conclusion
The design of steam piping installations requires the knowledge of the Codes of Practice and manufacturers' load limitation for piping and plant.

To deal with the effects of thermal expansion on complex systems the designer must be familiar with the devices and procedures that can be applied to absorb, divert and reduce the forces, moments and stresses in the piping and on machinery.

A repetitive process of examination and analysis to identify the mechanisms and then to compensate for the effects, leads to successful solutions for most configurations.