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Basics of Piping System Thermal Expansion for Process Engineers

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INTRODUCTION

Piping system design comes in two pieces: the P&ID (Process and Instrument Diagram) created by the process engineers and the piping system design (layout) from the designers. In the worst case scenario the piping layout is handled by the contractor or local pipe fitters with little or no training or interest in pipe thermal expansion considerations. The engineer and designer need to work together to ensure there are no expansion problems.

Most engineering schools offering Chemical Engineering (Process Engineers) leave thermal expansion to the Physics Department, the Mechanical Department or someone else. Thus the Process Engineer is quite capable of designing the piping system to accomplish the process needs but may forget potential process interruptions caused by thermal expansion in his piping system.

Engineering companies generally do not bother with pipe stress analysis in pipes smaller than two inches unless very high temperatures, high pressures, toxic materials or restricted pipe routing are involved. Even small pipes can create stresses on equipment and anchors. Most can be ignored but all should at least receive a cursory examination.

This material will provide the basics for understanding pipe expansion and prepare the engineer to review designs with expansion problems in mind. As an up-front caution the ASME test equation presented is not intended to replace engineering experience; this test coupled with understanding of its limitations will provide a useful tool to the process engineer. The final decision of how much analysis a section of pipe needs lies with the responsible engineer.

BASIC EXPANSION CONCEPT

The Physics Department or someone else left most engineers with a basic understanding of thermal expansion, most likely of a straight piece of steel and not likely of a piece of pipe. It is left up to the engineer to carry over what the physics professor taught to his piping system design.

As metal temperature changes metal dimensions also change. Most materials, under rising temperature conditions, will enlarge in three directions; X, Y and Z. Assuming that the long dimension of our pipeline runs in the X direction we initially have little concern or interest in expansion in the Y and Z directions. Throughout this material when we talk about pipe expansion we are discussing longitudinal growth.

The physics formula and the piping formulas for linear expansion are the same. Namely:

$$\Delta x = \acute{\alpha} L \Delta T,$$ defined as follows:

Δx is the increase or decrease in length, inches
$\acute{\alpha}$ is the thermal coefficient of linear expansion, in./in.°F over the range of temperatures from installation to operation
L is the original straight length of the pipe, in.
ΔT is the change in temperature, usually from *installed temperature* to *operating temperature,* °F

Note there is nothing in the formula relating to pipe wall thickness or schedule. We're dealing only with linear expansion and that is independent of thickness, thickness does become important when actual stresses in the pipe wall are to be calculated..

Coefficients of thermal expansion are available from many sources. However it is sometimes presented in a confusing manner. The things you need to be aware of as possible sources of error in calculations are:

- Data is given as expansion in inches / inch deg F and sometimes as inches / inch deg C.
- It is often presented as inches of expansion / 100 feet of pipe
- Some tables use an installation temperature of 70 °F and some a temperature of 32 degrees °F
- Most data tables will list multiple alloys for the various metals [ie. 316, 304, 18-8, etc. for stainless materials]

Note the emphasis above on ***installed*** *temperature*; this is a critical factor frequently incorrectly incorporated into calculations. This is always the starting point for an expansion calculation, the pipe has a specific length based on the temperature at which it is installed. That temperature is whatever it happens to be in the pipe storage area on the day the pipe is installed.

Note also the emphasis on ***operating*** *temperature*. Normally one would consider this to be the temperature of the materials in the pipe; steam, water, solvents, etc. The temperature of steam is directly related to pressure and can be determined easily. However, temperatures of liquids may not actually be what is measured in storage tanks. Some common errors in determining operating temperatures are:

- Stagnant pipes full of liquid in the sun may be much hotter than the temperature of a liquid stored in a tank
- Empty pipes such as closed liquid lines, etc. may heat up due to sunlight to well above "normal" operating temperatures
- Heat traced lines which may have long periods where there is no flow may reach temperatures well above normal operating temperatures depending on the temperature control system used on the trace, if any.

- Gases tend not to be a good source of cooling for pipes in direct sunlight because of their relatively low heat capacity, even with moderate flows the pipeline may be hotter than design.
- Introduction of extremely cold liquids, refrigerants or brines, into pipes installed at summer time temperatures causes reverse stresses as the pipe attempts to shrink against the anchors or equipment.

It is important for the engineer to go through the various environments, internal and external, that a pipeline will experience.

For our sample problems in this paper we will use plain carbon steel pipe which has expansion coefficients as follows:

Table 1
Linear Coefficient of Expansion for Carbon Steel

Temperature, °F	Mean Coefficient of Expansion Between 70 °F and Listed Temperature, µ in/in°F
100	6.13
150	6.25
200	6.38
250	6.49

µ equals micron or 10^{-6}
SEE ADDITIONAL DATA ON ATTACHMENT 1

EXAMPLE 1

A single run of 2 inch schedule 40 carbon steel pipe is installed on overhead supports in the Spring with an ambient temperature of 70°F. The pipeline is rigidly attached at each end and simply supported / guided along the remainder of its 100 foot length. Expected process temperature in the insulated pipe is 250°F. How much expansion can we expect?

Using the formula $\Delta x = \acute{\alpha} L \Delta T$

$\acute{\alpha}$ = 6.49 µ in/in°F or 6.49 x 10^-6 in/in°F [from Table 1]
L = 100 feet or 1200 inches
ΔT = 250 °F – 70 °F = 180 °F

Δx = 6.49 x 10^-6 in/in°F x 1200 in x 180 °F
= 1.402 in.

Or approximately 0.12% increase in length.

This doesn't seem like a lot of growth in a hundred foot long pipe, however, if not allowed to move at the ends then the pipe will bow out where the longest unsupported section of pipe is located. This bowing may be horizontal or vertical and may not be noticeable. If the restraints / guides are sufficiently close and stiff the pipe may be forced to fail to relieve stresses. See Figure 1.

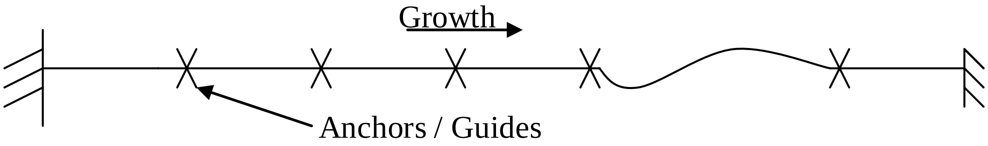
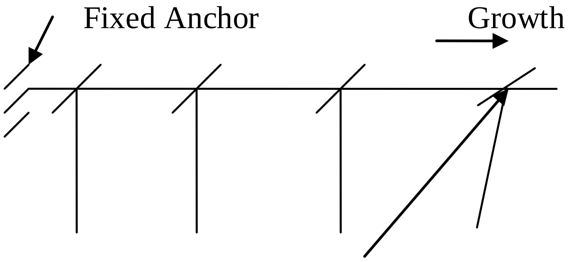


FIG. 1 Plan View of Pipe Showing Horizontal Deflection Caused by Thermal Expansion

Pipe stresses built up from thermal expansion will be unintentionally transferred directly to anchor points and guides if not properly accounted for in design. Sufficient forces are generated by improperly supporting expanding pipelines to bend “tee” bridge columns and pull anchors out of walls. See Figure 2.



Fixed connection between pipe and “tee” column causes column to deflect to relieve thermally generated stresses as the pipe expands its length.

FIG. 2. Relief of Thermal Growth by Column Deflection, Elevation View

The end column with a fixed connection to the pipe will bend as necessary to absorb the growth of the pipe. If the pipe is free to grow by distorting the column then the stress is reduced or eliminated by transferring the stresses to the bridge column.

ANALYSIS OF POTENTIAL PROBLEMS

ASME B31.3 offers a simplified formula for determining if a pipe section requires stress analysis; by analysis is meant a total pipe stress analysis such as would be provided by the Caesar II® pipe stress analysis program. The program is based on available manual methods. This analysis is a complicated calculation, involves a lot of time and hours of labor and is to be avoided if it is safe to do so.

The ASME test formula is relatively simple and provides a quick check of pipe stresses. It does not provide stress values but does tell us if the pipe line might be in trouble from expansion stresses. Remember expansion can be negative and still be a problem.

The formula is:

$$K = \frac{Dy}{(L-U)^2}$$

K = test value and if less than 0.03 using the following dimensions the pipe routing does not require formal stress analysis under normal conditions
D = Nominal pipe diameter (2 inch pipe is input as 2 inches)
y = total expansion [Δx] in inches from the equation above, this is expansion between the anchors as if the pipe ran straight from anchor to anchor
U = total straight line length between anchors, feet
L = actual length of pipe including elbows etc, feet

See Figure 6 for examples of L and U.

CAUTION: This formula is only valid for very simple piping systems where there are only two anchors, no branch circuits and all of the pipe is the same diameter and thickness. Finally for an ell shaped pipe run the ratio of the total length to the longest straight section of pipe cannot exceed 2.0.

The above CAUTION would appear to eliminate most piping arrangements. Actually by selecting anchor points on the piping plan this formula allows for checking most piping arrangements.

Let’s apply the ASME test to our sample above.

EXAMPLE 1 Part 2

$$K = \frac{Dy}{(L-U)^2} = \frac{2\text{ in x } 1.40\text{ in}}{(100\text{ ft.} - 100\text{ ft})^2} = \infty$$

In our case of a straight pipe L and U are identical so we end up dividing by “0” and K goes to infinity. Obviously our pipe failed the test and one of the following needs to be accomplished to protect the pipe:

- Install a commercial expansion joint to absorb the 1.4 inches of growth
- Reroute the pipe in such a way that L is larger than U by about 10%
- Install an expansion loop
- Reroute the pipe at one end to allow the pipe to grow by “bending” a 90° leg
- Hot bolt the pipe so the expansion has occurred before the final pipe to equipment connection is made up.

Commercially made expansion joints take very little space and are generally not too expensive in this size. They can become maintenance problems with larger pipe sizes.

Rerouting the pipe may be a problem on a pipe rack and in our case would require the addition of approximately 10 feet of pipe installed with elbows and basically being at 90° to the long run of the pipe. See Figure 3 for a "standard" expansion loop. Although not a loop in the true sense a 90 degree bend accomplishes the same effect. in reducing stresses to less than the ASME limit. A recalculation of L and Δx is required with a loop since additional pipe has been installed in the expansion loop.

Hot bolting is common and acceptable in systems which are started up and left hot for extended periods. Care must be taken to unbolt the piping prior to cool down or contraction stresses will cause as much damage as heat up generated stresses.

RELIEVING EXPANSION STRESSES

The following are some of the approaches which can be used to eliminate expansion problems in long pipe runs. Care must be taken to allow the pipe to move or force it to move as desired. The figures, dashed lines, indicate probable direction of movement due to expansion.

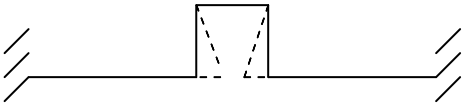


FIG. 3 Expansion Loop showing deformation due to thermal growth

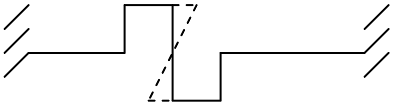
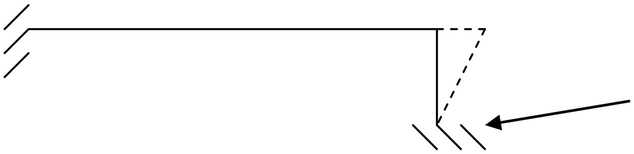


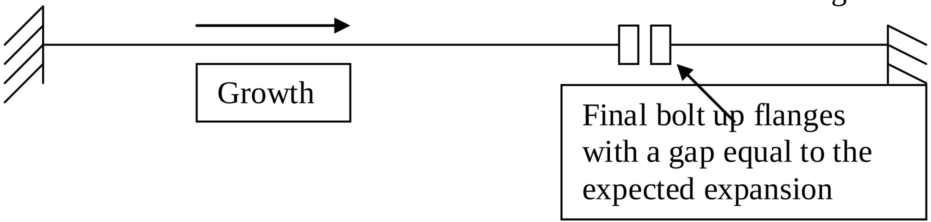
FIG. 4 Double loop showing one form of deformation due to thermal growth



Anchor Points

FIG. 5 Single ninety degree leg absorbing all the growth in one location

- - - - - Indicates probable shape with thermal growth



Final bolt up flanges with a gap equal to the expected expansion

FIG. 6, Hot Bolting Solution

Depending on the pipe contents the direction of the expansion loop can be horizontal or vertical. For steam using a vertical loop requires additional condensate traps whereas a horizontal loop does not. For liquids a vertical loop may create undesirable "pockets" in the pipeline.

We’ll use FIG. 5 above as our solution since this leg turn down could be a common piping arrangement when going from a pipe bridge to internal piping inside a building. Assume that the downward leg is eleven feet long as shown below and use the data from Example 1 to determine what happened in our ASME test. The pipe now looks like FIG. 7 with dimensions as shown.

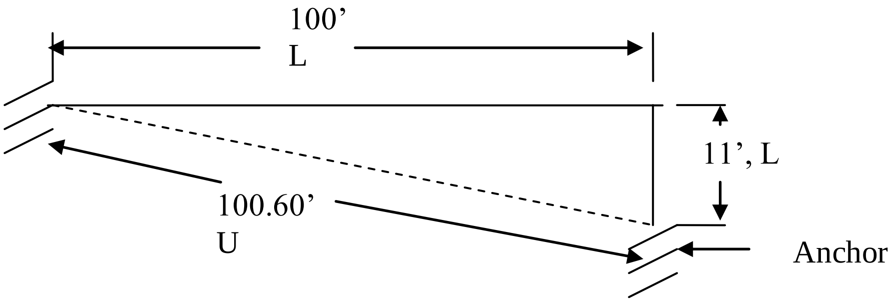


FIG. 7

For ASME Formula
U = 100.60’, L = 100’ + 11’ = 111’

Note that “U” has become the hypotenuse of the triangle formed by the two straight legs. This is the straight line distance between anchors.

Δx = 6.49 x 10^-6 in/in°F x 1207.2 in x 180 °F
= 1.41 in.

Substituting in the formula

$$K = \frac{Dy}{(L-U)^2}$$

D = Nominal pipe diameter, 2 inches
K = test value and if less than 0.03 is acceptable
y = 1.41 inches
U = 100.6 feet
L = 111 feet

$$K = \frac{2 \text{ in} \times 1.41 \text{ in}}{(111 \text{ ft.} - 100.6 \text{ ft.})^2}$$
$$= 0.026 \text{ in}^2 / \text{ft.}^2$$

This indicates that the short section of downward turned pipe reduces the overall stresses to an acceptable level. Our length ration is 111 / 100 = 1.11 which is also acceptable.

EXAMPLE 3

Let’s assume our pipe was installed to carry water and has been shut down and drained. Installation was done at 70°F and sitting in the sun the pipe has now reached a 140°F, not an uncommon temperature in direct sunlight.

At 140°F ά is about 6.23 from interpolation.

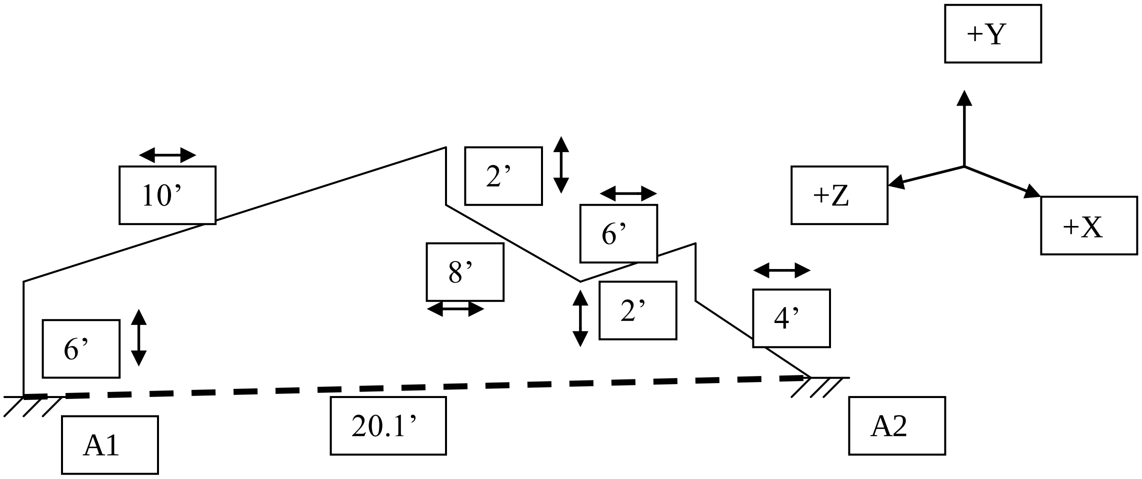
$\Delta x = ά\,L\,\Delta T$

ά = 6.23 μ in/in°F or 6.23 x 10^-6 in/in°F
L = 100 feet or 1200 inches
ΔT = 140 °F – 70 °F = 70 °F
Δx = 6.23 x 10^-6 in/in°F x 1200 in x 70 °F
= 0.52 in.

Not a significant expansion but one which can become a serious problem if this pipe is tied directly to equipment which is sensitive to misalignment as is the case for pumps, turbines and compressors. Likewise if this pipe is securely anchored to the first and last columns in the pipe bridge then one or both columns will experience the same movement as the pipe.

EXAMPLE 4

Most piping systems do not stay in a simple X-Y plane but travel in all three dimensions. Let’s look at a three dimensional pipe run. The rules don’t change and the math is still relatively simple.



Because the pipe path is difficult to show in two dimensions I’ve added the XYZ axes to assist in orientation; that along with the following table of individual pipe runs should make the arrangement clear. When you're faced with multiples of pipe runs to test I suggest a simple Excel® spreadsheet where you can input length as positive or negative XYZ lines to make the math simple and ensure proper relationships line to line.

Pipe Run	Length, ft.	Direction Starting from A1
1	6	+Y
2	10	-Z
3	2	-Y
4	8	+X
5	6	-Z
6	2	-Y
7	4	+X

We will not do all the math here but you should verify that the total length of pipe is 38 feet and that the straight line distance between A1 and A2 is 20.1 feet. Note that this straight line distance involves all three dimensions.

Data: Pipe is 6 inch schedule 40 carbon steel
Therefore D will be 6 inches
Design Temperature is 250 ºF

So we have:

$$\Delta x = \acute{\alpha}\, L\, \Delta T = 6.49 \times 10^{-6} \text{ in/in}^\circ\text{F} \times 20.1 \text{ ft.} \times 12 \text{ in/ft.} \times (250 - 70)^\circ\text{F}$$

$$= 0.282 \text{ inches}$$

Substituting in the ASME test formula:

$$K = \frac{0.282 \text{ in.} \times 6 \text{ in.}}{(38 \text{ ft.} - 20.1 \text{ ft})^2} = .005$$

Since .005 < .03 our pipe in three dimensions has sufficient flexibility to absorb the thermal expansion without problems.

THERMAL COEFFICIENTS OF LINEAR EXPANSION

A final word about coefficient data to be used to determine expansion.

Table 2 shows some miscellaneous data for pipe. Note that there is no detail on the applicable temperature range for this data. In order to properly calculate the expansion to be expected you need data similar to that shown in Table 1 where the applicable range of temperatures is shown assuring maximum accuracy in your calculations.

Table 3 gives data for a wide range of materials and demonstrates one of the variations in how the coefficient data is expressed.

Table 4 provides an example of the variety of data presentations and should be used as an indicator of the necessity of carefully reviewing the method of using the data presented. Using data from two different sources is something to be avoided if at all possible.

Table 5 uses degrees Kelvin for the calculations but the data is only valid at 20 ºC.

It is critical that you use valid data, either directly from the pipe manufacturer or from a reliable source such as ASME, ASTM or an accepted engineering reference. Poor quality input data will result in problems.

SHRINKAGE

We’ve taken a cursory look at expansion and hopefully learned enough to be aware of the problems which might develop. Pipe expansion goes hand in hand with pipe shrinkage which occurs when pipes installed in the summer are exposed to severe winter conditions or extremely cold flowing contents. This is generally much less frequent than growth and the analysis is exactly the same.

CONCLUSION

Pipe growth from thermal expansion is going to happen, how it is handled is critical to avoiding problems. Each section of pipe needs to be reviewed, not necessarily by mathematical means but at least looked at from a potential standpoint. Likewise supports for pipes need to be considered and properly designed to allow for growth. Supports are not simply hangers; there is a wide range of support types, connections to building steel and connections for the pipe. Working in pipe stress requires a familiarity with pipe supporting techniques.

Some pipes will require extensive analysis to avoid later problems. Money can be saved by the engineer who can competently look at piping design and eliminate those pipes which are not a concern.

REFERENCES

Perry’s Chemical Engineer’s Handbook, 6th Edition, pages 6-73 ff
ASME B31.3
The Grinnell Company, “Piping Design and Engineering” 3rd Edition, 1971 [available on the Internet]
Spirax Sarco Module 10.4 “Pipe Expansion and Support”
Caesar II® software, Coade, Inc. 12777 Jones Road, Houston, Texas, 77070

ATTACHMENT 1

TABLE 2 MISCELLANEOUS COEFFICIENTS - PIPE

MATERIAL	LINEAR COEFFICIENT OF THERMAL EXPANSION, In/In ºF
ABS pipe (Acrylonitrile Butadiene Styrene)	5.5×10^{-5}
Aluminum Pipe	1.3×10^{-5}
Ductile Iron Pipe	5.8×10^{-6}
HDPE Pipe (High density polyethylene)	1.2×10^{-4}
PVC Pipe (Polyvinyl Chloride)	3.0×10^{-5}
Steel Pipe	6.5×10^{-6}

TABLE 3 MISCELLANEOUS COEFFICIENTS

MATERIAL	$\times 10^{-6}$ In / In ºF	$\times 10^{-6}$ In / In ºC
Aluminum Alloy	12.8	23.0
Brass	10.0	18.0
Cast Iron	5.6	10.1
Chromium	3.8	6.8
Concrete	6.7	12.0
Copper	8.9	16.0
Glass, Plate	4.9	8.9
Glass, Pyrex™	1.8	3.2
Invar	0.39	0.7
Lead	15.6	28.0
Magnesium Alloy	14.5	26.1
Marble	6.5	11.7
Platinum	5.0	9.0
Quartz, Fused	0.2	0.4
Steel	6.5	11.7
Tin	14.9	26.9
Titanium Alloy	4.9	8.8
Tungsten	2.4	4.4
Zinc	14.6	26.3

TABLE 4 TEMPERATURE RANGED COEFFICIENTS OF LINEAR

EXPANSION [From Perry's Handbook, 3rd Edition, 1950, partial data shown]

TEMPERATURE °F	CAST IRON	WROUGHT IRON	STEEL	COPPER or BRASS
0	0.0	0.0	0.0	0.0
100	0.72	0.79	0.76	1.14
200	1.50	1.65	1.57	2.38
300	2.35	2.58	2.47	3.74
400	3.30	3.63	3.46	5.24
500	4.45	4.90	4.67	7.06

Instructions for Table 4: The expansion in inches for a pipe of any length between any two given temperatures is found by taking the difference in length at those temperatures, dividing by 100, and multiplying by the length of the pipe in feet.

TABLE 5

COEFFICIENT OF LINEAR THERMAL EXPANSION	
MATERIAL	α in 10^{-6}/K at 20 °C
Mercury	60
Lead	29
Aluminum	23
Brass	19
Stainless steel	17.3
Copper	17
Gold	14
Nickel	13
Concrete	12
Iron or Steel	11.1
Carbon steel	10.8
Platinum	9
Glass	8.5
Tungsten	4.5
Glass, Pyrex	3.3
Silicon	3