Heat and Thermodynamics - Course PI 25

EXPANSION AND CONTRACTION

Objectives

1. Given all variables but one, use $\Delta L = L_o \alpha \Delta T$ to determine the unknown variable.

2. Given a sketch of a bimetal strip and the coefficients of linear expansion of the metals in the strip, state in which direction the strip will bend as it is heated or cooled. Briefly explain why the strip will bend in the stated direction.

3. Given values representing initial and final conditions of a unit mass of water or heavy water and appropriate tables, determine the ratio representing the volume change that will occur as the water or heavy water goes from the initial to the final condition.

   The changes may be any of the following:

   (a) Liquid at one temperature to liquid at another temperature.

   (b) Vapour (saturated or wet) at one pressure to vapour (saturated or wet) at another pressure.

   (c) Liquid at a given temperature to vapour (saturated or wet) at the same temperature.

   (d) Vapour (saturated or wet) at one temperature to liquid at the same temperature.

4. Explain the terms shrink and swell as they apply to:

   (a) A liquid that is changing temperature while remaining liquid.

   (b) Water in a boiler that is experiencing step increases or decreases in steam flow rate.

5. Explain why the programmed level of water in the boiler changes as power is changed.

6. Explain how steam entering the condenser at a CANDU station can be at about 30°C and 4 kPa(a).

Most substances expand when heated and contract when cooled. The behaviour of substances due to heating and cooling must be taken into account in the design and operation of a CANDU generating station. In this module you will be learning some methods of predicting how metals will behave when they are heated or cooled. You will also be determining volumetric changes that various states of water undergo as they are heated or cooled.

Linear Expansion and Contraction:

Generally, when we consider the behaviour of metal fabricated parts as heating or cooling occurs, we are concerned only with changes in one dimension.

We call this behaviour linear expansion or linear contraction - the change in length a substance undergoes as it is heated or cooled.

The amount of expansion/contraction a particular object undergoes is proportional to three factors:

(1) the change in temperature the object undergoes. This temperature difference (between the initial and final temperatures) is measured in °C and is labelled ΔT. The larger the temperature difference, the greater the expansion or contraction.

(2) the original length of the object, L_o. The longer the original length, the more expansion or contraction.

(3) the substance the object is made of. Different substances will expand/contract different amounts, even if they have the same original length and if they undergo the same temperature difference. This behaviour is quantified by measuring the amount of expansion/contraction of each substance per unit length per °C temperature change. The measurement is known as the "coefficient of linear expansion," α.

The dimensions of the coefficient are length, length^{-1}, temperature^{-1}; since the length dimensions cancel, the unit for the coefficient is °C^{-1}.

The combination of the above three factors can be used to predict the amount of expansion or contraction that a metal will undergo. If we label the amount of expansion/contraction ΔL,

$$\text{then } \Delta L = L_o \alpha \Delta T.$$

The use of the above equation to predict the behaviour of metals with heating or cooling is an approximation. It is a valid approximation because:

(1) the expansion and contraction processess due to heating and cooling are sensibly reversible; that is, if a metal is heated, then cooled to its original temperature it will expand, then contract to its original length.

(2) the coefficients of expansion vary only slightly over the range of temperatures normally experienced in our stations.

You will be asked to use $\Delta L = L_o \alpha \Delta T$ in two ways:

a) in solving simple numerical examples.

b) in predicting the behaviour of bimetal strips.

Let's look at (a) first.

(a) Numerical Examples

⟶ Answer the following questions in the spaces provided, then check your answers with those in the "TEXT ANSWERS" section.

2.1) The steam supply line to Bruce Heavy Water Plant "A" (BHWP-A) has a pipe run that is 655 m long at 25°C. The pipe is made of carbon steel ($\alpha = 10 \times 10^{-6}\ °C^{-1}$) and when steam is being supplied to BHWP-A the pipe temperature is 190°C. Determine the amount of expansion the pipe undergoes.

2.2 The low pressure (LP) turbine shaft at BNGS-B is 51.2 m long at 25°C. If the linear expansion coefficient is $11 \times 10^{-6}\ °C^{-1}$ and the average shaft temperature at power is 105°C, what is the amount of expansion of the shaft?

2.3) A stainless steel sleeve ($\alpha = 16 \times 10^{-6}\ °C^{-1}$) is to be installed on a shaft with an interference fit. To accomplish this the sleeve is to be heated until it slides easily over the shaft. If the sleeve has 0.55 m diameter at 20°C and if it must be heated until its diameter is 0.552 m, to what temperature should it be heated?

b) Bimetal Strips:

A bimetal strip is a common device used as a thermal switch or as a thermometer. In its most basic form, it can be represented as shown in Figure 2.1:

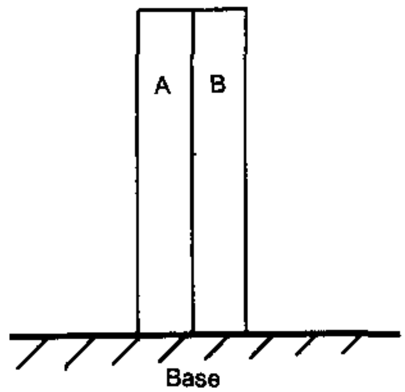

Figure 2.1

Two different metals, A and B, are joined firmly together, then fastened to the base.

2.4) If A is brass ($\alpha = 18 \times 10^{-6}$ °C^{-1}) and B is carbon steel ($\alpha = 10 \times 16^{-6}$ °C^{-1}), what will happen to the strip if it is heated uniformly 5°C? ____________________

____.

2.5) Explain why the strip will behave as in question 2.4.

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⟶ Answer the above questions before you proceed, then check your answers with those in the "TEXT ANSWERS" section.

You should now be able to predict the behaviour of a bimetal strip as it is heated or cooled, and you should be able to briefly explain this behaviour.

⟶ Try question 2.7, then check your answer with the one in the "TEXT ANSWERS" section. You should now be able to do the first two objectives for this module. If you feel you need any more practice, see the course manager.

2.7) Towards which contact will the strip shown in Figure 2.2 move as it is cooled? Briefly explain why.

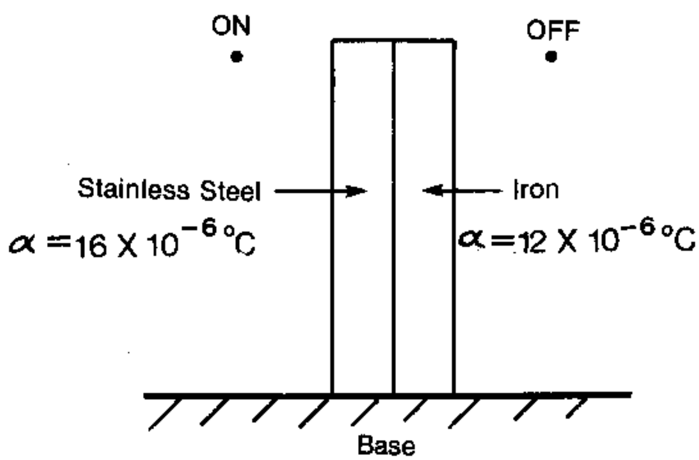

Figure 2.2

Volumetric Expansion and Contraction:

Almost all fluids expand upon heating and contract when cooled. When we consider the behaviour of fluids with respect to thermal expansion/contraction, we are concerned with changes in volume. We call this behaviour volumetric expansion or volumetric contraction.

Since water and heavy water are the working fluids of CANDU generating units, we will only consider the behaviour of these two substances in this module.

→ Locate your copies of "Steam Tables in SI Units" and "Heavy Water Steam Tables" and refer to them as indicated.

The steam tables for water and for heavy water include entries for specific volume - that is, the volume per kilogram of fluid. You will be using these entries to predict the ratio of change of volume when water is changed from one given set of conditions to another.

— Turn to Table 1 in the "Steam Tables in SI Units". The entries you will be using are found in the first four columns on the right side of the page. The column on the extreme right is the given saturation temperature. The column headed V_f is the specific volume of saturated liquid at the given saturation temperature. The column headed V_f is the specific volume of saturated steam at the given saturation temperature. The column headed v_{fg} is the change in volume as water is boiled at the given saturation temperature. The unit of specific volume in these tables is dm^3/kg, or ℓ/kg.

→ Now turn to Table 1 in the "Heavy Water Steam Tables". The entries in these tables differ in two ways:

(a) they represent the specific volume of heavy water, in m^3/kg.

(b) they are located on the left side of the page.

You will be using these tables to determine the initial and final values of specific volume for water and heavy water that are undergoing various changes. To determine the ratio of any volume change, divide the larger specific volume by the smaller one.

→ Try the following practice questions, then check your answers with those in the "TEXT ANSWERS" before proceeding.

2.8) Determine the ratio of the change in volume as water at 254°C is boiled to produce saturated steam at 254°C.

2.9) Determine the ratio of the change in volume as liquid heavy water at 60°C is heated to produce liquid heavy water at 260°C.

How can you determine the specific volume of wet steam? The answer is to treat it in exactly the same way as you did the enthalpy of wet steam: to the specific volume of the saturated liquid add the product of the steam quality and the change in volume from liquid to vapour. This can be expressed as follows:

$$V_{ws} = V_f + q\,V_{fg}$$

where V_{ws} is the specific volume of the wet steam.

→ Answer the following questions before you proceed. Check your answers with those in the "TEXT ANSWERS" section .

2.10) Determine the ratio of the change in volume of steam going through the turbine set at PNGS-A. The steam enters the set saturated at 250°C and leaves the set 10% wet at 33°C.

2.11) Determine the ratio of the change in volume in the condenser at BNGSA. Steam (moisture content 12%) at 30°C enters the condenser and is condensed to form water at 30°C.

→ If you are confident you can do objective (3) at this point, proceed to the next section in this module. If you feel you need more practice, obtain some extra questions from the course manager.

Shrink and Swell

The terms shrink and swell are commonly used terms that are applied to the change in volume of water in two specific circumstances in a CANDU station.

1. Shrink and Swell in a Liquid System

The first circumstance deals with the primary heat transport (PHT) system. This system removes heat from the fuel and transports it to the boilers, where the heat is transferred to light water to produce steam. The heavy water in the PHT system is in the range of 250°C to 300°C when the unit is "at power" (i.e. ready to produce power) and it is highly pressurized (9 to 10 MPa(a)) so that vaporization will not occur.

After a lengthy shutdown, the PHT average temperature is about 60°C. As it is brought up to the operating temperature range, the heavy water will undergo a 25% expansion (as you calculated in question 2.9). This change in volume as the average PHT system temperature is increased is referred to as swell in the PHT system.

Conversely, as the system is taken from "at power" state to "cold pressurized" (i.e. 60°C and 9 to 10 MPa(a)) it will undergo a 25% contraction. This decrease in volume as the PHT average temperature is decreased is known as shrink in the PHT system.

Note that shrink and swell tend to occur any time the PHT average temperature changes.

2. Shrink and Swell in a Boiler:

When a CANDU boiler is operating, boiling is occurring throughout most of the liquid. The fluid in the boiler is thus a mixture of vapour and liquid. Since the vapour has approximately 40 times the liquid volume per kilogram at boiler conditions, it contributes significantly to the volume of fluid in the boiler. This volume is monitored by measuring the liquid level in the boiler. As the amount of vapour in the fluid varies, the liquid level will vary.

Consider an operating boiler that experiences a step increase in steam flow - that is, the steam flow out of the boiler is instantly increased by a certain amount.

2.12 What will happen to the pressure in the boiler?

____

2.13 (a) What will happen to the boiler level?

____

____

(b) Why will this occur?

____

____

→ Answer questions 2.12 and 2.13 in the space provided, then check your answers with those in the "TEXT ANSWERS". If you have any questions at this point, consult with the course manager.

This increase in level due to a very rapid or step increase in steam flow from the boiler is called swell in the boiler. It can be a significant amount: for example, at PNGSA for a steam flow increase corresponding to a change in power from 0% to 100% at the rate of 1%/s, the swell is 0.66 m.

Now consider an operating boiler that undergoes a step decrease in steam flow.

2.14) What will happen to the pressure in the boiler?

____

2.15) (a) What will happen to the boiler level?

____

____

(b) Why will this happen?

____

→ Answer questions 2.14 and 2.15 before you proceed, then check your answers with those in the "TEXT ANSWERS".

The decrease in level due to a a very rapid or step *decrease in steam flow from the boiler is called* *shrink*. *The* worst case shrink occurs when the unit is at 100% full power and a turbine trip occurs with no corresponding reactor trip. At PNGS-A the shrink would be 1.5 m in this case.

Both shrink and swell occur only during transitions following a very rapid change in the steam flow from the boiler. When the boiler pressure is constant, neither shrink nor swell occurs.

→ Answer the following questions before you proceed, then compare your answers with those in the "TEXT ANSWERS".

2.16) Explain shrink and swell as they apply to:

(a) the PHT D_2O as its temperature is changed.

(b) water in the boiler that experiences a step increase or decrease in steam flow rate.

Boiler Level Control:

The level of water in the boiler is controlled automatically when the unit is at power. The level is maintained at a minimum when the unit is at 0% full power. As the unit is taken from 0% to 100% power, the level in the boiler is continually increased. When the unit is at 100% power the level is maintained at a maximum value.

There are two reasons for this change in programmed level with power changes:

(1) As power increases, more and more steam is produced. Since the steam appears from within the liquid and since there is an expansion of about 40 times on vaporization, as more steam is produced the apparent volume of the liquid increases and thus the boiler level increases. The programmed level must take this effect into account. If the boiler level were maintained constant as power increases, the mass of water contained in the boiler would be reduced. Should a loss of feedwater condition occur, the heat sink capacity for the PHT system would be reduced and the boiler water inventory boiled off in a shorter time.

(2) The most likely change in steam flow at low power levels is an increase. This will cause swell, and if the level were high to begin with, there would be a chance of liquid being forced into the steam lines. This would cause serious problems in the turbine.

The most likely change in steam flow at high power levels is a decrease. This will cause shrink. If the boiler level is low before the shrink occurs, the drop in level could uncover the top section of the boiler tubes with subsequent deposition and baking of solids on the hot, dry tubes. This deposition would permanently impair heat transfer and increase corrosion rate.

The boiler level is thus kept low at low power levels and high at high power levels to avoid the problems mentioned above. The level setpoint changes are mainly due to the shrink and swell considerations mentioned in (2) above.

→ Answer the following question in the space provided, then check your answer with the one in the "TEXT ANSWERS" section.

2.17) Explain why the programmed level of water in the boiler changes with power changes.

Condenser Conditions

The condenser's main purpose is to change the vapour exiting the turbine set to a liquid so it can be returned to the boilers. An additional benefit (better unit efficiency) occurs because the steam that enters the condenser can be maintained at a high vacuum. (For the explanation of this benefit see module PI 25-7). The purpose of this section is to explain how condenser conditions can be maintained.

The vacuum is a result of using cold lake water as the condensing fluid. The lake water temperature is seasonally variable between 0°C and about 20°C. The lake water flowing through the condenser tubes will condense the steam on the shell side at about 30°C. At this temperature, steam decreases in volume by about 25,000 times (refer to question 2.11 for details). It is this large change in volume that maintains a very low pressure.

→ Answer the following question in the space provided, then check your answer with the one in the "TEXT ANSWERS".

2.18) Explain how steam entering the condenser of a CANDU unit can be at about 30°C and 4 kPa(a).

→ Read over the objectives for this module. If you are confident you can perform these objectives now, obtain the PI 25-2 criterion test and answer the questions on it. If you feel you need more practice, consult with the course manager.

PI 25-2 TEXT ANSWERS

2.1) In this question,

L_o is 655 m

α is 10×10^{-6} °C^{-1}

ΔT is 190 - 25 = 175°C

Thus, $\Delta L = 655 \times (10 \times 10^{-6}) \times 175 = \underline{1.15\ m}$. How could this expansion be accommodated?

2.2) Here,

L_o is 51.2 m

α is 11×10^{-6} °C^{-1}

ΔT is 105 - 25 = 80°C

Thus, $\Delta L = 51.2 \times (11 \times 10^{-6}) \times 80 = \underline{0.045\ m}$ (or 4.5 cm)

2.3) Here, you are looking for the final temperature. If you first determine the temperature difference, the final temperature can be calculated quickly.

$\Delta L = 0.552 - 0.55 = 0.002$ m

$L_o = 0.55$ m

$\alpha = 16 \times 10^{-6}$ °C^{-1}

Thus, $0.002 = 0.55 \times (16 \times 10^{-6}) \times \Delta T$

$\Delta T = 227$ °C

$\therefore$ the final temperature is 20 + 227 = <u>247°C</u>.

2.4) The strip will bend towards the right.

2.5) The original lengths of the two materials are the same and both substances undergo a 5°C temperature difference. The behaviour of the strip thus depends on the coefficients of linear expansion of the two metals. Since the coefficient for brass is greater than that for carbon steel, the brass will become longer. The only way this situation can occur in this strip is if the strip bends as shown in Figure 2.2.

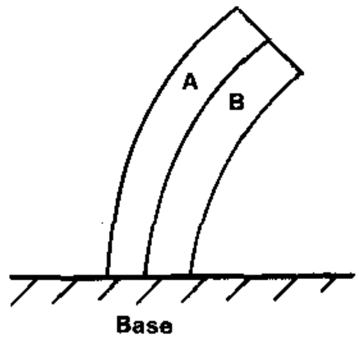

Figure 2.3

"A" is longer than "B" since it is on the outside of the arc.

2.6) The strip will bend towards the left as it is cooled. (Since the coefficient for brass is greater than the coefficient for carbon steel, the brass will contract more. It would have to be on the inside of the arc that would be formed.).

2.7) The strip will move towards the *ON* contact as it is cooled. Since the linear expansion coefficient for stainless steel is greater than that of iron, as cooling occurs the stainless steel will become shorter - that is, it must be on the inside of the arc. This will move the strip towards the ON contact.

2.8) You should assume the water at 254°C to be saturated liquid. This is a reasonable assumption unless the pressure is very much higher than the saturation pressure. Thus the specific volume of water at 254°C is

$V_{f_{100°C}} = 1.2607\ \ell/kg$ (From Table 1, "Steam Tables in SI Units")

The volume of saturated steam at 100°C is:

$V_{g_{100°C}} = 46.692\ \ell/kg$ (From Table 1, "Steam Tables in SI Units"

The ratio of the change in volume is:

$$46.692 \div 1.2607 = \underline{37.0 \text{ times}}.$$

(This is representative of the change in volume at BNGS-A: in general, water expands about 40 times in a CANDU boiler as it changes from liquid to vapour).

2.9) The specific volume of liquid heavy water will also be assumed to be the same as the saturated liquid volume at the same temperature.

Thus, the specific volume of liquid heavy water at 60°C is:

$$v_{f_{60°C}} = 0.000916 \text{ m}^3/\text{kg},$$

and the specific volume of liquid heavy water at 260°C is:

$$v_{f_{260°C}} = 0.001157 \text{ m}^3/\text{kg},$$

Hence, the ratio of the change in volume is:

$$0.001157 \div 0.000916 = \underline{1.26 \text{ times}}$$

(The heavy water in the primary heat transport system undergoes approximately the same expansion as you have just calculated. A couple of rhetorical questions:

What would happen if this volume increase could not be accommodated in the system?

How could the expansion be accomodated?

(You should be able to answer these questions after you have completed module 4.)

2.10) The specific volume of saturated steam at 250°C is:

$$v_{g_{250°C}} = 50.037 \ \ell/\text{kg}$$

The specific volume of 10% wet steam at 33°C is:

$$v_{ws} = v_{f_{33°C}} + q\, v_{fg_{33°C}}$$

$$= 1.0053 + 0.90 \times 28040.9$$

(remember $q = 1 - 0.10 = 0.90$)

$$= 25237.8 \ \ell/\text{kg}$$

The ratio of the change in volume is:

$$25237.8 \quad 50.037 = \underline{504 \text{ times}}.$$

(This represents the expansion of steam at PNGS-A as it goes from the inlet to the turbine set to the outlet at the condenser.)

2.11) The specific volume of the 12% wet steam at 30°C is:

$$V_{w_s} = V_{f_{30^\circ C}} + q\, V_{fg_{30^\circ C}}$$

$$= 1.0043 + 0.88 \times 32927.9$$ (remember $q = 1 - 0.12 = 0.88$)

$$= 28977.6\ \ell/\text{kg}$$

The specific volume of the water at 30°C is:

$$V_{f_{30^\circ C}} = 1.0043\ \ell/\text{kg}$$

The ratio of the change in volume is:

$$28977.6 \div 1.0043 = \underline{28853 \text{ times}}$$

2.12) When the steam flow suddenly increases, the pressure in the entire boiler (on the light water side) will decrease.

2.13) (a) The boiler level will suddenly rise.

(b) This rise will occur because more vapour is suddenly produced, causing the apparent volume of liquid in the boiler to increase, and thus also the level.

2.14) When the steam flow suddenly decreases, the pressure in the entire boiler (on the light water side) will *increase*.

2.15) (a) The boiler level will suddenly drop.

(b) When the pressure increases, the boiling process ceases. The vapour bubbles that are present in the liquid will condense, and the apparent volume of the liquid in the boiler will decrease. This will cause the level to drop.

2.16) (a) As the PHT D_2O temperature increases, the liquid will expand. This expansion is called swell.

As the PHT D_2O temperature decreases, its volume will decrease. This is called shrink.

(b) When the boiler is operating, the apparent volume of liquid in the boiler is not only due to the volume of liquid, but also due to the volume of vapour present within the liquid.

If the steam flow from the boiler experiences a very rapid or step increase, the pressure in the boiler will drop. The boiling rate will increase, causing more vapour to be present in the liquid. The apparent volume of the liquid will increase, and the boiler level will suddenly go up. This is called swell in the boiler.

If the steam flow experiences a very rapid or step decrease, the pressure in the boiler will increase. The vapour present in the liquid will condense, causing the apparent volume of liquid to suddenly decrease. This causes a drop in boiler level which is called shrink.

2.17) The programmed level in the boiler increases with power increases and it decreases with power decreases. There are two reasons for these level changes:

(a) There is a natural variation in the apparent volume of liquid in the boiler. The more boiling that occurs, the more vapour is present in the liquid. Since the vapour has a higher specific volume than the liquid, the volume of the mixture increases with increasing amounts of vapour. Thus the level will increase with increasing power (and increasing boiling). The opposite effect occurs with power (and boiling) decreases. If the boiler level were maintained constant as power increases, the boiler water inventory would be reduced. This would decrease the heat sink capability and the boiler water would boil off in a shorter time, should a loss of feedwater occur.

(b) The boiler level is changed <u>more than</u> would naturally occur. This is done to minimize the possible effects of shrink and swell in the boiler.

At low power levels, the most likely steam flow change is an increase (as power is raised). This will cause swell to occur. The boiler level is maintained low to minimize the danger of carrying over liquid in the steam lines.

At high power levels the most likely steam flow change is a decrease (as power is dropped). This will cause shrink to occur. The boiler level is maintained high to prevent uncovering of the top section of the boiler tubes which would result in deposition of solid on the hot dry tubes. This would permanently impair heat transfer and increase corrosion rate.

2.18) The steam is maintained at about 30°C and 4 kPa(a) by using cold lake water to condense the steam. Lake water at a maximum temperature of about 20°C flows through condenser tubes. This will enable the temperature of the condensing steam to be about 30°C. At this temperature the steam decreases in volume about 25,000 times - this decrease maintains the pressure at about 4 kPa(a).