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Leakage inspection of the stepped solar still using the magnetic particle testing method

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Abstract

The shortage of drinking water in many regions of the world that lack access to freshwater is one of the major challenges faced by humanity today, as 98.77% of the world's water is saline. One method of supplying water is by using saline water, which requires desalination due to its salinity. This process typically demands high energy consumption, making solar desalination, which utilizes the abundant energy from the sun, the best method for obtaining drinking water during the hot seasons. Current studies on solar stills focus on increasing their efficiency and producing more freshwater using conventional methods. Since the stepped solar still must be completely sealed to prevent water leakage, which is crucial for improving efficiency and ensuring the production of drinking water, the welded sections of the stepped solar still were inspected using the non-destructive magnetic particle testing method instead of visual testing. After necessary inspections, all pores and seams were completely sealed against water and moisture penetration using sealing adhesive. The results of the solar desalination device showed that its efficiency increased by 55.2% compared to the state before the tests were conducted.

1. Introduction

A test, examination, or evaluation conducted on any object under examination without altering or changing it in any way, to determine the presence or absence of conditions or discontinuities that may affect its usefulness and serviceability, is called non-destructive testing (NDT) [A1]. Non-destructive tests may also be carried out to measure other properties of the object under examination, such as size, dimensions, shape, and structure, which include alloying elements, hardness, grain size, etc. Essentially, the simplest definition is a test performed on any type of object, regardless of size, shape, or material, to determine the

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presence or absence of discontinuities or to evaluate other material properties [A2]. Although this technology has been effectively used for several decades, it remains unknown to the general public, who assume that buildings will not collapse, airplanes will not crash, and products will not fail. Non-destructive testing can be considered an extension of the human senses, often through the use of complex electronic devices and other specialized equipment [A3]. On the other hand, the sensitivity and application of human senses can be enhanced when using this equipment. Misuse or incorrect application of non-destructive testing can also lead to irreparable consequences. If the test is not performed correctly or if the results are not accurately interpreted, it may lead to irreversible outcomes. It is essential to employ the appropriate non-destructive testing technique and method, carried out by trained personnel, to minimize such issues [A4]. Some concerns need to be addressed. One widespread misconception is that non-destructive testing has limitations. Non-destructive testing alone is not a solution. In most cases, a comprehensive inspection requires at least two methods: one method for assessing the internal condition of the component and another that is more sensitive to the surface condition. It is crucial to understand the limitations of each method before use. For instance, a specific discontinuity may be positioned in such a way that it cannot be detected by a particular non-destructive testing method. The detection threshold is also an important variable that must be understood for each method. Standards and codes exist that indicate acceptable or unacceptable discontinuities in size and type, but if the testing method used is unsuitable for detecting these conditions, the codes and standards become essentially meaningless [A5]. Other misconceptions relate to the nature and properties of the component or object under test. It is essential to gather as much information as possible as a prerequisite to testing. Important factors, such as the processes applied to the component and its application, as well as applicable codes and standards, should be comprehensively learned as prerequisites for conducting non-destructive testing [A6]. Additionally, a good understanding of the nature of the expected discontinuities in a specific test subject should be available. As previously mentioned, magnetic particle testing is used as a non-destructive testing method to detect linear discontinuities located on or near the surface of ferromagnetic components and structures [A7]. This test is limited to inspecting materials capable of conducting magnetic flux lines. Materials can be classified into three categories based on their response to magnetic fields: ferromagnetic, paramagnetic, and diamagnetic. Ferromagnetic metals include those strongly attracted to a magnet and easily magnetized, such as iron, nickel, and cobalt. Paramagnetic metals, like austenitic stainless steel, are very weakly attracted by magnetic forces and cannot be magnetized. Diamagnetic metals such as bismuth, gold, and antimony are repelled very slightly by a magnet and cannot be magnetized. Only ferromagnetic materials can be effectively inspected using magnetic particle testing. After the aforementioned explanations, the magnetic particle testing method can be applied to inspect the weld defects of a stepped solar still with 28 steps, each with a height of 30 millimeters, a width of 110 millimeters, and a length of 840 millimeters. It could be said that in other researches, investigating the leakage of other types of solar stills such as single slope, single basin, etc. mainly the visual inspection has been used, but in this research, investigating the leakage of stepped solar still using magnetic particle testing was done, which could be considered as an innovative research aspect. To understand this method, an individual must have a basic understanding of magnetism and electromagnetism. Before investigating the leakage of solar still with this method, it is necessary to have a brief understanding of the entire method.

2. Magnetism

2.1. Flux Density

The driving force of the magnetic field is called "magnetic flux" [A8]. A "magnetograph image" does not show the direction of the flux, but it does indicate that the region of maximum flux concentration is at the poles. Flux density is defined as the "number of lines of force per unit area." The unit area in question is a cross-section perpendicular to the lines of force. Flux density is measured in units of Gauss or Tesla. Tesla is the unit of flux, and flux density is represented by the symbol β.

2.2. Magnetizing Force

The total number of lines of force that constitute a magnetic field determines the strength of the attraction or repulsion of that magnet and is known as the "magnetizing force," represented by the symbol H.

2.3 Magnetic Permeability

A German physicist named Wilhelm Weber developed a theory about the ability of materials to produce or concentrate a magnetic flux field. This theory became known as the magnetic dipole theory, based on the premise that a magnetic dipole is the smallest independent particle in a material that still shows a north and south pole. In non-magnetic materials, these magnetic dipoles are randomly oriented so that their magnetic fields cancel each other out when considering the overall magnetic field of the material. When a magnetic field is applied to the material, the dipoles tend to align themselves with the magnetizing force, such that the north poles align in one direction while the south poles align in the opposite direction. The material now has an overall polarization equal to the sum of all the magnetic dipoles present. As shown in Fig 1, there will be a flux field around and within the material. Permeability is the ease with which these dipoles align, denoted by the symbol μ. Materials whose dipoles easily align at low magnetizing forces are said to have high permeability. To determine the absolute values of permeability, the produced flux density is divided by the applied magnetizing force, represented as a formula. However, for practical applications, it is simpler to use relative permeability measurements, which are determined by comparing the material's permeability to that of a vacuum, referred to as relative permeability and also denoted by μ. Permeability in magnetic theory can be compared to conductivity in electrical theory. Relative permeability can be measured using the IACS (International Annealed Copper Standard) conductivity scale, where the conductivity of all conductive materials is expressed as a percentage of that of copper. Ferromagnetic materials, which have relative permeability values much greater than one, have a base value of the vacuum (sometimes referred to as the unit). They can also have a value several hundred times the permeability of a vacuum. Paramagnetic materials, in which the dipoles resist alignment even in the presence of high magnetizing forces, have low permeability. Paramagnetic materials have relative permeability slightly greater than 1, such as 1.003 for some stainless steels. The third category of metals includes diamagnetic materials. The magnetic dipoles in diamagnetic materials will rotate to positions that are 90 degrees relative to the direction of the applied magnetizing force, creating a very slight repulsion to the magnetizing force. Diamagnetic materials have relative permeability much less than one, for example, 0.9996. Due to their minimal or lack of response to magnets, diamagnetic and paramagnetic materials are usually referred to as non-magnetic.

$$\mu = {}^{\beta}/_{H} \tag{1}$$

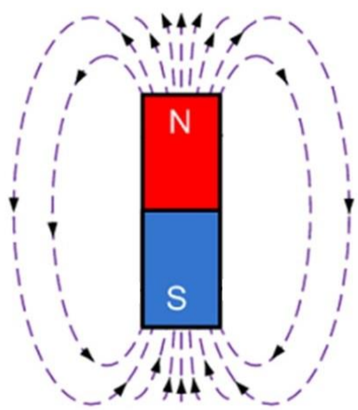

Fig 1: A magnetograph diagram showing polarization and flux direction.

2.4 Magnetic Reluctance

Magnetic reluctance in a magnetic circuit is equivalent to resistance in an electrical circuit. Magnetic flux always follows the path of least magnetic reluctance in a ferromagnetic material. The factors that influence magnetic reluctance include:

- The length of the magnetic path (λ)
- The cross-sectional area of the magnetic path (A)
- The permeability of the magnetic path (μ)

The magnetic reluctance (R) of a magnetic path can be mathematically calculated using Equation 2:

$$R = {}^{\lambda}/_{A\mu} \tag{2}$$

In other words, a material with low permeability is a material with high magnetic reluctance. The power dissipated in an electrical circuit is measured in watts and is the product of the applied voltage (V) and the resulting current (I):

$$W = VI \quad (3)$$

2.5. Magnetic Saturation

In a magnetic field, the lines of force repel adjacent lines that are in the same direction. As the flux density increases, this repulsive force also increases. Each material has a maximum flux density it can sustain, known as saturation. When a material reaches this level, it is said to be "saturated." As flux density approaches saturation, the material's magnetic reluctance increases, and its permeability decreases towards that of a vacuum. In saturation, any further increase in the magnetizing force causes the additional flux to be expelled into the surrounding air, following the path of least magnetic resistance.

2.6. Hysteresis

Hysteresis describes how the flux density (β) in a magnetic material, changes when the magnetizing force (H) is altered. A schematic representation of how flux density increases with an increase in magnetizing force is shown in Fig 2.

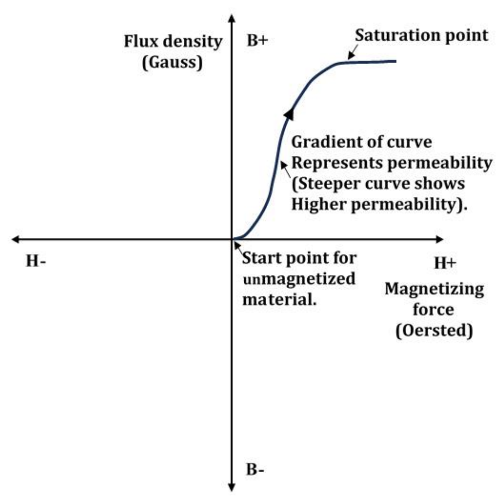

Fig 2: Hysteresis Curve - Flux Density Resulting from the Initial Magnetization of a Ferromagnetic Material [A5]

The diagram shows that in a ferromagnetic material, an initial curve is created due to the relatively small magnetizing force required to produce high flux density. The initial steepness of the curve indicates the material's permeability, as flux becomes concentrated due to the material's permeability. The curve of the ferromagnetic material changes from a steep slope toward a peak and then flattens out. Beyond this point, any increase in magnetizing force will not increase flux density. As previously mentioned, this position is referred to as saturation. The change in slope is due to the reduction in the number of available magnetic dipoles for alignment. The total number of dipoles remains constant, and beyond this amount, additional magnetizing force will lead to a locking effect in alignment. There will be fewer free dipoles to create the effect of permeability. As the material becomes more magnetized, its relative permeability decreases. The diagram shown in Fig 3 illustrates a positive magnetizing force producing an increasing positive flux density.

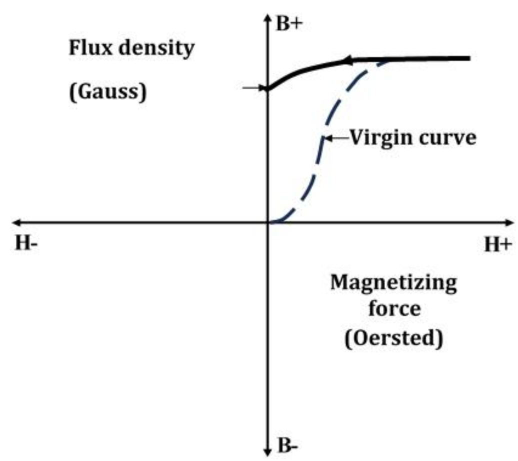

Fig 3: Hysteresis Curve - Residual Magnetism

3. Discontinuity Detection

3.1. Distortion Fields

In a magnetized material, the lines of force tend to distribute uniformly within the material, creating a homogeneous substance. The presence of a discontinuity disrupts the field and increases magnetic reluctance. The field lines prefer the path of least magnetic reluctance and thus redistribute around the discontinuity in the material, bending around it. The field is distorted by the discontinuity.

3.2. Leakage Fields

As the discontinuity becomes larger, the remaining metallic path in the component becomes more restricted, and the magnetic flux approaches saturation of the material. Some of the magnetic field lines follow a path in the air or discontinuity, which has lower magnetic reluctance compared to the remaining metal. As a result, some flux lines break from the surface of the material into the air. This phenomenon is known as "leakage field" [A9]. Notably, a leakage field may exist both near the surface and at an invisible or distant level. To create a leakage field, the discontinuity must intersect the lines of force in the material. A narrow discontinuity parallel to the flux lines will not produce a leakage field. To create a leakage field, the discontinuity must cut through the field, usually at an angle of about 45 degrees to the perpendicular. To detect a discontinuity with any orientation, the components must be magnetized in at least two directions at 90 degrees to each other.

3.3. Visible Leakage Field

When a leakage field is generated, a north and south pole will form at that location. It has recently been demonstrated that the maximum flux density occurs at the poles. Therefore, wherever a discontinuity disrupts the flux lines and leakage occurs, it will create a region of maximum flux density. When ferromagnetic particles are applied to the surface of the test object, they strongly adhere to this leakage flux area, forming a cluster of particles and creating a visible indication of discontinuity. The formation of the indication is related to the gathered flux lines producing leakage flux (Fig 4).

Certain geometric shapes of a component can also cause flux leakage. For example, screws, holes, and other rough effects on the surface thickness led to flux leakage and create indications referred to as "irrelevant".

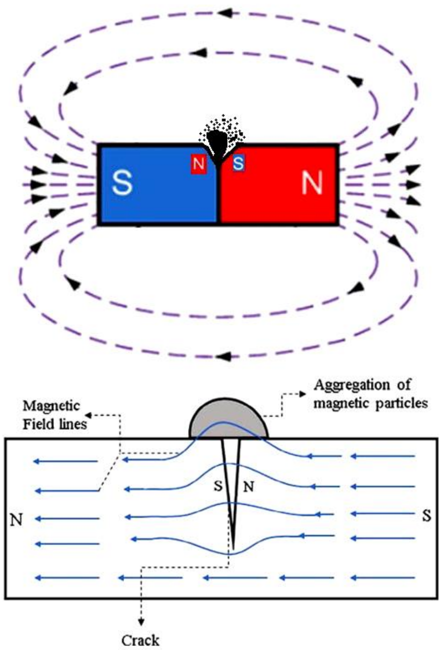

Fig 4: Applied Particles

4. Magnetization Methods

Various factors are considered when selecting a magnetization method for a specific component. The first factor is the likely orientation of the expected discontinuities. Typically, the direction of fatigue cracks can be determined by examining the loading of the component and points of stress. However, in other cases, the direction can be completely unpredictable. Whether the direction is known or not, the component should be inspected using two perpendicular field directions. This can be further explained using one or more magnetization methods. Another important factor is the strength of the applied field. Other considerations include the component's final application, its location (whether in a factory, a remote place, or within a structure), and its susceptibility to failure due to heat or arc burns. Some of the methods used in industry and component inspection are described below:

In the direct method, the magnetizing current passes through the component and completes an electrical circuit by placing the component between the poles of a fixed unit or using prods. The magnetic field formed by the direct method is perpendicular to the direction of the current. For a round bar held horizontally between the poles, as current flows from one end to the other, magnetic force lines spread around the bar. This method produces "circular magnetization." When using prods, the flux line pattern is in a flat plane. One risk with the direct method is that a strong current passing through a small contact area can cause the prod or contact head to burn the component. Therefore, contact areas should be flexible, and the tips of the prods should have a low melting point to manage thermal load. When current passes through a coil, longitudinal magnetization is produced in the component, creating a longitudinal field inside and around the coil, known as "longitudinal magnetization." The advantage of this method is that it does not cause thermal damage since the current does not pass through the component. In horizontal units, a fixed coil with about 5 turns is commonly used, while in portable units, a current-carrying wire is usually wound around the component to form a coil.

4.1. Central Conductor Method

Sometimes the term "central conductor" is not entirely accurate because the opening where the non-magnetic conductor is placed is not always central. This method is sometimes referred to as the "threaded rod method" to reflect this difference. Like the coil method, this is an indirect method because the current passes through the conductor, not the component. This method produces circular magnetization and can be used to inspect both external and internal surfaces. In the inspection of welding defects in the solar desalination unit, a yoke has been used. To generate a longitudinal magnetic flux, a yoke can be employed. A yoke is an electromagnet consisting of a magnetic core and a coil wound around it. When current passes through the coil, a linear magnetic field is created between the yoke's poles. By positioning two yoke poles on either side of the weld bed and using direct current, the ability to detect subsurface defects that occur in butt welds and between relatively thin plates can be enhanced. Due to the lack of magnetic flux leakage typically emitted from the yoke poles, acceptable results are obtained in detecting subsurface defects.in inspection of welded parts of solar still this method was done.

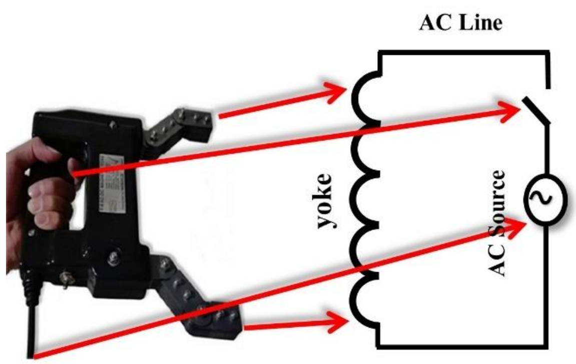

Fig 5: Yoke

Fig 6: Dry Powder Bulb

5. Magnetic Particles Used in Magnetic Particle Testing

These particles are very fine [A10] and are often colored to facilitate their visibility on the test piece. The colors of these materials are usually gray, white, red, yellow, blue, or black. In magnetic particle testing, these materials are referred to as visible particles, meaning their indications are observable under visible light. Magnetic particles may also be impregnated with fluorescent materials, in which case the indications will be visible under ultraviolet light. The sensitivity of inspection with fluorescent particles is higher than that with visible particles. The application of magnetic particles to the piece can be done in two ways:

- As a dry powder [A11]
- Suspended in water or oil

Both methods have their advantages and limitations, but the wet fluorescent method provides greater sensitivity.it would be mentioned that in inspection of welded parts of solar still dry powder was used. (Fig 6)

6. Solar still

The solar still which welded parts were evaluated with magnetic particle testing is shown in Fig 9. Fig 8 shows a part of the solar still that has been examined using the magnetic particle testing method to prevent leakage. Fig 6 shows magnetic particle test evaluation using yoke and dry powder on the welded parts of solar still. Placement of the yoke and magnetic field generation in different directions which is necessary for magnetic particle evaluation has been investigated. The welded parts of the solar still was magnetized by the yoke, then the magnetic powder (Fig 7) was applied on its surface, a field leakage was created around the defects, and the design of the magnetic particles was checked. then, the location of the defects was identified and the leakage was sealed.

Fig 7: Magnetic Particle Test

Fig 8: Welded Ladder of the Solar Desalination Unit

Fig 9: Solar Desalination Unit

7. Evaluation of Test Results and Reports

The evaluation of test results is the most critical phase in the magnetic particle inspection process and largely depends on the inspector's qualifications. The inspector's ability to detect indications, apply the correct methods, and use properly functioning equipment and tools is crucial [A12]. Additionally, the inspector must perform the test correctly, and this capability should be verified through necessary qualification requirements. Qualification processes include visual tests to confirm the ability to recognize colors related to the magnetic particle method used. Indications should be categorized as "false," "irrelevant," or "relevant" before final evaluation [A13]. Generally, surface discontinuities create distinctive sharp indications that accurately reveal the shape and size of the discontinuities causing the leakage field. Describing every possible type of discontinuity and its clarity during magnetic particle testing is not practical. Subsurface discontinuities produce weaker, more confusing, and broader indications, and their detectability decreases as their depth increases. Precisely defining how deep a discontinuity can be detected is not simple as it depends on many variables. Generally, sensitivity varies with subsurface depth. A surface crack can usually be detected easily with the correct current and direction of the field lines. Accurate detection of cracks up to 0.040 inches (1 mm) in length is possible. Discontinuities can occur at any stage of the product lifecycle. During the cooling of metal and the production of the initial mold, numerous discontinuities can occur that can be detected by magnetic particle testing. During the solidification of the primary material, the product must be worked to create a rough product. Initial processes the part undergoes include forging, casting, rolling (hot and cold), extrusion, and drawing. These processes can produce discontinuities or alter existing discontinuities. Examples of initial process discontinuities detectable by magnetic particle testing include forging cracks, overlap forging, rolling overlaps, cracks and voids, rolling cracks, lamination at sheet ends and shells, casting shrinkage on the surface, casting impurities, cold casting welds, and hot casting cracks on the surface. After the rough shaping of the metal in the secondary process, further work is done to produce the final product. Processes such as machining, grinding, plating, and heat treatment fall into this category. These processes may create discontinuities or alter existing materials. Examples of secondary process discontinuities detectable by magnetic particle testing include thermal and plating cracks, grinding cracks, machining cracks, and plating and welding cracks. When parts are joined by welding, large discontinuities may arise. Some welding-related discontinuities that are close to or at the surface and detectable by magnetic particle testing include longitudinal cracks, transverse cracks, weld pits, incomplete fusion, inadequate penetration, slag inclusions, impurities, and cold laps or overlaps. Discontinuities that occur during service, when the part is subjected to stresses and environments that may have a significant impact on its structure, are termed service-induced discontinuities. Those detectable by magnetic particle testing include fatigue cracks, stress corrosion cracks, and static failure cracks in high-stress structures. Examples of materials, structures, and components that can be inspected using magnetic particle testing include billets, blades, bearing balls and races, threaded rods, shells, bars, wires, castings, threaded shafts, splines, welds, nuts and bolts, gears, cylinders, discs, forgings, pipe products, and plates. Therefore, all these explanations about the magnetic particle evaluation of the welded parts of this stepped solar still could be generalized too. Welded solar still parts unit were evaluated in about 2 weeks on June 2023.then, the solar still tank was filled and the solar still was launched. The results from testing the solar desalination unit, after performing non-destructive magnetic particle testing on 2th July and 3th, 2023, are presented in Table 1 and in Figs 10 and 11. Table 1, shows the parameters related to relative humidity, solar radiation intensity, basin temperature, water temperature and glass temperature. According to the mentioned parameters, the solar still power is calculated about 940 $^{J}/_{Kg}$.

Table 1: Results of the Solar Desalination Unit Test

Time (Hour)	T_{air} (°C)	V ($^{m}/_{s}$)	RH %	G (LUX)	T_{basin} (°C)	T_{water} (°C)	T_{glass} (°C)	m (gr)
09:00	34.2	2.7	20	102.2	41.5	41.9	39.9	0
10:00	35.8	2.7	21	116.6	43	42.1	41.3	28
11:00	36.5	4	20	119.2	46.5	45.5	43.3	48
12:00	37.7	4. 4	20	119.8	49.1	48.1	45	112
13:00	37.7	3	19	126.8	51.1	50	47.6	180
14:00	38.1	7	15	120.9	53.5	52.5	50	227
15:00	38	7	15	102.4	48.2	47.6	45.6	300
16:00	37.8	7	15	100	42.2	42	41	200

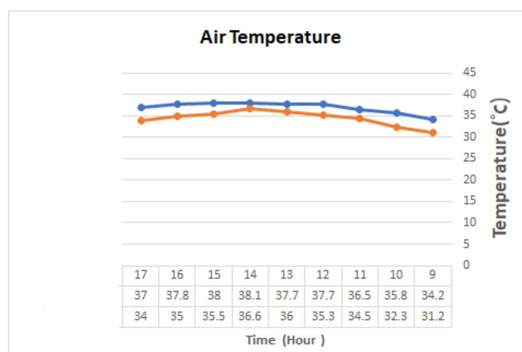

Fig 10: Comparison of Air Temperature Over Two Days of Testing for the Conventional Solar Still

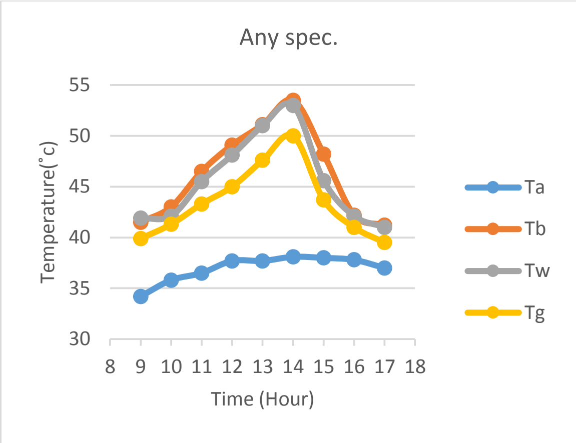

Fig 11: Comparison of Temperatures in Different Parts of the Conventional Solar Still

In comparison with other non-destructive testing methods, the advantages of magnetic particle testing can be categorized as follows:

- Immediate Results: Test results are immediately visible. The indications form one or two hours after the application of particles, not including the time required for the process or its spread.

- Permanent Records: Permanent records of the results can be created using photography, magnetic rubber, or transparent recording methods.

- No Need for AC Power: Magnetic particle testing can be conducted without an AC power source, using permanent magnets or battery-operated yokes.

- Simple Interpretation: Interpretation of the indications is straightforward.

- Accurate Indications: The particles accurately display the shape and type of discontinuity.

- Cost-Effective Equipment: Magnetic particle testing equipment can be less expensive compared to other non-destructive testing equipment, depending on automation level and performance, and may be more economically viable compared to many other methods.

- Versatile Inspection: Parts of any size or shape can be inspected immediately.

- Inspection at All Stages: Inspections can be performed at all stages of manufacturing.

- Surface Penetration: The surface penetration of the test part is less critical compared to liquid penetrant testing.

- Inspection of Various Coatings: The method can be used for inspecting non-metallic and metallic coatings or plated surfaces. However, sensitivity decreases with increased coating thickness. Maximum coating thickness should be specified in qualification tests or customer specifications.

- Safety Considerations (No Personal Risk): There is no personal risk in this process as the magnetic fields produced have a short lifespan [A14]. However, precautions such as avoiding electrical shocks, manual lifting, and handling chemical derivatives should be considered. Additionally, high amperage may cause parts to warm up during testing [A15]. Ultimately, precise inspection using magnetic particle testing can identify issues in welded sections that may lead to leaks in solar desalination units, impacting the results and efficiency of the device. Using magnetic particle testing to detect defects in solar desalination units improved its efficiency to 55.2%.

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