FEB 2021

APPLIED MARINE ENGINEERING

Attempt ALL questions
Marks for each part question are shown in brackets

1. With reference to carbon fibre used in marine construction:

 (a) describe the properties that make it suitable for EACH of the following:

  (i) hull construction; (2)

  (ii) mast construction; (2)

 (b) explain its undesirable properties for the applications in part (a); (3)

 (c) explain the safety considerations necessary when working with carbon fibre. (3)

2. With reference to manufacturing components from aluminium:

 (a) explain why it may be necessary to anneal aluminium; (2)

 (b) describe the problems encountered when working with annealed aluminium; (4)

 (c) describe how it could be annealed on board a vessel. (4)

3. Describe, with the aid of load extension graphs, EACH of the following engineering terms:

 (a) limit of proportionality; (2)

 (b) yield point; (2)

 (c) Ultimate Tensile Strength; (2)

 (d) 0.1% Proof Stress. (4)

4. (a) Explain the process of *brazing* for the joining of metals and alloys. (4)

 (b) State TWO methods by which a cracked aluminium alloy pump casting might be repaired. (2)

 (c) List the FOUR functions that the flux performs in the brazing process. (4)

5. (a) Describe the problems associated with two dissimilar metals in contact in the presence of sea water. (4)

 (b) Describe THREE different methods that may be used to reduce the problems described in part (a). (6)

6. With reference to the cathodic protection of hull fittings:

   (a) explain how sacrificial anodes achieve this; (2)

   (b) state where sacrificial anodes would be fitted and why; (4)

   (c) describe an impressed current system, stating the principle on which it works. (4)

7. With reference to osmosis in glass reinforced plastic (GRP) hulls:

   (a) explain how osmosis may be detected in service; (2)

   (b) explain why simply drying out the hull is not a cure for the effects of osmosis; (2)

   (c) describe the FULL process for the treatment of a hull suffering from the effects of osmosis. (6)

8. Describe, with the aid of a sketch, a method of measuring and remotely indicating EACH of the following:

   (a) temperature; THERMISTOR (Thermal resistor) (4)

   (b) rate of flow. Turbine flowmeter (6)

9. With reference to a main engine lubricating oil system, explain, with the aid of a sketch, the principle of a *closed loop* temperature control system. (10)

10. (a) Explain EACH of the following control terms:

    (i) proportional bandwidth; (2)

    (ii) integral action; (2)

    (iii) derivative action. (2)

    (b) Describe a 3-step method for tuning a PID controller. (4)

1. With reference to carbon fibre used in marine construction:

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(ii) mast construction; (2)

(b) explain its undesirable properties for the applications in part (a); (3)

(c) explain the safety considerations necessary when working with carbon fibre. (3)

Part (a): Describing the properties of carbon fiber for hull and mast construction

- Hull construction:
  - High strength-to-weight ratio: Carbon fiber is incredibly strong for its weight, making it ideal for building lightweight hulls that can withstand the stress of waves and currents. This can improve a vessel's fuel efficiency and performance.
  - Corrosion resistance: Carbon fiber is highly resistant to corrosion from saltwater and other marine environments, unlike metals like steel which can rust and deteriorate. This reduces maintenance costs and extends the lifespan of the hull.
  - Stiffness and dimensional stability: Carbon fiber composites have minimal thermal expansion and contraction, helping the hull maintain its shape and integrity even in changing temperatures.
- Mast construction:
  - High stiffness and low weight: These properties allow for taller and lighter masts that can carry more sail area without bending excessively. This can improve a vessel's sailing performance and stability.
  - Fatigue resistance: Carbon fiber masts can withstand repeated cycles of stress without breaking, making them ideal for long voyages and harsh conditions.
  - Improved sail control: The stiffness of carbon fiber masts provides a more responsive feel to the sails, giving the crew greater control over the vessel.

Part (b): Explaining the undesirable properties of carbon fiber for marine applications

- High cost: Carbon fiber is significantly more expensive than traditional materials like fiberglass or wood, making it a less economical choice for some applications.
- Brittle failure: While strong, carbon fiber can be brittle and prone to catastrophic failure if damaged. This can be a safety concern, especially for high-performance vessels.
- Repair difficulty: Repairing damage to carbon fiber can be complex and expensive, requiring specialized training and materials.

Part (c): Explaining safety considerations when working with carbon fiber

- Sharp fibers: Carbon fibers can be sharp and cause skin irritation or even puncture wounds if handled improperly. Proper personal protective equipment (PPE) like gloves and long sleeves is essential when working with carbon fiber.
- Dust hazard: Cutting or sanding carbon fiber releases dust particles that can be harmful if inhaled. Proper ventilation and respiratory protection are necessary to avoid health risks.
- Galvanic corrosion: When combined with metals, carbon fiber can create galvanic corrosion, which can damage both materials. Careful selection of compatible materials and proper insulation are necessary to prevent this.

2. With reference to manufacturing components from aluminium:

(a) explain why it may be necessary to anneal aluminium; (2)

(b) describe the problems encountered when working with annealed aluminium; (4)

(c) describe how it could be annealed on board a vessel. (4)

Annealing Aluminium on Board a Vessel:

(a) Reasons for Annealing Aluminium:

Annealing involves heating aluminium to a specific temperature, holding it for a certain time, and then cooling it slowly. This process softens the material and improves its ductility and workability, making it easier to shape and form. Here's why annealing might be necessary:

- **Work hardening:** Cold working (e.g., bending, rolling, drawing) strengthens aluminium but reduces its ductility. Annealing restores its workability, allowing further forming without cracking.
- **Internal stress relief:** Casting, welding, and machining can introduce internal stresses within the aluminium. Annealing relaxes these stresses, preventing warping and improving long-term stability.
- **Grain size control:** Annealing controls the size and distribution of aluminium grains, optimizing its properties for specific applications, like improving electrical conductivity or weldability.

(b) Problems with Annealed Aluminium:

While annealing enhances workability, it also presents challenges:

- **Reduced Strength:** Compared to work-hardened aluminium, annealed aluminium has lower strength, which might be inadequate for certain structural components.
- **Dimensional Changes:** Annealing can cause slight dimensional changes due to grain growth and stress relief, requiring post-annealing machining or adjustments.
- **Corrosion Resistance:** In some alloys, annealing can affect the corrosion resistance by altering the microstructure or precipitations. Careful selection of annealing parameters and corrosion protection measures are crucial.

(c) Annealing on Board a Vessel:

While feasible in specific scenarios, on-board annealing of aluminium components presents practical limitations:

- **Equipment Restrictions:** Vessels typically lack dedicated annealing furnaces or controlled heating chambers. Improvised setups using available heating sources might not achieve uniform or precise temperature control.
- **Safety Concerns:** Open flames or uncontrolled heating elements pose fire and safety hazards in confined onboard spaces. Alternative methods like induction heating might be safer but require specialized equipment.
- **Material Expertise:** Selecting the appropriate annealing parameters and interpreting their impact on specific alloys requires metallurgical knowledge and understanding of potential risks.

Alternatives to On-board Annealing:

- **Pre-annealed Materials:** Utilizing pre-annealed aluminium sheets, bars, or profiles eliminates the need for on-board annealing while ensuring desired workability.
- **Portable Induction Heaters:** Compact and controllable induction heaters offer localized heating options for small-scale annealing of specific areas.
- **External Services:** When feasible, collaborating with onshore repair facilities or specialized workshops for controlled annealing of critical components might be a safer and more reliable option.

Important Note:

On-board annealing of aluminium components should only be attempted as a last resort and with careful consideration of potential risks and limitations. Consulting with qualified engineers and metallurgists is crucial to ensure safety, material compatibility, and desired properties are achieved.

3. Describe, with the aid of load extension graphs, EACH of the following engineering terms:

(a) limit of proportionality; (2)

(b) yield point; (2)

(c) Ultimate Tensile Strength; (2)

(d) 0.1% Proof Stress. (4)

(a) Limit of Proportionality:

Imagine pulling a rubber band gently. Initially, it stretches proportionally to the pulling force. This linear relationship between stress and strain defines the elastic region. The limit of proportionality, represented by a point on the graph, marks the transition from this linear region to a slightly curved region. Beyond this point, the material starts to deform slightly more than expected for the applied stress.

(b) Yield Point:

Continue pulling the rubber band harder. At some point, it suddenly stretches significantly even with a small increase in force. This abrupt jump on the graph is the yield point. It signifies the onset of plastic deformation, where the material begins to deform permanently even after the stress is removed.

(c) Ultimate Tensile Strength (UTS):

Keep pulling the rubber band relentlessly. It continues to stretch, but at a slower rate as its internal resistance builds up. Eventually, it reaches a peak point on the graph, the ultimate tensile strength (UTS). This represents the maximum stress the material can withstand before finally breaking.

(d) 0.1% Proof Stress:

Not all materials have a distinct yield point. In such cases, we use the 0.1% proof stress. Imagine pulling the rubber band slightly again and measuring its length after releasing the force. If the permanent elongation reaches 0.1% of its original length, the stress at that point is called the 0.1% proof stress. It serves as a practical measure of the material's yield strength in the absence of a clear yield point.

Visualizing the Graph:

Think of the graph as a mountain trail. We start walking on a flat (elastic) path, then encounter a slight incline (limit of proportionality), followed by a steeper climb (yield point), reaching the peak (UTS), and finally, the trail drops off before we fall (fracture). The 0.1% proof stress would be like stopping at a certain point on the slope and checking how far down the path we've permanently slid.

Understanding these terms and their visual representations is crucial for selecting materials appropriate for different engineering applications. Knowing their limits helps us design components that can safely handle expected loads and deformations without compromising their integrity or performance.

4. (a) Explain the process of *brazing* for the joining of metals and alloys. (4)

(b) State TWO methods by which a cracked aluminium alloy pump casting might be repaired. (2)

(c) List the FOUR functions that the flux performs in the brazing process. (4)

(a) Brazing Process:

Brazing is a metal joining process where a filler metal with a lower melting point than the base metals is used to create a strong bond. Here's how it works:

1. **Preparation:** The surfaces to be joined are cleaned and fitted closely together, with a small gap (0.002-0.005 inches). Flux is applied to aid cleaning and promote wetting.
2. **Heating:** The joint is heated using various methods like torches, induction heating, or furnaces, reaching the brazing temperature of the filler metal (typically above 450°C but below the base metal melting point).
3. **Filler Metal Application:** The filler metal, in the form of wire, rod, or paste, is introduced to the heated joint.
4. **Capillary Action:** Due to surface tension and wetting properties, the molten filler metal flows into the gap by capillary action, filling it completely.
5. **Solidification:** As the heat source is removed, the filler metal solidifies, joining the base metals together.

(b) Repairing a Cracked Aluminium Alloy Pump Casting:

1. **Brazing:** This is a common method for repairing small cracks and leaks. The brazing process described above can be used with an aluminium brazing filler metal. However, careful selection of the filler metal and brazing technique is crucial to ensure compatibility with the specific aluminium alloy and avoid distortion.
2. **Welding:** For larger cracks or when high strength is required, welding might be an option. However, due to the lower melting point of aluminium and its sensitivity to heat, special techniques like TIG welding with appropriate filler metals are necessary to minimize distortion and maintain casting integrity.

(c) Functions of Flux in Brazing:

1. **Cleaning:** Flux removes oxides and impurities from the metal surfaces, improving wetting and adhesion of the filler metal.
2. **Deoxidation:** Fluxes often contain deoxidizers that neutralize oxides during heating, further promoting wetting and flow of the filler metal.
3. **Protection:** Flux can provide a protective atmosphere around the joint, preventing oxidation and contamination during heating.
4. **Wetting:** Some fluxes contain wetting agents that enhance the surface tension of the molten filler metal, allowing it to flow more easily into the joint gap.

Important Note: Repairing cracked castings requires expertise and proper selection of materials and techniques. Consulting a qualified welding or brazing professional is essential for a successful and safe repair.

5. (a) Describe the problems associated with two dissimilar metals in contact in the presence of sea water. (4)

(b) Describe THREE different methods that may be used to reduce the problems described in part (a). (6)

Dissimilar Metals in Seawater: A Recipe for Corrosion Trouble

(a) Problems with Dissimilar Metals in Seawater:

When two dissimilar metals come into contact in the presence of seawater, a recipe for corrosion disaster is brewed. Here's why:

1. Galvanic Corrosion: The primary culprit is galvanic corrosion. Dissimilar metals have different electrochemical potentials, meaning they possess varying tendencies to give up electrons and corrode. The more active metal (lower potential) acts as the anode, readily losing electrons and dissolving into the seawater. The less active metal (higher potential) becomes the cathode, attracting these electrons and remaining protected. This "sacrificial" process rapidly corrodes the anode metal.

2. Increased Corrosion Rate: Seawater acts as an excellent electrolyte, facilitating the flow of electrons between the metals. This significantly accelerates the corrosion process compared to each metal exposed to seawater alone.

3. Localized Corrosion: The corrosion often concentrates at the point of contact between the metals, creating deep pits and grooves. This localized attack can weaken the structure and compromise the integrity of the components.

4. Stress Corrosion Cracking: In some cases, the combined effect of stress and the corrosive environment can lead to stress corrosion cracking. This can cause sudden and catastrophic failures, especially in critical components like propellers or shafts.

(b) Reducing the Problems of Dissimilar Metal Contact:

Fortunately, several methods can be employed to reduce or eliminate the problems associated with dissimilar metals in seawater:

1. Material Selection: Choosing metals with similar electrochemical potentials minimizes the potential difference and significantly reduces the driving force for galvanic corrosion. This can be achieved by using stainless steel alloys, copper-nickel alloys, or even plastic components in strategic locations.

2. Cathodic Protection: This method actively protects the more active metal by applying an external current that shifts its potential to become cathodic. Sacrificial anodes (made of even more active metals) or impressed current systems can be used to achieve this.

3. Electrical Isolation: In some cases, it's possible to physically isolate the dissimilar metals from each other through non-conductive coatings, gaskets, or washers. This prevents direct electrical contact and eliminates the pathway for galvanic currents to flow.

4. Protective Coatings: Applying specialized coatings like epoxy resins, polyurethanes, or zinc primers can create a barrier between the metal and the seawater, further mitigating corrosion. However, regular inspection and reapplication may be necessary.

By carefully considering these methods and choosing the appropriate approach for your specific application, you can effectively minimize the problems associated with dissimilar metals in seawater and ensure the longevity and integrity of your marine structures and equipment.

Remember, corrosion is a constant threat in marine environments, and proactive measures are crucial for keeping your vessels and components safe and operational. Don't hesitate to consult with experienced professionals and choose the solution that best suits your needs and budget

6. With reference to the cathodic protection of hull fittings:

(a) explain how sacrificial anodes achieve this; (2)

(b) state where sacrificial anodes would be fitted and why; (4)

(c) describe an impressed current system, stating the principle on which it works. (4)

Protecting the Underwater Warriors: Unveiling Cathodic Protection of Hull Fittings

(a) Sacrificial Anodes: Guardians of the Hull:

Imagine these gallant knights, made of zinc or aluminum, standing guard on the hull, sacrificing themselves to protect the nobler metals around them. These are sacrificial anodes, the champions of cathodic protection for hull fittings. They work by creating a galvanic cell with the steel hull:

1. Potential Difference: Sacrificial anodes have a lower electrochemical potential than the steel hull. This creates a voltage difference between them.
2. Anode & Cathode Formation: The anode becomes the anode, readily releasing electrons and dissolving into ions. The steel hull becomes the cathode, attracting electrons.
3. Electron Flow: Electrons flow from the anode through the conductive seawater to the cathode (hull).
4. Cathodic Reaction: Electrons at the cathode react with oxygen and water to form harmless compounds like hydroxide ions.

This cycle essentially shifts the corrosion away from the hull onto the sacrificial anode. As the anode corrodes, it gradually shrinks, eventually needing replacement. But during its noble sacrifice, it protects the vital hull from the ravages of corrosion.

(b) Strategic Positioning: Protecting the Vulnerable:

Like wise generals placing their troops, sacrificial anodes are strategically positioned on the hull, focusing on areas most susceptible to corrosion:

- Propeller: The spinning propeller creates turbulence, accelerating corrosion. Anodes near the propeller ensure its protection.

- Rudder and Stern: These areas experience high water flow and stress, making them vulnerable. Strategically placed anodes shield them.
- Seawater Inlets and Outlets: Where water enters and exits the hull, corrosion risk is high. Anodes protect these crucial points.
- Bilge keels: These protrusions on the hull bottom are prone to corrosion, and anodes strategically placed underneath offer protection.

By placing anodes in these vulnerable areas, we ensure the vital parts of the hull remain shielded from corrosion, extending their lifespan and safeguarding the vessel's integrity.

(c) Impressed Current Systems: Engineered Protection:

For situations where sacrificial anodes aren't sufficient, or for more precise control, an impressed current system can be employed. This system operates based on the same principle of cathodic protection but uses an external power source:

1. Reference Electrode: A reference electrode measures the hull's potential against seawater.
2. Control Unit: The control unit analyzes the potential and adjusts the current output from a DC power source.
3. Anode: A specially designed anode, often made of platinum or graphite, releases current into the seawater.
4. Electron Flow: The current flows from the anode through the seawater to the hull, making it the cathode.
5. Cathodic Reaction: Similar to sacrificial anodes, electrons on the hull react with oxygen and water to form harmless compounds.

By adjusting the current output, the system can precisely control the cathodic protection over the entire hull surface. This offers advantages like:

- Tailored Protection: Adjusting the current allows for customized protection for different hull areas and materials.
- Longer Anode Life: Impressed current systems can use non-sacrificial anodes, which last much longer than sacrificial ones.
- Remote Monitoring: The system can be monitored and controlled remotely, simplifying maintenance and adjustments.

However, impressed current systems are more complex and require additional maintenance compared to sacrificial anodes. Choosing the right approach depends on the size and complexity of the vessel, specific corrosion risks, and operational requirements.

Remember, both sacrificial anodes and impressed current systems play crucial roles in protecting hull fittings from corrosion, ensuring the safety and longevity of vessels navigating the watery depths.

7. With reference to osmosis in glass reinforced plastic (GRP) hulls:

(a) explain how osmosis may be detected in service; (2)

(b) explain why simply drying out the hull is not a cure for the effects of osmosis; (2)

(c) describe the FULL process for the treatment of a hull suffering from the effects of osmosis. (6)

Part (a): How osmosis may be detected in service

Osmosis is a process where water diffuses through a semipermeable membrane from a less concentrated solution to a more concentrated one. In the case of GRP hulls, the semipermeable membrane is the gelcoat, and the more concentrated solution is the seawater outside the hull. This can cause the gelcoat to blister and delaminate.

Here are some ways to detect osmosis in service:

- Visual inspection: Look for blisters, cracks, or changes in the color or texture of the gelcoat.
- Tapping: Gently tap on the hull with a mallet or other blunt object. A hollow sound may indicate delamination beneath the surface.
- Moisture meter: Use a moisture meter to measure the moisture content of the hull. This can be a more quantitative way to detect osmosis.

Part (b): Why simply drying out the hull is not a cure for the effects of osmosis

Simply drying out the hull will not cure the effects of osmosis because it does not address the underlying cause of the problem, which is the presence of water trapped within the laminate. Once water has entered the laminate, it can react with the resin and cause it to break down. Even if the hull is dried out, the damage has already been done and the blisters and delamination will likely reappear.

Part (c): The FULL process for the treatment of a hull suffering from the effects of osmosis

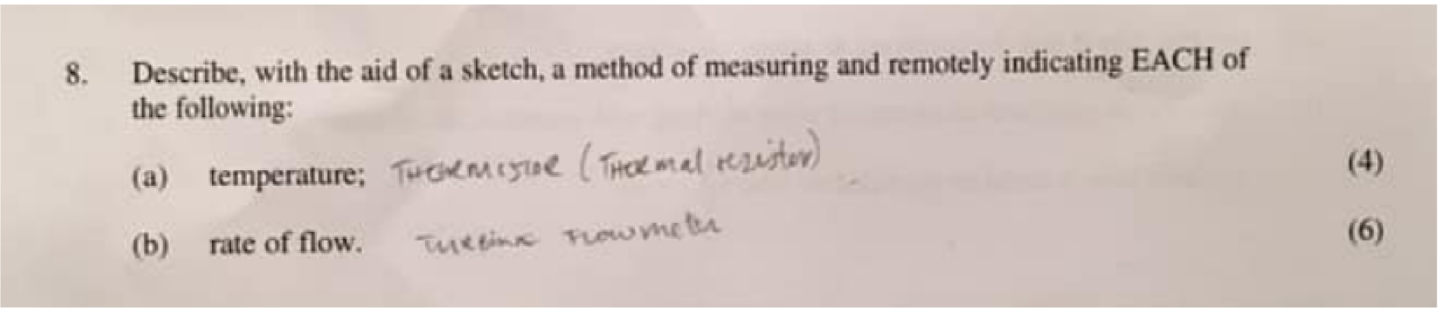
The full process for treating a hull suffering from osmosis is a complex one and can vary depending on the severity of the damage. However, here are the general steps involved:

1. Cleaning and drying the hull: The hull must be thoroughly cleaned to remove any dirt, grime, or salt deposits. It should then be dried out completely, ideally using a combination of heat and ventilation.
2. Grinding: The blisters and any delaminated areas must be ground out to remove the damaged material.
3. Neutralizing the acids: The exposed laminate must be neutralized to remove any acidic salts that can cause further damage.
4. Filling and fairing: The ground-out areas must be filled with a suitable epoxy filler and faired smooth.

5. Re-laminating: A new layer of gelcoat or epoxy resin must be applied to the repaired areas.
6. Painting: The hull may need to be repainted to restore its appearance and protect it from further damage.

Part (d): The chemical reaction that occurs during osmosis

The chemical reaction that occurs during osmosis is complex, but it essentially involves the diffusion of water molecules through the gelcoat and into the laminate. The water molecules react with the resin in the laminate, causing it to break down and lose its strength. This can lead to the formation of blisters and delamination.


8. Describe, with the aid of a sketch, a method of measuring and remotely indicating EACH of the following:

(a) temperature; THERMISTOR (Thermal resistor) (4)

(b) rate of flow. Turbine flowmeter (6)

(a) Temperature:

Method: Resistance Temperature Detector (RTD) with wireless transmitter

Sketch:

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RTD temperature sensor with a wireless transmitter

Description:

1. An RTD is a temperature sensor whose electrical resistance changes predictably with temperature. It is placed in contact with the object whose temperature needs to be measured.
2. The change in resistance is converted into a voltage signal by a transmitter circuit.
3. A wireless transmitter then sends the voltage signal as a radio wave to a remote receiver.
4. The receiver converts the received signal back into a voltage and processes it to display the actual temperature on a monitor or dashboard.

Advantages:

- Accurate and reliable over a wide temperature range.
- Simple and robust design.
- Wireless transmission eliminates wiring complexity.

Disadvantages:

- Limited transmission range depending on the transmitter power and environment.
- Requires a separate receiver and display unit.

(b) Rate of Flow:

Method: Ultrasonic Flowmeter with wired or wireless transmitter

Sketch:

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ultrasonic flowmeter with a wired transmitter

Description:

1. Ultrasonic flowmeters use sound waves to measure the flow rate of a liquid or gas. Two transducers are mounted on the pipe, sending and receiving ultrasonic pulses.
2. The difference in travel time between the upstream and downstream pulses is proportional to the flow velocity.
3. The flowmeter electronics convert the time difference into a flow rate signal.

4. A wired transmitter sends the signal through a cable to a remote receiver and display unit. Alternatively, a wireless transmitter can be used for remote monitoring.
5. The receiver displays the flow rate on a monitor or dashboard.

Advantages:

- Non-invasive measurement, no need to contact the fluid.
- Wide range of flow rates and pipe sizes.
- Suitable for various liquids and gases.

Disadvantages:

- Can be affected by bubbles, suspended solids, or complex flow patterns.
- Higher cost compared to some other flowmeters.

Additional Notes:

- These are just two examples, and the specific methods used for measuring and remotely indicating temperature and flow rate can vary depending on the specific application and requirements.
- Other factors to consider include accuracy, cost, installation complexity, and environmental conditions.
- Always consult with specialists to select the most appropriate method for your specific needs.

9. **With reference to a main engine lubricating oil system, explain, with the aid of a sketch, the principle of a *closed loop* temperature control system.** **(10)**

Here's an explanation of a closed loop temperature control system for a main engine lubricating oil system, along with a sketch:

Components:

- **Lubricating Oil Pump:** Circulates oil throughout the engine for lubrication and cooling.
- **Oil Cooler:** Transfers heat from the oil to a cooling medium (usually water or seawater).
- **Temperature Sensor:** Measures the oil temperature at the outlet of the engine or cooler.
- **Temperature Controller:** Analyzes the sensor data and compares it to the desired oil temperature (setpoint).
- **Control Valve:** Regulates the flow of cooling medium through the oil cooler based on the temperature controller's output.
- **Bypass Valve:** Allows oil to bypass the cooler if the measured temperature is below the setpoint.

Principle:

1. The lubricating oil pump circulates oil through the engine, absorbing heat due to friction and combustion.
2. The hot oil flows through the oil cooler, where the heat is transferred to the cooling medium through the tubes.
3. The temperature sensor measures the oil temperature at the outlet of the engine or cooler.
4. The temperature controller receives the sensor data and compares it to the setpoint.
5. If the measured temperature is higher than the setpoint, the controller sends a signal to the control valve.
6. The control valve opens, increasing the flow of cooling medium through the oil cooler, which removes more heat from the oil.
7. As the oil cools down, the sensor detects the decrease in temperature, and the controller adjusts the control valve accordingly.
8. If the measured temperature is below the setpoint, the controller opens the bypass valve, allowing some oil to bypass the cooler and maintain the desired temperature.

10. (a) Explain EACH of the following control terms:

(i) proportional bandwidth; (2)

(ii) integral action; (2)

(iii) derivative action. (2)

(b) Describe a 3-step method for tuning a PID controller. (4)

(a) Control Terms:

(i) Proportional Bandwidth (PB):

Proportional bandwidth (PB) refers to the range of input values around the setpoint that will cause the proportional controller's output to span its entire range. It can be expressed as a percentage of the setpoint and is calculated as the inverse of the proportional gain (K_p):

PB = 100 / K_p

A higher PB corresponds to a smaller gain, meaning the controller reacts less aggressively to input changes, leading to slower but more stable behavior. Conversely, a lower PB signifies a higher gain, resulting in faster response but potentially causing oscillations if not tuned properly.

(ii) Integral Action:

Integral action, also known as "reset" or "I action," accumulates the error over time and contributes an additional term to the controller output based on the integral of the error signal. This helps eliminate steady-state errors that proportional control alone might not address.

The integral term gradually increases the output as long as the error persists, eventually bringing the output to a value that cancels out the error. The integral gain (K_i) determines how quickly this adjustment occurs. Too high a value can lead to overshoot and instability, while too low a value might leave steady-state errors uncorrected.

(iii) Derivative Action:

Derivative action, also known as "rate" or "D action," considers the rate of change of the error signal and adjusts the controller output accordingly. This helps to anticipate future changes and provides faster response to transient disturbances.

The derivative term adds a component to the output proportional to the rate of change of the error. The derivative gain (K_d) determines the sensitivity to error rate. High values can lead to excessive control action and instability, while low values might cause sluggish response.

(b) 3-Step PID Tuning Method:

1. Start with Proportional control only (set Ki and Kd to zero):
    - Increase the proportional gain (K_p) gradually until the system starts to oscillate.
    - Note the value of K_p at which oscillations begin (P_osc).
    - Reduce K_p to approximately 50% of P_osc to achieve a stable but oscillatory response.
2.
3. Introduce Integral action:
    - Increase the integral gain (K_i) slowly while observing the system response.
    - The integral term will gradually eliminate the steady-state error introduced by the proportional control alone.
    - Stop increasing K_i when the response becomes sluggish or overshoots significantly.
4.
5. Fine-tune with Derivative action (optional):
    - If further response improvement is desired, introduce derivative action cautiously.
    - Increase the derivative gain (K_d) slightly while monitoring the system's stability.
    - The derivative term can help dampen oscillations and improve transient response, but avoid excessive values that might cause instability.