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New *In-situ* Heating Apparatus Setup for Universal Testing Machine

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Abstract

This paper presents a novel idea of establishing a low cost and highly efficient heating apparatus. This apparatus can be used along with any universal testing machines (UTM) for various tests, such as fracture, fatigue, torsion, and shear. This low cost and highly efficient option for researchers in solid mechanics may be used in a broad range of promising research areas. Moreover, this novel apparatus is beneficial for all researchers interested in high-temperature solid mechanics and applications. An extensive literature review presented reveals the existing heating apparatus currently used in mechanical testing labs globally, along with their pros and cons. A comparative study of the new heating apparatus and the current ones shows the advantages of the new heating apparatus and reveals how it overcomes the drawbacks of the existing heating apparatuses. The setup and connection of the new heating apparatus illustrate its secure operation and its easy commercial acquisition.

Abstrak

Pengaturan Baru Apparatus Pemanasan *In-Situ* untuk Mesin Pengujian Universal. Paper ini menyajikan sebuah ide baru untuk membangun sebuah peralatan pemanas yang berbiaya rendah dan juga sangat efisien. Peralatan ini dapat digunakan bersama dengan mesin uji universal (UTM) untuk berbagai pengujian, seperti *fracture, fatigue, torsion,* dan *shear*. Dalam *solid mechanics*, peralatan berbiaya rendah dan sangat efisien ini menjadi sebuah pilihan yang menjanjikan untuk para peneliti dalam berbagai bidang penelitian. Selain itu, peralatan baru ini bermanfaat bagi semua peneliti yang tertarik pada *solid mechanics* dan aplikasi temperatur tinggi. Tinjauan literatur extensif yang disajikan mengungkapkan peralatan pemanas yang ada saat ini digunakan di laboratorium pengujian mekanis secara global, bersama dengan pro dan kontranya. Sebuah studi perbandingan peralatan pemanas baru dan pemanas yang ada saat ini menunjukkan peralatan pemanas baru lebih menguntungkan dan dapat mengatasi kelemahan dari peralatan pemanas yang ada. Penyiapan dan penyambungan peralatan pemanas baru menjelaskan pengoperasian yang aman dan akuisisi komersialnya yang mudah.

Keywords: heat band nozzle, heating apparatus, high-temperature testing, thermal shock, thermocouples

1. Introduction

This paper aims to describe an efficient new heating system that is used along with a universal testing machine (UTM). The UTM or tensometer is used to apply various types of mechanical tests, which can help in understanding the behavior of materials under different types of load. These different types of loads include tension, compression, cyclic, torsion, shear, and bending. Each test applied by the UTM provides different aspects of the mechanical properties of a material. Different mechanical tests can include fracture, fatigue, creep, and wearing. These mechanical tests provide us with the characteristic features of metal materials before failure. The characteristic features of the materials define their thresholds before failure. These characteristics are necessary for designers and engineers to ensure safe usage of the materials.

Many previous studies have determined the mechanical characteristics of numerous materials, which are all set in well-known handbook references (i.e., [1, 2]). However, the ongoing development of new materials requires conducting extensive mechanical tests and defining their mechanical characteristics to update the handbook references. In real-world operating conditions, engineering parts and structures may face different environments, such as high temperatures, cryogenic, onshore, humidity, corrosive, and high pressure. In each environment, engineers and designers require special attention to study the performance of the materials and reconsider the environmental effects on metal or composite material life. An example of engineering parts in high-temperature environments is gas turbine blades (made of Inconel 718 super alloy), operating at temperatures over 1000 ºC [3, 4]. This paper will focus on the influence of high temperatures on material behavior and life and will describe a new way to test materials under such high temperatures.

Many extensive ongoing studies and published research have investigated the different behaviors of materials under a variety of high temperatures. Two years ago, Yuan R. *et al.* [5] examined silicon carbide ceramics (ABC-SiC) with different percentages of Al content under a remarkably high temperature (1300 °C). They found that the fatigue limit for all materials was less compared with the fatigue limit at 25 °C. In another recent study, Al-Alkawi *et al.* [6] tested three different carbon-based steel alloys (they differed in carbon content percentage) to compare and investigate the effect of carbon content on fatigue life in a moderate high-temperature environment (100 °C). The fatigue results were compared to room temperature fatigue life to illustrate the effects of high temperature on the three materials. The research team found that fatigue life and strength dramatically decrease when raising the temperature. In addition, the fatigue strength of the material with a lower content of carbon showed a high resistance to cyclic loading and a negligible reduction in fatigue strength. The high-temperature effects on the three materials weaken the fatigue strength and life.

Nogami *et al.* [7] presented a new method to evaluate the low-cycle fatigue life of small specimens, including the effect of specimen size. The applied high temperature was 550 °C. The results of the high-temperature effect show a reduction in the fatigue life by 40%–90% compared with room temperature fatigue life. The final fracture stage also occurred rapidly under high temperatures. Luis *et al.* [8] investigated the fatigue life of a new steel (17Cr13Ni-W) under high temperature (650 °C). They revealed a minor change in the fatigue life under high temperatures due to the high content of Cr and Ni.

Another study investigated the effect of high temperature on the aluminum alloy 7055 microstructure, fracture for longitudinal and transverse orientations, and anisotropic behavior in the high-cycle fatigue regime at ambient (27 °C) and high temperatures (190 °C) [9]. The results showed a significant reduction (35%) in yield and ultimate tensile strength for longitudinal and transverse orientations in fracture experiments. Similarly, at high temperatures and cyclic stress amplitudes, the fatigue life of the transverse is shorter when compared with the longitudinal orientations. Choe *et al.* [10] compared the fatigue crack propagation behavior of the 1Mo–12Si–8.5B alloy under room and high temperatures. They showed a relatively high crack initiation and increasing fracture toughness at 800 °C. In addition, they discovered that the stress intensity threshold for fatigue due to cycling loading under high temperatures increased.

The above literature review shows that recent research has investigated the influence of a high-temperature environment on material behavior and service life. A variety of heat sources and methods were used in all the research to heat material specimens during or before experiments based on the research needs and the capability of their facilities.

Background. This heating apparatus services a vast community of mechanical engineers, civil engineers, and researchers, who have an interest in discovering macro- and micro-mechanical properties of metals and composite materials under high temperatures. The apparatus also provides many advantages over other existing heating methods.

Existing heating systems. For high-temperature experiments, the heating systems used in UTMs currently include *in-situ* furnaces, such as the MTS Model 653 family of furnaces. This heating system is well known in the market for its reliability and efficiency but is remarkably expensive to purchase. Acquiring such furnaces requires a considerable amount of budgeting, special care, and training. Although this furnace serves the purpose, relatively few laboratories, research centers, and universities worldwide (particularly in developing countries) can afford to acquire this sophisticated furnace. In addition, shipping from the manufacturer (i.e., in the US or Europe) is a major obstacle for developing countries and rural universities.

Environmental chambers are another type of heating system used in many specialized types of research. These chambers provide a good simulation of real-world operating conditions, such as temperature, humidity, and caustic conditions. However, this apparatus is substantially complicated, heavy, and expensive and requires special training and spacing. Moreover, the apparatus does not provide access to the sample during the test for strain measurements. This heating system is highly sophisticated, and requires special operational training.

Another existing option for heating specimens is the induction heating system. This system is based on the laws of electromagnetism. The inductor coil part, which comprises copper, considerably closely surrounds a metal specimen with no direct contact. A high-frequency AC current runs through the coil. The metal specimen is then heated by the induced current flow in the metal specimen. This method offers an excellent combination of speed and consistency. However, the heat generated in the metal specimen due to the induced current flow is not radially uniform. The temperature is high at the surface of the specimen and at a minimum in its core. Induction heating is also inapplicable to non-metallic and non-magnetic materials. Thus, using this system during testing and strain measurement is challenging.

Joule heating is another heating method used mostly for miniature and nano-specimens. This method is conducted by introducing a DC voltage to the two ends of the specimen that leads to a current flow. The high-density current flow will facilitate the specimen heat-up in its minimal area. This method requires special attention and calculation in the design of the specimen to ensure that the heating area is located in the intended zone of the specimen. Moreover, this heating system requires sophisticated experimental tools and setup. Thus, this system necessitates basic knowledge in the electric field to calculate the required experimental temperature. This method is only applicable for metals that allow the flow of electric current unlike composite materials.

Heating methods that are commonly used in UTM testing experiments and research are available. Each method has its pros and cons during the experimental setup and tests. However, the common disadvantages of the aforementioned heating methods lie in their considerable budget requirements. Research funding is a significant obstacle for many research centers and universities, particularly for developing countries. This issue prevents them from contributing to the international research community who shares the same interests. Moreover, the cost of the annex services, such as training, installation, continuous maintenance, and shipping, can be prohibitive. The new heating apparatus setup herein can overcome these cons and yet maintain the pros of the other heating systems. Therefore, researchers and graduate students can easily contribute while preserving the best quality experimental setup at minimal cost.

2. Methods

Locally purchasing and delivering the parts of the heating apparatus will result in limited time and cost compared with international purchasing of heating systems. The ease and simplicity of the setup are major advantages over all other heating systems. Thus, a significant difference is observed for end users to establish their high-temperature experimental stations. Accordingly, the number of research studies in the high-temperature domain tests and research papers globally may grow to a new considerable level.

Components description. The heating apparatus setup comprises the following components.

Proportional–Integral–Derivative (PID) digital controller. A Proportional–Integral–Derivative, known as a PID controller, is an industrial control system that uses a control loop feedback mechanism. The PID (Figure 1a) is used to control the temperature of the ceramic heater. This component controls the temperature by applying the correction on the calculated *error value* $e(t)$ of the difference between a preferred temperature set point and a measured process variable without delay or overshoot. This process occurs by controlling the socket power output.

Ceramic band heater nozzle. This device is an essential part of the new apparatus setup. The nozzle is made with a helix wound resistance coil that is uniformly distributed and embedded in between two ceramic layers (Figure 1b). The outer ceramic layer has fiber insulation to prevent heat dissipation and energy loss. The inner ceramic core tiles have noticeable spaces in between them to allow for highly efficient heat conduction and radiation toward the specimen. A stainless steel housing then covers the ceramic heater with a terminal box notch, which will be used to attach the ceramic heater to the stand.

Ceramic heaters are offered in many sizes, dimensions, and heat capacities in the market. Selecting a heater depends on the needs and requirements of the test. Another factor that influences the selection process is the chosen wattage requirements based on the varying lab power capabilities from one country to another.

Solid-State Relay (SSR). A solid-state relay is an electronic on–off switching device that acts similarly to an electromechanical relay; however, SSR has no movable contacts and is soundless (Figure 1c). A circuit is actuated when a voltage higher than the SSR indicates the pickup voltage connection and deactivation when the voltage is not as much as the base prop out voltage. A control circuit determines when the output component is energized or de-energized. The control circuit works as the coupling between the input and output circuits.

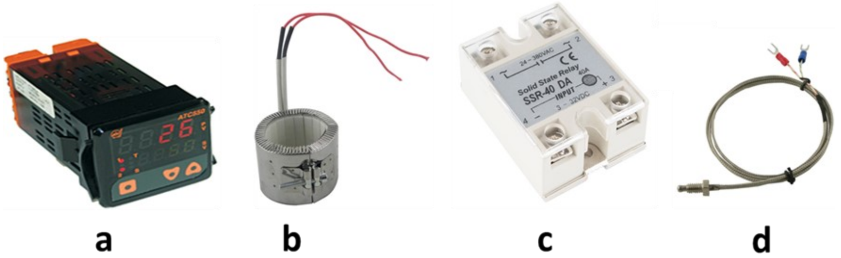

Figure 1. The Heating Apparatus Components: (a) PID Digital Controller (b) Ceramic Band Heat Nozzle (c) SSR (d) Thermocouples

Thermocouples. A thermocouple or thermometer is a sensor that measures temperature (Figure 1d). The thermocouple comprises two dissimilar metals, which are joined together at one end and separated at the other. The joined and separated ends of the thermocouple are known as the measuring and reference junctions, respectively. An electric current flows in the presence of a temperature difference between the two junctions. Therefore, the temperature at the measurement junction is determined when voltage is measured at the reference junction.

Stand. The stand is the structure of the new setup and is designed in a way that holds the ceramic heater and maintains stability and stiffness to withhold the heater weight and any other existing load where simple stress analysis can be conducted to validate the set dimensions (Figure 2 and 3). The stand dimensions and features can differ from one UTM to another based on the UTM configuration. The stand can comprise any low-strength metal that can carry the ceramic heater and should have a higher melting point than the maximum heater temperature.

High-temperature thermal insulation. This optional part depends on the test requirements and the size of the ceramic heater. The selection of the high-temperature thermal insulation should consider airflow and humidity prevention. An appropriate selection of high-temperature thermal insulation can reduce the total operation wattage to preserve energy consumption.

Advantages. The new apparatus shows many advantages over the existing heating systems on the market. As previously mentioned, the parts cost far less than other heating systems. Moreover, regardless of whether the UTM is vertical or horizontal, servo-hydraulic, or electromechanical, and miniature or macro size specimens, fitting any UTM configuration is considerably adaptable. In addition, the apparatus does not require any particular type of specimen clamp because the ceramic heater is insulated to avoid any thermal damage to the clamps and the heat is focused toward the specimen. Moreover, the ceramic heater position is adjustable to target a desired part of the specimen. Additionally, the PID controller regulates the gradient increase in temperature. Therefore, the new apparatus can rapidly or gradually increase the temperature to the desired set point. The sharp rise in temperature is an additional feature of the apparatus that is useful for researchers who are interested in studying thermal shock, which leads to metal or composite material failure [11, 12]. The easy access to the specimen, while exposed to high temperatures, facilitates strain measurement by using either a high-temperature extensometer, a laser extensometer, or digital image correlation technology.

Description of the New Heating Apparatus. As mentioned, the heating apparatus comprises simple parts and devices that can be easily setup and assembled. The apparatus assembly and the electric circuit arrangement is described and displayed in this section.

Heating apparatus steel structure. The structure of the heating apparatus is basic and easily constructed. The apparatus steel structure must be adaptive to be placed into any UTM. The concept herein is to design the structure based on the needs of the lab specialist. UTMs worldwide have different and unique shapes and dimensions. Therefore, the steel structure should first be designed in SOLIDWORKS® software to ensure proper dimension that fits into the UTM. The SOLIDWORKS® software also provides simple stress analysis tools that help design the steel structure for adequate load and heat distribution.

Figure 2 shows an example of a stress analysis using SOLIDWORKS® software. The boundary conditions and mesh size were set along with the gravitational load of the ceramic band weight on the middle horizontal arm. The vertical stand deflection angle toward the left is exaggerated by the software to show the deflection angle. The contour plot shows the stress distribution throughout the stand structure.

The construction material of the structure, which is steel in this case, where it is open for the end-user to choose whatever material they have. Thus, the metal used should be inexpensive to reduce overall costs and ensure reliability considering the heating device weight. The vertical stand is the backbone of the steel structure that carries the heating apparatus. This stand must be stable, balanced, and strong for improved performance (Figure 3a). The horizontal arm, which carries the ceramic band heater nozzle, should be designed in such a way to reach the UTM testing area where the specimen is being tested (Figure 3b). The horizontal arm can be extended or shortened to move the ceramic band heater nozzle horizontally. This arm can also be moved vertically and fixed by a pin to adapt to any required height (Figures 4a and 4b).

Heating apparatus connection scheme drawing. The four parts of the heating apparatus are all connected, as shown in Figure 5. The PID digital controller acts as the central regulator of the entire apparatus set. The wiring and connections should be safely set and secured. Thus, an extensive study of selecting a suitable experimental temperature or range of temperatures must be conducted on the basis of type of material and test. Accordingly, the required temperature for the experiment is set on the PID controller using the up/down buttons. These buttons represent the temperature of the band heater nozzle needed for the experimental temperature. The PID controller then sends electrical signals through the SSR

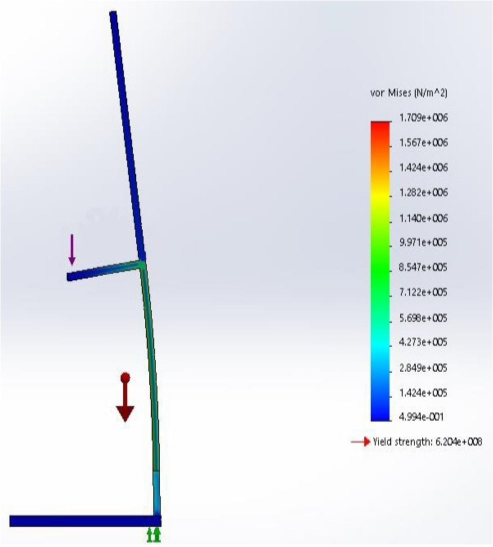

Figure 2. Stress Analysis of the Steel Structure. The Contour Plot Demonstrates the Stress Distribution under Loading Conditions

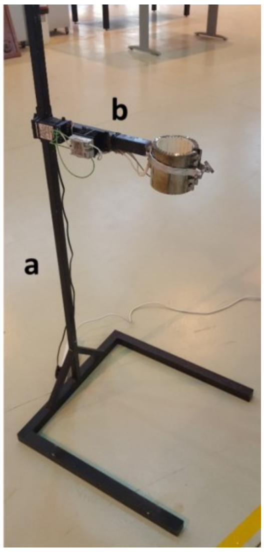

Figure 3. Steel Structure of the Heating Apparatus (a) Vertical Stand (b) Horizontal Arm

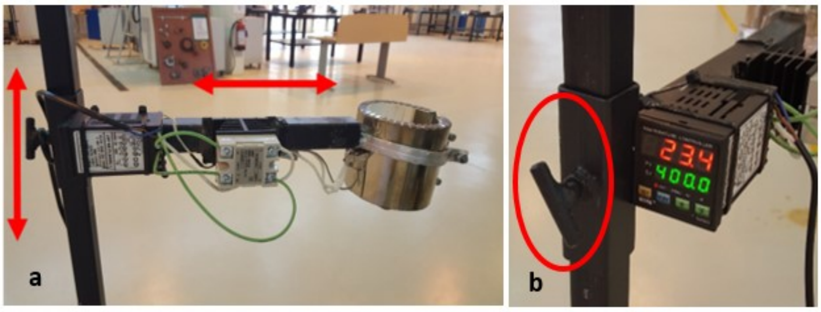

Figure 4. (a) The Horizontal Steel Arm Changes its Position Vertically and may be Horizontally Extended to Allow the Horizontal Movement of the Heat Nozzle (b) Steel pin to Control the Height of the Horizontal Arm Manually

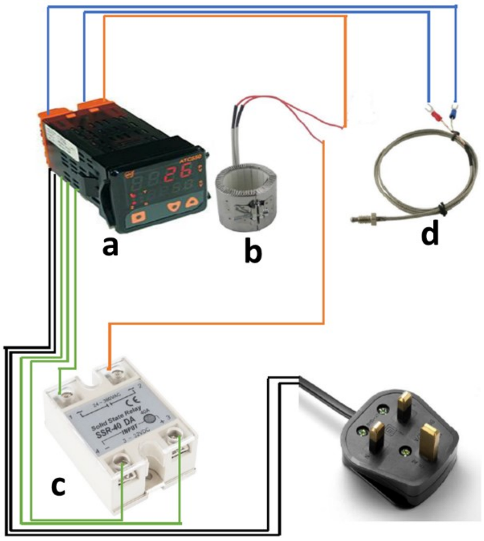

Figure 5. Heating Apparatus Color-coded Connection Scheme Shows the (a) PID Digital Controller (b) Ceramic Band Heat Nozzle (c) SSR (d) Thermocouples

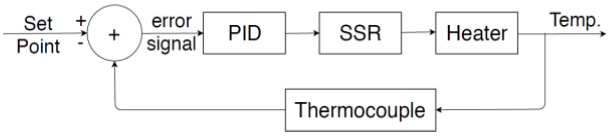

Figure 6. Heating Apparatus Block Diagram

to the ceramic band heater nozzle to start the heat-up. The ceramic nozzle heats up rapidly via the inner helix wound resistance coil, as discussed earlier. The thermocouples send signals to the PID once the ceramic band heater nozzle reaches the required temperature. At that moment, the SSR shortcuts the circuit instantly to halt the temperature increase. The temperature of the ceramic band heater nozzle decreases after some time. At this point, the SSR stops and the PID controller resends electrical signals through the SSR to the ceramic band heater nozzle to heat-up again to the set temperature. The PID controls the difference between the set temperature and the temperature of the drop (ΔT). The ΔT can be set as a range of temperatures (i.e.,

±2 °C, ±5 °C, or ±10 °C) depending on the temperature factor sensitivity desired in the experiment. The heating apparatus schematic block diagram is shown in Figure 6.

3. Results and Discussion

This apparatus provides a high-temperature environment for various mechanical tests, such as tension, compression, torsion, and shear. The geometry of the specimen defines the mechanical test type (i.e., tensile and shear test specimens, which are shown in Figure 7a and 7b, respectively). The specimen and heater nozzle assembly are demonstrated in Figure 7c. The new heating apparatus was tested to a temperature of 400 ºC. The UTM and the metal specimen (a steel rebar is used for this testing example, (Figure 8a)) are tightly clamped and securely gripped. The heating apparatus is set close to the UTM and properly positioned. The temperature is set by the PID up/down buttons (Figure 8b). The ceramic band heater nozzle heats up while the thermocouple senses the nozzle temperature in real time (as denoted by the red arrow in Figure 9a). The thermocouple sends the temperature signals to the PID and the temperature is then shown on the screen in red (Figure 8b). Notably, the thermocouple junction can be adjacent to the sample to ensure that it reaches the required testing temperature. Section 4.1 explained that the temperature of the heater nozzle (or metal specimen) reaches the set point and stabilizes. The temperature of the band nozzle can be double-checked by a non-contact digital laser infrared thermometer gun, as in Figure 9b. The high-temperature experiment test is ready to commence once the temperature is stabilized at the required temperature.

Additional options are available in raising the temperature using this heating apparatus, such as determining the temperature rise gradient. The user can determine whether the temperature increment is rapid or slow. In addition, the size of the ceramic band heater nozzle, height, and diameter can be selected on the basis of specimen and the UTM. Finally, the thermal insulation can be used for energy saving purposes.

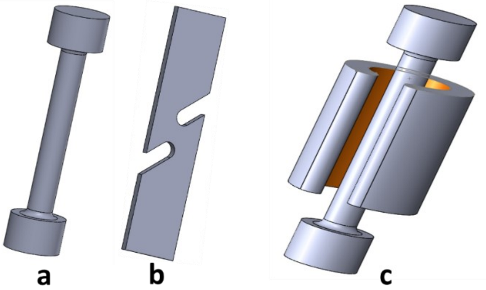

Figure 7. Specimens Designed for (a) Tensile Test (b) Shear Test (c) An Example of the Specimen and Band Heater Nozzle Assembly During Testing. The Spacing in the Heater Nozzle is for the Extensometer Device to Measure Strain Increase

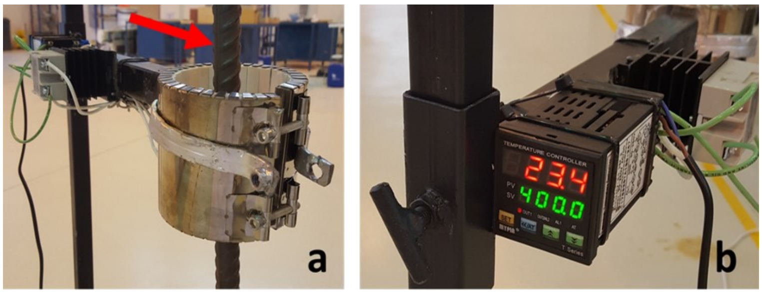

Figure 8. (a) Steel Rebar Placement in the Middle of the Heater Nozzle (b) The Input Temperature is Shown in Green (Lower Screen) and the Numbers in Red (Upper Screen) Represent the Heater Nozzle Temperature Read by the Thermocouple

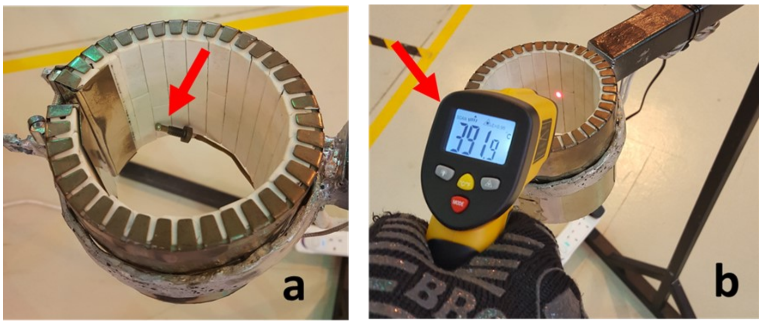

Figure 9. (a) The Arrow is Pointing to the Thermocouple Junction in the Heater Nozzle (b) Non-contact Digital Laser Infrared Thermometer Gun for Measuring the Heater Nozzle Temperature

4. Conclusions

Overall, this secure and simple setup heating apparatus is remarkably promising, particularly for research centers and universities with small budgets. The apparatus provides a quick, valid, and effective solution to research communities who are interested in testing materials under high temperatures. Moreover, the apparatus can be easily setup by undergraduate level students in their engineering senior design project. This heating apparatus comprises the stand, ceramic band heater, PID digital controller, SSR, thermocouples, and high-temperature thermal insulation. The connection scheme drawing of all parts with the logic they follow is also discussed. Finally, an experimental test is successfully run.

A list of existing heating systems was discussed along with their pros and cons. The advantages of this heating apparatus were compared to the existing ones, and promising comparison results are found. The author believes that this heating apparatus is vital serving its purpose and many enhancements can be added on the basis of needs of each user.

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