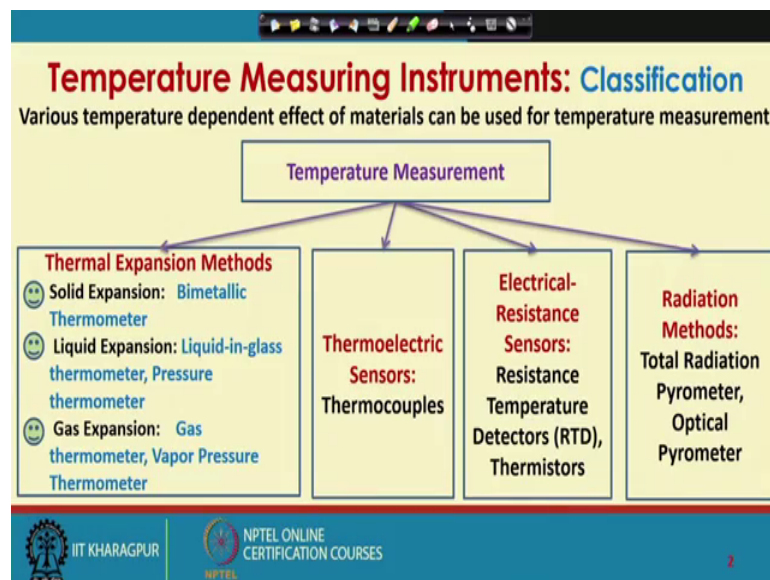


Chemical Process Instrumentation
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Lecture – 35
Temperature Measurement (Contd.)

Welcome to lecture 35, the last lecture of week 7. So, we are talking about temperature measuring instruments and we have talked about temperature measurements based on thermal expansion of materials, thermal expansion of solid, thermal expansion of liquid and thermal expansion of gas. So, let us again look at our classification.

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So, we have talked about bimetallic thermometers under solid expansion, we have talked about liquid in glass and liquid in metal or pressure thermometers, we have talked about gas expansion thermometers, namely gas thermometers and vapor pressure thermometer.

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Temperature Measurement

Today's Topic:

- Liquid Expansion Thermometer
- Gas Expansion Thermometer

} Filled System Thermometers

- ❑ Error in Filled System Thermometers
- ❑ A Numerical Example

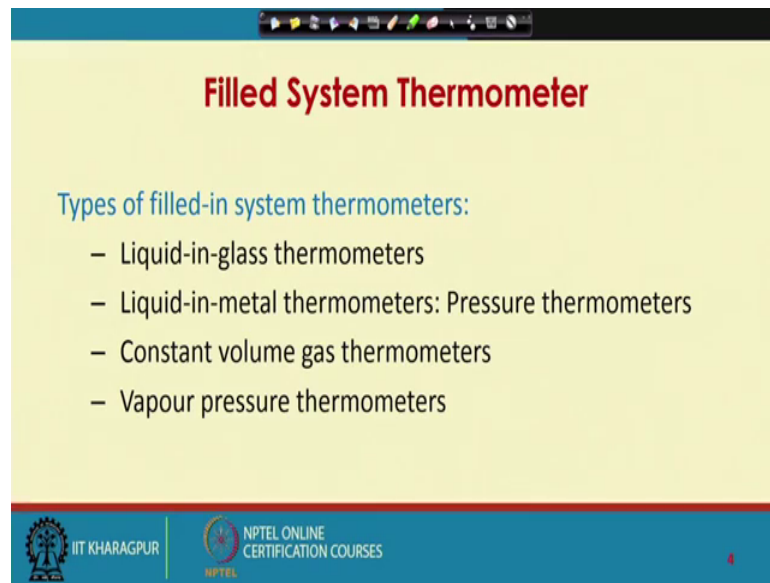
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So, today we will talk about some more aspects of liquid expansion thermometers and gas expansion thermometers. Liquid expansion thermometers and gas expansion thermometers are collectively known as filled system thermometers. Now, this filled system thermometers have certain errors associated with them.

So, first we will talk about the errors associated with the filled system thermometers, before that will also talk about some classification of filled system thermometers and then finally, we will take a numerical example to understand more about the different errors associated with the filled system thermometers. So, in today's lecture we are talking about filled system thermometers by which we mean liquid filled thermometers as well as gas filled thermometers.

So, in liquid filled thermometers, vapor pressure thermometers as well as gas filled thermometers all we are collectively talking about filled system thermometers.

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Filled System Thermometer

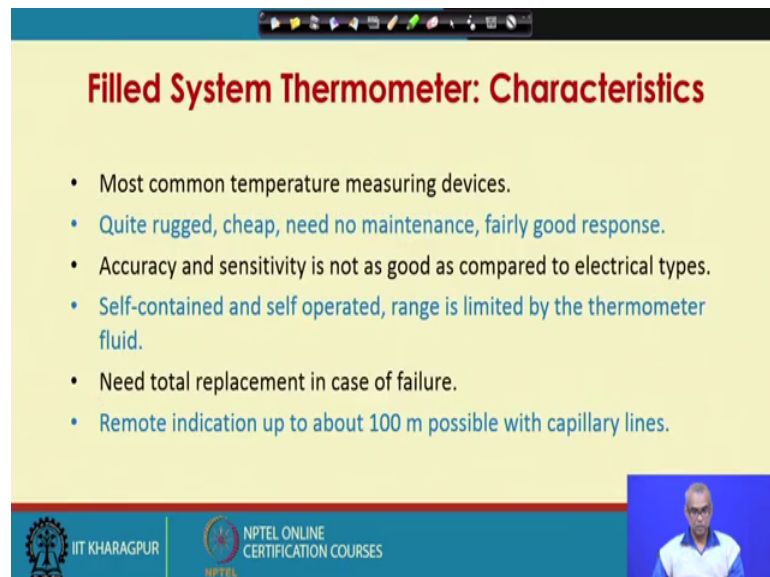
Types of filled-in system thermometers:

- Liquid-in-glass thermometers
- Liquid-in-metal thermometers: Pressure thermometers
- Constant volume gas thermometers
- Vapour pressure thermometers

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Now, there are various types of filled system thermometer as we discussed liquid in glass thermometers, liquid in metal thermometers also known as pressure thermometers, constant volume gas thermometers and vapour pressure thermometers and all these we are we have discussed already.

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Filled System Thermometer: Characteristics

- Most common temperature measuring devices.
- Quite rugged, cheap, need no maintenance, fairly good response.
- Accuracy and sensitivity is not as good as compared to electrical types.
- Self-contained and self operated, range is limited by the thermometer fluid.
- Need total replacement in case of failure.
- Remote indication up to about 100 m possible with capillary lines.

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Now, some general characteristics of this filled system thermometers, they are common temperature measuring devices quite rugged cheap, need no maintenance, fairly good response. Accuracy and sensitivity is ok, but not great or very good as compares to

temperature measuring instruments, which are electrical types we will talk about such electrical types instruments later. Filled system thermometers are self contained and self operated no auxiliary power source is required; range is limited by the thermometer fluid.

Total replacement is needed in case of failure; remote indication up to about 100 meter is possible with extended capillary lines. So, these are some general characteristics of filled system thermometers.

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Filled System Thermometer: Another Classification

The Scientific Apparatus Manufacturers Association classifies filled system thermometers as follows:

- Class-I : Liquid Filled Thermometers** (filled with a non metallic liquid, mercury-filled thermometers not included, operate on the principle of liquid expansion)
- Class-II : Vapour-Pressure Thermometers** (partially filled with volatile liquid, operates on the principle of vapour pressure)
- Class-III : Gas Thermometers** (operates on the principle of pressure change with temperature)
- Class-IV : Mercury-Filled Thermometers** (filled with mercury or mercury-thallium eutectic amalgam and operates on the principle of liquid expansion)
- Class-V : Mercury-Filled Thermometers**

The manufacturers of American instruments classifies Mercury-Filled Thermometers as Class-IV, but the Scientific Apparatus Manufacturers Association classifies Class-V.

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Now, there are lot of information on the slide because I wanted to put a classification proposed by Scientific Apparatus Manufacturers Association and I wanted to put all the classifications in 1 slide only.

The Scientific Apparatus Manufactures Association classifies filled system thermometers as follows class 1, class 2, class 3, class 4, class 5. Class 1 liquid filled thermometers, which are filled with the nonmetallic liquid and operate on the principle of liquid expansion, are class 1 filled system thermometers. So, mercury filled thermometer is not included here.

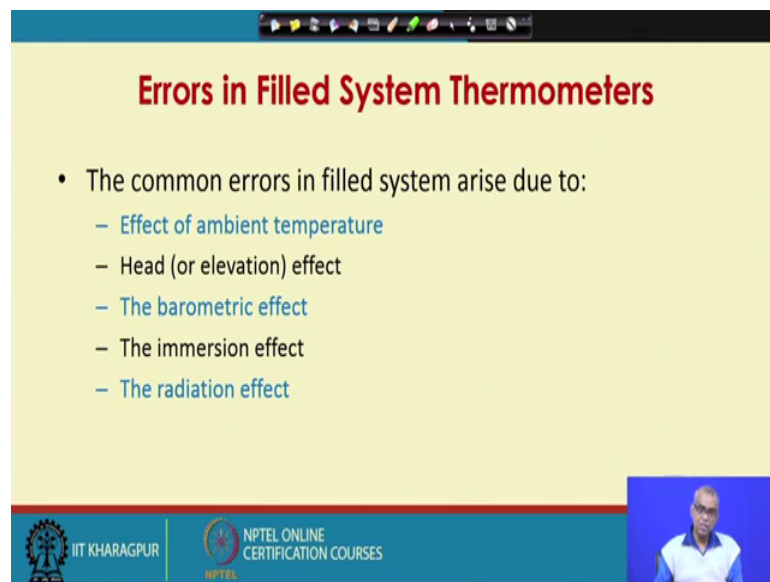
So, the class 1 filled system thermometers are all liquid filled thermometers which are filled with a non metallic liquid and operate on the principle of liquid expansion, these does not include mercury filled thermometers; class 2 filled system thermometers are

vapor pressure thermometers. So, they are partially filled with volatile liquid operates on the principle of vapor pressure, change of vapor pressure with change in temperature.

Class 3 filled system thermometers are gas thermometers, it operates on the principle of pressure change with temperature at constant volume; class 4 is mercury filled thermometers, class 5 is also mercury filled thermometers. Mercury filled thermometers, are filled with mercury or mercury thallium eutectic amalgam and operates on the principle of liquid expansion.

The manufacturers of American instruments classifies mercury filled thermometers as class 4, but the scientific apparatus manufacturers association classifies the mercury filled thermometer as class 5. So, mercury filled thermometers are known as both class 4 and class 5. The manufacturers of American instruments classifies mercury filled thermometers as class 4, but the scientific apparatus manufacturers association classifies mercury flat, mercury filled thermometers as class 5 filled system thermometer, but there is no confusion about class 1 class 2 and class 3.

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Errors in Filled System Thermometers

- The common errors in filled system arise due to:
 - Effect of ambient temperature
 - Head (or elevation) effect
 - The barometric effect
 - The immersion effect
 - The radiation effect

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Now, there are certain errors which may be associated with filled system thermometers. So, you should know what are those common errors and how to cope up with this errors or how to reduce thus this error? The common errors in filled system thermometers arise due to effect of ambient temperature, we have talked about this on several occasions.

Effect of elevation also known as head effect, the barometric effect, the immersion effect, the radiation effect, so the error 5 different common errors in filled system thermometers, effect of ambient temperature, head or elevation effect, barometric effect, immersion effect and radiation effect.

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Errors in Filled System Thermometers

1. **Effect of Ambient Temperature:** A change in ambient temperature will cause volume changes in the capillary and the pressure spring (Bourdon tube or diaphragm). Thus it will cause an error in measurement.

- ☐ Use of large bulb reduces the error.
- ☐ Temperature compensation is possible.

Compensation with bimetallic strip (Case compensation)

Compensation with differential link (Full Compensation)

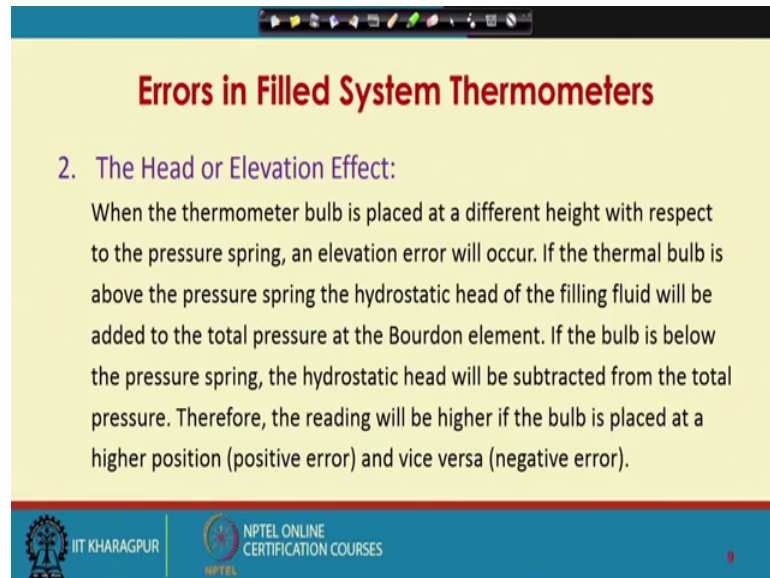
The slide contains two diagrams. The left diagram, labeled 'Compensation with bimetallic strip', shows a thermometer with a large bulb and a capillary tube. A bimetallic strip is attached to the capillary tube, and a red circle highlights the strip. A blue arrow labeled 'Case compensation' points to the right. The right diagram, labeled 'Compensation with differential link', shows two identical thermometers connected at their capillaries. A red circle highlights the connection point. A blue arrow labeled 'Full Compensation' points to the right. The slide footer includes the IIT KHARAGPUR logo and the text 'NPTEL ONLINE CERTIFICATION COURSES'.

Now, let us talk about each in term, we start with effect of ambient temperature. A change in ambient temperature will cause volume changes in the capillary and the pressure spring such as bourdon tube or diaphragm, thus it will cause an error in measurement. If I use large bulb, the error will be reduce because the change in bulb volume which is coming from the effect of temperature of the medium which I am going to measure will be more compare to the volume change in the capillary or pressure spring, which is done by the effect of ambient temperature.

So, by making the bulb off the pressure thermometer large, we can reduce the effect of ambient temperature. We have also seen that temperature compensation is possible, we have talked about full compensation, we have also talked about case compensation or partial compensation. In case of full compensation you take an exactly identical element which we call compensating system and connect them in a position. So, the compensating system will subtract the additional deflection caused here due to effect of ambient temperature.

The case compensation or the partial compensation is achieved by putting a bimetallic spring which is suitably designed. So, that the deflection caused in the bimetallic spring is equivalent opposite to the dif additional deflection caused in the pressure spring by the ambient temperature. So, the effect of ambient temperature can be reduced by using large bulb or by using full compensation or case compensation techniques.

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Errors in Filled System Thermometers

2. The Head or Elevation Effect:

When the thermometer bulb is placed at a different height with respect to the pressure spring, an elevation error will occur. If the thermal bulb is above the pressure spring the hydrostatic head of the filling fluid will be added to the total pressure at the Bourdon element. If the bulb is below the pressure spring, the hydrostatic head will be subtracted from the total pressure. Therefore, the reading will be higher if the bulb is placed at a higher position (positive error) and vice versa (negative error).

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The effect of elevation or head effect or elevation effect, when the thermometer bulb is placed at a different height with respect to the pressure spring an elevation error will occur.

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Errors in Filled System Thermometers

The relative size of the error is a function of the size of the hydrostatic head relative to the total pressure.

Elevat

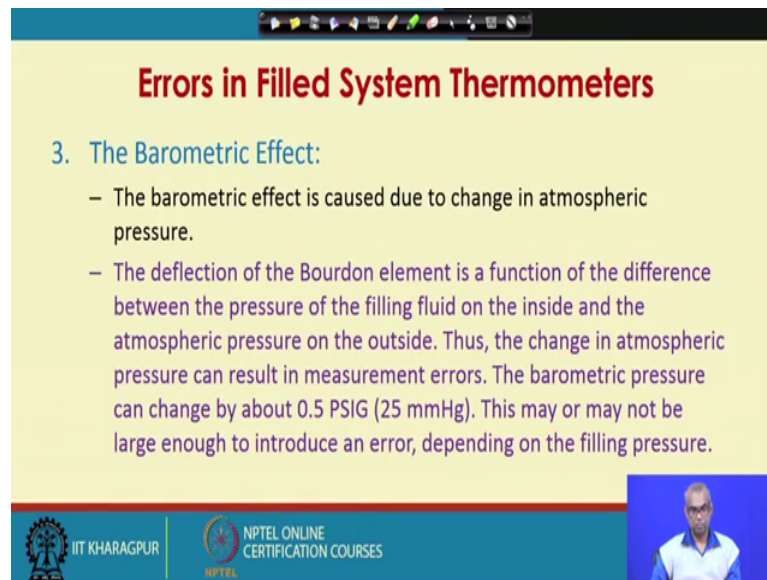
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So, this is the bulb and this is the pressure spring, note that they are at different elevations. So, there is an additional pressure head which is the source of error. So, in the thermometer bulb is placed at a different height with respect to the pressure spring and elevation error will occur. If the thermal bulb is above the pressure spring the hydrostatic head of the filling fluid will be added to the total pressure at the bourdon element.

If the bulb is below the pressure spring, the hydrostatic head will be subtracted from the total pressure. Therefore, the reading will be higher if the bulb is placed at a higher position, we call it positive error and vice versa we call that negative error. So, if the thermal bulb is placed above the pressure spring, the hydrostatic head of the filling fluid will be added to the total pressure of the bourdon element; if the bulb is below the pressure spring the hydrostatic head will be subtracted from the total pressure.

Therefore, the reading will be higher if the bulb is placed at a higher position and the reading will be lower if the bulb is placed at the lower position; we call this either positive error or negative error. The relative size of the error is a function of the size of the hydrostatic head relative to the total pressure.

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Errors in Filled System Thermometers

3. The Barometric Effect:

- The barometric effect is caused due to change in atmospheric pressure.
- The deflection of the Bourdon element is a function of the difference between the pressure of the filling fluid on the inside and the atmospheric pressure on the outside. Thus, the change in atmospheric pressure can result in measurement errors. The barometric pressure can change by about 0.5 PSIG (25 mmHg). This may or may not be large enough to introduce an error, depending on the filling pressure.

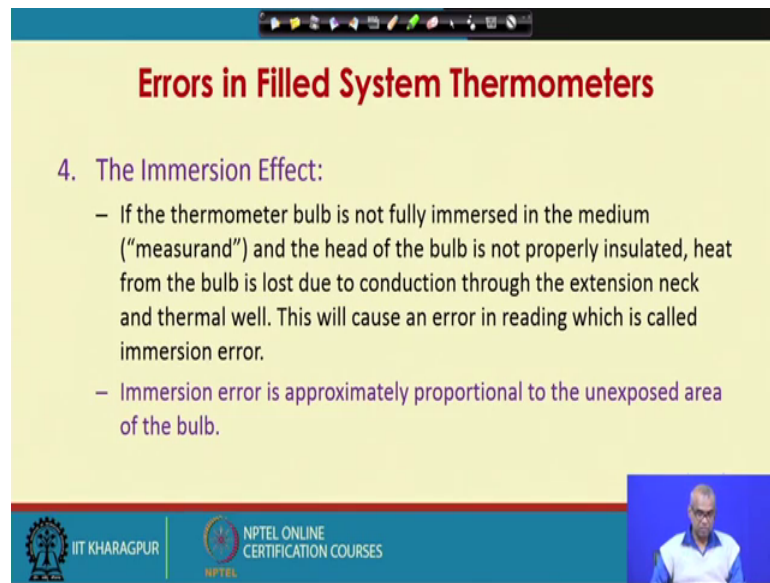
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The barometric effect; the barometric effect is caused due to change in atmospheric pressure. The deflection of the bourdon element is a function of the difference between the pressure of the filling fluid on the inside and the atmospheric pressure on the outside.

Thus, the change in atmospheric pressure can result in measurement errors. The barometric pressure can change by about 0.5 PSIG or 25 millimeter of mercury. This may or may not be large enough to introduce an error depending on the filling pressure. So, the barometric effect is caused is due to change in atmospheric pressure, the deflection of the bourdon element depends on the pressure inside the bourdon tube and the pressure outside the bourdon tube.

The pressure outside the bourdon tube is the pressure of the atmosphere. So, the atmosphere pressure changes the deflection will be changed. So, thus the effect of change in atmospheric pressure can introduce an error, but this error will be large or small will depend on the filling pressure.

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Errors in Filled System Thermometers

4. The Immersion Effect:

- If the thermometer bulb is not fully immersed in the medium (“measurand”) and the head of the bulb is not properly insulated, heat from the bulb is lost due to conduction through the extension neck and thermal well. This will cause an error in reading which is called immersion error.
- Immersion error is approximately proportional to the unexposed area of the bulb.

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The immersion effect, we have talked about partial immersion, total immersion, when we talked about liquid in glass thermometer, we are now looking talking about filled system thermometers.



If the thermometer bulb is not fully immersed in the medium whose temperature I am going to measuring and the head of the bulb is not properly insulated, heat from the bulb is lost due to conduction through the extension neck and thermal well; this will cause an error in reading which is called immersion error. Immersion error is approximately proportional to the unexposed area of the bulb, so the bulb has to be fully immersed, so that immersion error is reduced.

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Errors in Filled System Thermometers

5. The Radiation Effect:

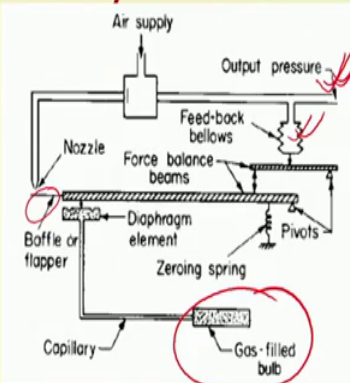
- Radiation error occurs due to temperature difference between the bulb and other solid bodies around it.





The radiation effect; radiation error occurs due to temperature difference between the bulb and the solid bodies around it.

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Filled System Thermometer: Pneumatic Transmitter



An increase in bulb temperature causes the flapper to move closer to the nozzle, increasing the nozzle back pressure. This increases the output pressure, which increases the force exerted by the feedback bellows. The system returns to equilibrium when the increase in bellows pressure exactly balances the effect of the increased diaphragm pressure. The bulb temperature is directly related to the output air pressure.



Now, let us talk about a pneumatic transmitter that can be obtained from the filled system thermometers. So, the question is how do I convert a filled system thermometer to a pneumatic transmitter? That means, the output of the filled system thermometer should be a pneumatic signal.

The schematic shows how you can do this. You have the gas filled bulb let us we are talking about a gas thermometer, we are talking about a gas filled, filled system thermometer. So, we have a gas filled bulb this is the capillary and the other end we have this diaphragm, we can also have a bourdon tube here, you can also have a bourdon tube, you could have also take bourdon tube here. So, the pressure spring, the pressure spring taken here is diaphragm element.

Now, note that I take out help of a flapper nozzle system to get a pneumatic transmitter out of a filled system thermometer. So, I have attached a force balance beam to the diaphragm and this is a flapper nozzle system you have the nozzle, you have the air supply and you have the output pressure, we have also use the feedback bellows which is connected to the force balance beam. So, you have 2 force balance beams 1 is connected to the diaphragm another is connected to the feedback bellows both applies on this 2 pivot. Now, the way it will lower is as follows.

An increase in bulb temperature causes the flapper to move closer to the nozzle. So, if there is an increase in the bulb temperature this flapper will go closer to the nozzle, this will increase the nozzle back pressure, this will increase the output pressure, which increases the force exerted by the feedback bellows. The system returns to equilibrium when the increase in bellows pressure exactly balances the effect of the increased diaphragm pressure.

The bulb temperature is directly related to the output air pressure. So, an increase in bulb temperature causes the flapper to move closer to the nozzle increasing the nozzle back pressure, this increases the output pressure which increases the force exerted by the feedback bellows. The system returns to equilibrium when the increase in bellows pressure exactly balances the effect of the increased diaphragm pressure.

The bulb temperature is directly related to the output air pressure. So, basically you attach a flapper nozzle system to the pressure element.

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A Numerical Example

Problem : A mercury-in-steel thermometer uses a Bourdon pressure element which has a range of 0 - 5 MPa for the pointer rotation from 0 to 250 °C. During temperature calibration, the pointer movement was set to 0° rotation at 0°C and the instrument indicated 225° rotation corresponding to 200°C. The volume of the bulb is 8 times that of combined volume of capillary and the bourdon tube.

Determine:

- The sensitivity of the thermometer in rad/°C.
- The error due to rise in ambient temperature of 20°C.
- The error in measured temperature if the bulb is raised by 50 cm from the calibration elevation.

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Now, let us take a numerical example to understand more about the error associated with the filled system thermometers. So, mercury in steel thermometer uses a bourdon pressure element which has a range of 0 to 5 mega pascal for the pointer rotation from 0 to 250 degree Celsius.

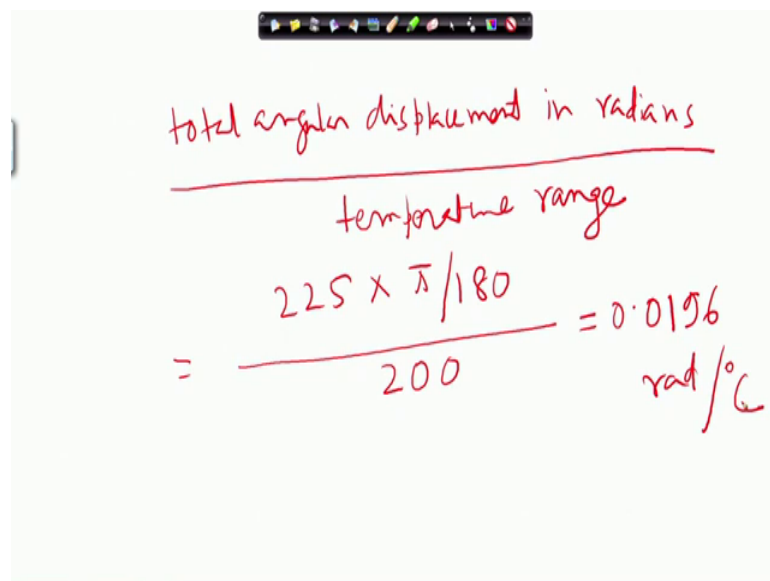
During temperature calibration the pointer movement was set to 0 degree rotation at 0 degree Celsius and the instrument indicated 225 degree rotation corresponding to 200 degree Celsius. The volume of the bulb is 8 times that of combined volume of capillary and the bourdon tube. Determine the sensitivity of the thermometer expressed in radian per degree Celsius.

The error due to rise in ambient temperature of 20 degree Celsius, the error in measured temperature if the bulb is raised by 50 centimeter from the calibration elevation. So, we are given a mercury in steel thermometer, the thermometer uses the bourdon tube as a pressure sensing element, the range of the bourdon element is 0 to 5 mega Pascal for the pointer rotation of 0 to 250 degree Celsius.

During temperature calibration the pointer movement was set to 0 degree rotation at 0 degree Celsius and the instrument indicated 225 degree rotation corresponding to 200 degree Celsius. Given that, the volume of the bulb is 8 times that of the combined volume of capillary and the bourdon tube we have to determine the sensitivity of the thermometer in radian per degree Celsius.

The error due to rise in ambient temperature by 20 degree Celsius, the error in measured temperature if the bulb is raised by 50 centimeter from the calibration elevation. So, how do we solve this problem? Now, the sensitivity of the thermometer can be found out by total angular displacement divided by the temperature change, we have to express in radian per degree Celsius. So, I have to express total angular displacement in radians and I will divide that by temperature range.

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A handwritten calculation on a whiteboard showing the sensitivity of a thermometer. The text is written in red ink. It starts with a fraction: 'total angular displacement in radians' over 'temperature range'. Below this, the calculation is shown as $\frac{225 \times \pi / 180}{200} = 0.0196$ rad/°C.

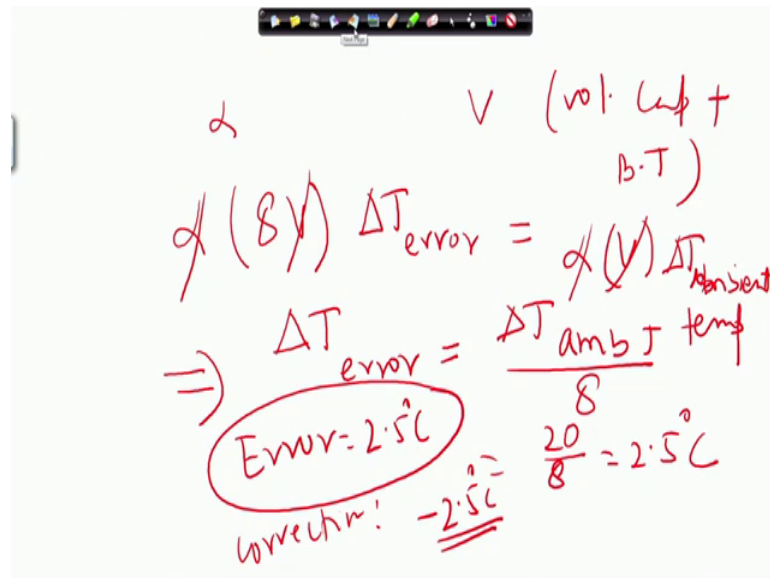
$$\frac{\text{total angular displacement in radians}}{\text{temperature range}} = \frac{225 \times \pi / 180}{200} = 0.0196 \text{ rad/}^\circ\text{C}$$

So, sensitivity of the thermometer sensitivity of the thermometer which is mercury in steel thermometer can be found out by total angular displacement in radians divided by temperature range; now, temperature range 200, 225 into pi by 180 to convert it to radian, so this will be 0.0196 radian per degree Celsius.

So, this is how you can find out the sensitivity of the thermometer. Now, let us try to find out error due to rise in ambient temperature by 20 degree Celsius. So, the error increases, the temperature ambient temperature increases by 20 degree Celsius and we know that there will be error due to increase in ambient temperature. So, how to find out the error that will be caused due to increase in temper ambient temperature by 20 degree Celsius.

So, the volume change in the capillary and the bourdon tube due to change in ambient temperature will introduce an error in the reading to find this error you have to calculate the temperature rise in the bulb, that will cause the same volume change in the bulb.

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The image shows a handwritten derivation on a whiteboard. At the top, it defines α as the coefficient of volumetric expansion and V as the volume of the capillary plus Bourdon tube. The main equation is $\alpha (8V) \Delta T_{\text{error}} = \alpha (V) \Delta T_{\text{ambient}}$. This is rearranged to $\Delta T_{\text{error}} = \frac{\Delta T_{\text{ambient}}}{8}$. A numerical example shows $\frac{20}{8} = 2.5^\circ\text{C}$. The final result is circled as "Error = 2.5°C" with a note "correction! -2.5°C" written below it.

So, if we define alpha as coefficient of volumetric expansion and V as the volume of capillary plus bourdon tube. So, V is volume of capillary plus bourdon tube and alpha is the volume expansion coefficient.

Then, we can write alpha into 8 V into delta T error is equal to alpha into V into delta T ambient temperature. We are just equating the volumes; we have to calculate the temperature rise in the bulb that will cause the same volume change in the bulb. So, delta T error can be calculated now as alpha V alpha V gone delta T ambient temperature divided by 8 and this is 20 by 8, so this is 2.5 degree Celsius.

So, the error is 2.5 degree Celsius due to change in ambient temperature by 20 degree Celsius correction is minus 2.5 degree Celsius and finally, we have to find out the error in measure temperature if the bulb is raised by 50 centimeter from the calibration elevation. So, basically you have to find out what is the pressure exerted by a 50 centimeter column of mercury.

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A Numerical Example

Solution

(a) Sensitivity of the mercury-in-steel thermometer

$$= \frac{\text{total angular displacement in radians}}{\text{temperature range}}$$
$$= \frac{225 \times \pi / 180}{200} = 0.0196 \text{ rad/}^\circ\text{C}$$

Now, before I go that, before I go there, so this is how again we saw the sensitivity of the mercury thermometer can be found by total angular displacement in radians divided by temperature range which comes out that 19 radian per degree Celsius.

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A Numerical Example

(b) The volume change in the capillary and the Bourdon tube due to change in ambient temperature will introduce an error in the readings. To find this error, we have to calculate the temperature rise in the bulb that will cause the same volume change in the bulb. Thus, we can write:

$$\alpha(8V)(\Delta T)_{\text{error}} = \alpha(V)(\Delta T)_{\text{ambient temp}}$$

Where α is the coefficient of volumetric expansion and V the combined volume of the capillary and bourdon tube. Then, $\Delta T_{\text{error}} = \frac{20}{8} = 2.5^\circ\text{C}$

Thus the error due to change in ambient temperature is 2.5°C . Alternatively, the correction to be applied to the observed readings would be -2.5°C .

The second part was error due to change in ambient temperature and we calculate these by determining the temperature rise, in the bulb that will cause the same volume change in the bulb.

So, this is the volume change in the bulb and this due to that delta T error and this is the volume change in the capillary as well as bourdon tube due to change in ambient temperature. So, you equate that and from that I get delta T error as 2.5 degree Celsius. So, the error due to change in ambient temperature is 2.5 degree Celsius, alternatively we can say that the correction to be applied to the observed reading is minus 2.5 degree Celsius. We have to subtract 2.5 degree Celsius from the observed reading.

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A Numerical Example

(c) The pressure exerted by a 50 cm column of Hg = $\rho_{\text{Hg}}gh$

$$= \left(13.69 \times 10^3 \frac{\text{kg}}{\text{m}^3}\right) \left(9.81 \frac{\text{m}}{\text{s}^2}\right) \times \left(\frac{50}{100} \text{m}\right) = 6.7149 \times 10^4 \text{ Pa} = 67.15 \text{ kPa}$$

Angular movement caused by 67.15 kPa pressure in the Bourdon pressure element

$$= \frac{(250 \times \pi / 180) \times (67.15 \times 10^{-3})}{5} = 0.0586 \text{ rad}$$

So error due to elevation effect in measurement

$$= \frac{\text{angular movement due to elevation}}{\text{sensitivity of thermometer}} = \frac{0.0586 \text{ rad}}{0.0196 \frac{\text{rad}}{^\circ\text{C}}} = 2.98^\circ \text{C}$$

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Finally, to find out the elevation error, we have to find out the pressure exerted by a 50 centimeter column of mercury, we can find that how does rho gh. So, this is the density of mercury 13.69 gram per centimeter cube expressed as kg per meter cube, g 9.81 meter per second square and 50 centimeter, express as 50 by 100 meter. So, this turns out to be 6.7149 into 10 to the power 4 Pascal or 67.15 kilo Pascal.

So, the angular movement caused by 67.15 kilo Pascal pressure in the bourdon pressure element can be found out from this, this is the range 0 to 5 mega Pascal. So, 67.15 10 to the power minus 3 mega Pascal is 67.15 in 10 to the power minus 3 mega Pascal and 250, 0 to 250, 250 degree Celsius corresponding to 5 mega Pascal. So, 250 into pi by 180 radian.

So, this turns out to be 0.0586 radian; so the error due to elevation effect in measurement can be now found out as angular movement due to elevation divided by sensitivity of the thermometer or angular movement due to elevation is 0.0586 radian and the sensitivity

of the thermometer we have found out it in part A, which is 0.0196 radian per degree Celsius. So, this turns out to be 2.98 degree Celsius, so the error due to elevation effect is 2.98 degree Celsius for a difference in calibration height of 50 centimeter.

So, these, this is how you can find out the correction factor is required for your measurements. So, this stops our discussion for week 7, in the next week we will continue our discussion with temperature measuring instruments.