Design and Manufacturing of thermal cyclic Fatigue Apparatus

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Abstract: The thermal cyclic test is a way of measuring many thermal properties of engineering materials. Thermal fatigue resistance is one of the most important of such properties. As the industry is in a need for selecting suitable materials in relevant applications, evaluation and comparison among different materials have long been essentials issues.The present investigation aims to design and establish an assembled system to conduct an automatic cyclic (heating-cooling) test using electrical resistance technique for heating process and current water for cooling one. The components of the fatigue tester have been designed for the significant temperature differences in the range of 400 to 900°C. The temperature increases from room temperature to the required temperature value through controlled system, and returned to lower temperature by using cooling process. The time of one cycle can be varied and controlled as the test requirements. The constructed sets up of the thermal fatigue tester have been verified and prove to be durable to investigate different types of materials with small sections.

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1. Introduction

Thermal fatigue is a threat in any composite system that experiences thermal cycles during use. Historically, thermal fatigue has been a major reliability threat in systems used in structural applications. recently, concerns have been raised about thermal fatigue in much smaller structures [1].

In general, studying material's fatigue at room or at elevated temperature consumes long time. Our concern in this light is dealing with thermal fatigue which is considered as a problem for many investigators being in most cases not constrained with standard roles. Number of investigators introduced different methods for conducting thermal cyclic tests adopting various technical concepts. **Mönig et al,** [1] introduced an apparatus and an experimental method for performing thermal fatigue testing of thin films. The method uses Joule heating from alternating currents to generate temperature; (adopting concept of heat generation due to passing electrical current through metals as the source of heating process of the thermal test, such method is a convenient way to study thermal fatigue of materials in electronic sectors); the apparatus has been installed in a scanning electron microscope and allows in situ observations of the fatigue damage evolution. **Dobrzański et al, [2]** carried out the thermal fatigue investigation on a special constructed heated inductor which is connected to a power generator to accomplish heating up stage followed with cooling down by water supply; (heat conduction mode is adopted). **Blatt and Hartman** [3] introduced a mechanical test system that has been assembled to be capable of conducting fully automated, computer-controlled thermo mechanical fatigue crack growth tests using quartz lamp radiant-heating system to heat the specimen and forced cooling air jets in their cyclic technique; (heat radiation mode is carried out). Other investigators embraced different approaches in this concerns; laser technique is one of the most learnt in that area. Probably, major cases of determination thermal fatigue demand numerous numbers of thermal cycles. This research describes a simple method and an apparatus for carrying out thermal fatigue test on a large batch of samples as a contribution for reducing time. Also other physical properties like oxidation behavior can be studied in a particular manner that simulate many practical conditions, moreover, studying drastic effects of thermal stress on most of mechanical properties; (tensile, compression, impact, wear, ect.) are valid with this method.

Thermal cycles, in combination with the unavoidable mismatch in coefficients of thermal expansion, lead to cyclic straining of the metal [1]; eventually damage formation occurred and results in cracks on the metal surfaces. Measuring of total crack length after certain numbers of cycles is done by microscopic magnifier (±0.1 mm accuracy). The majority of this investigation will describe the experimental setup and the cyclic temperatures generated in the metal. Different thermal profile cycles are available by controlling heating process conditions. The basic concept underlying the method is the use of the electrical resistance method for heating and introduces thermal cycles on metal surfaces; (heat convection mode) followed with rapid cooling by running water. Heating process with this method simulate inducing thermal stresses in many practical mechanical applications e.g.; many mechanical parts in automotive sector, casting dies, power stations components, etc.) The advantages and limitations of the method in comparison with other fatigue experiments will be discussed. Finally some of recommendations for the reliability of the tester will be mentioned.

2- Design Procedures

The target of this work is conducting thermal cycles on material by heating up to a certain temperature by a specific rate and cooling down to ambient one by certain fluid followed with free drying in ambient air, this in continual manner. The apparatus will be constructed for the fulfillment of this purpose.

Mechanical design part is based on setting a closed loop for conducting thermal cycles. Thermal cycles are applied with the aid of a conveyor that carries samples, which moves from heating to cooling stages continually. A schematic diagram of the present working setup is shown in fig. (1). Major components of the setup are; thermal, rotation, and control systems.

2.1- Thermal system

A resistance furnace is designed to provide seven kW. Electrical power is used for heating process where, it simulates wide range of applications. It includes; heating elements and insulation stuff. Furnace configuration is shown in table (1).

Table (1): Furnace configuration

T_{max} (^oc)	Inner dim.(mm)			Outer dim.(mm)			Connecting power (kw)	Connecting voltage
	L	W	H	L	W	H		
1000	200	100	500	500	500	660	7	220 V, 1-phase

Heating elements (heat resistant wire, type KANTHAL- D) with 25 m. length and 2.5 mm. diameter, is coiled on ten exposure ceramic tubes with outer diameter equal 30 mm. to provide electrical power, exposed tubes are selected to minimize power loss. Calculation is done according to standard procedures of KANTHAL manual [4]. Basic calculation details are carried out to confirm safeness and efficiency of selected heat resistance wire that afford passing certain electrical current through it to supply particular power.

Insulation stuff; is perfectly constructed in the furnace to avoid heat loss. Heat flows through composite insulation medium from center to surface in constant heat flux. Insulation layers are determined according to basic formulas from reference [5] as stated here;

$$q = \Delta T / R \qquad \text{......(1)}$$

where:

q: Heat flux

ΔT: Temperature difference through slab thickness

R: Thermal resistance of material

R= Δx/k for solid

R=1/h, for fluid

k: Thermal conductivity

h=Heat transfer coefficient of medium

As heat flux is constant through insulation layers; ($q = q_1 = q_2 = q_3 = q_4 = q_5$), therefore, temperature graduation through insulation medium is depending onto thermal resistance of those materials.

2-2 Rotation mechanism

A simple mechanism is designed and constructed to enable samples to enter in and out the furnace systematically and repeatedly in closed cycle. Test samples are linked on a mechanical chain, which rotate by synchronized drive motor as shown in figure (1). A chain is responsible for conveying samples from heating furnace to cooling container and vice versa continually (loops).The design of the mechanism and the checking up of safeness is estimated according to basic design concepts of Ragab and Bayoumi [6]. Also studying and checking up stresses on furnace body are carried out according to Shigley *et al.* [7]. To clarify the furnace body deformation, the stress calculations are proceeded to avoid any deformations and buckling according to the basic design rules included in reference [7]. Deformation includes the transverse deformation along insulation composite layers and the longitudinal one onto the furnace surface (buckling due to thermal stress) are both calculated by the following formula;

$$\delta \ell = \alpha \times \Delta T \times \ell \qquad \text{.......(2)}$$

where

ℓ ; is the thickness of insulation layer and the furnace length for transverse and for longitudinal deformations, respectively.

α ; is the coefficient of thermal expansion of layer and steel for transverse and for longitudinal deformations, respectively.

ΔT; is the temperature difference through insulation stuff thickness and onto the furnace surface for transverse and for longitudinal deformations, respectively.

$\delta \ell$; is the deformation through insulation layer and along the furnace surface for transverse and for longitudinal deformations, respectively.

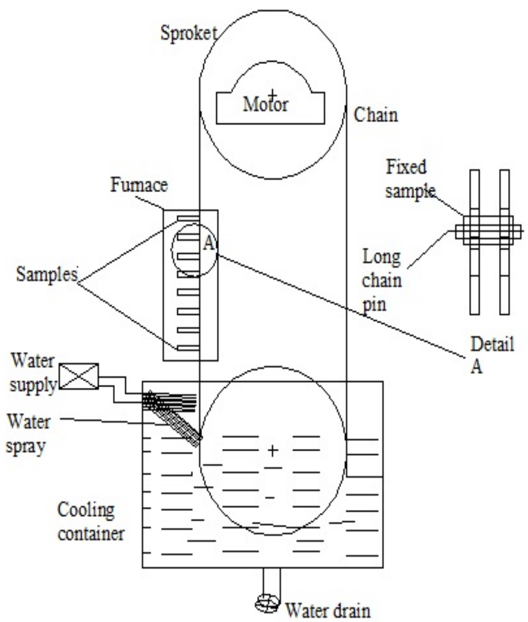


Figure 1: Schematic diagram of working setup

2-3 Control system

In order to keep the rated temperature inside furnace constant within in centigrade ±1%, thermocouple is used to cover measuring temperature range from zero to 1200 ^{o} C. A synchronized electrical motor 0.25 Hp is coupled with an inverter (ADLEEPOWER DSP INVERTER) [8], in order to sustain the temperature distribution onto the tested specimens which is linked to rotating chain.

3- Analytical problems of thermal system

It was essential to explain and analyze the problems of heat thermal system to determine the design factors required for constructing the setup. The factors required to accomplish a thermal cycle are such; heat energy (Q_1), upper temperature (T_1), initial temperature (T_0), heating time (t_1), negative heat capacity required for cooling down (Q_2), lower temperature (Tx_2), cooling time (t_2), and heat transfer rate (h).

Thermal cycle implies two processes; heating up process followed with cooling down.

3-1-Heating process

Heating process may be conducted at different conditions depending on many variables such as the maximum required temperature, required time for reaching specific temperature, constant temperature or ingredient ones from body surface to the core, sample dimensions, power capacity of furnace, adjusted furnace temperature, and material properties.

3-1-1- Heat transfer modes:

In the present work, heat transfers by convection mode from hot air to sample surface then by conduction from sample surface to its core. The basic equations of heat conduction are concerned in solving the problems of heat transfer through solids for most practical conditions are as follows.

1- One-dimensional heat conduction equations.

The equations for this condition is applied to determine change of solid temperature in one direction, say, x coordinate, with time, i.e. T= (x, t) and T= (r, t) for rectangular and cylindrical coordinates respectively. They are applied when one of three dimension of regular shaped solid is large enough compared with other two dimension,

*Rectangular coordinate system (x, y, z)

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad \text{……(3)}$$

*Cylindrical coordinate system (r, ϕ , z)

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad \text{……. (4)}$$

α : Thermal diffusivity: $\alpha = k/\rho\, C_p$

2-Three-dimensional heat conduction equations

This condition is applied when body dimensions are comparable, hence T(x, y, z, t)

*Rectangular coordinate system (x, y, z)

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{1}{k} g = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (5)$$

*Cylindrical coordinate system (r, ϕ , z)

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2} + \frac{1}{k} g = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (6)$$

One-dimensional steady-state heat conduction equation is a special case of three-dimensional of heat conduction equations, these equations solve problems of conditions that implies the temperature ingredient exists along one coordinate directional only and that temperature within the solid does not vary with time [5]. It is given by

$$d^2 T(x)/dx^2 + (1/k)\, g(x) = 0 \qquad (7)$$

$$(1/r)\, d/dr\, (r\, dT/dr) + (1/k)\, g(r) = 0 \qquad \text{…. (8)}$$

Knowing the boundary conditions the above equations can be solved.

3- Transient conduction

Transient conduction is our concern in this work, as it studies an essential practical sector in engineering applications. Determination of the temperature distribution within the solid during temperature transient is more complicated matter because temperature varies with both position and time. The case description is briefed as; (If the surface temperature of a solid body is suddenly altered, the temperature within the body begins to change over time. It will take some time before the steady- state temperature distribution is reached). In many practical applications, the variation of temperature with position is negligible during the transients, hence the temperature is considered to vary with time only. The analysis of heat transfer under such assumptions is called the *Lumped system analysis*. Otherwise, using of transient –temperature charts is used for solving simple transient heat conduction in which temperature varies with both time and position.

Lumped system analysis is concerned in our study being it suitable for solids having relatively small size, as most probably thermal fatigue test is carried out on relative small sizes.

Lumped system analysis

Lumped system analysis is applicable based on solid properties which give rise [5].

$$Bi = h L_s / k_s < 0.1 \qquad ......(9)$$

Where,

Bi: Biot number.

h: Heat transfer coefficient between solids and fluid.

L_s : Characteristic length=V/A

k_s : Thermal conductivity of solid

The difficulty in the above analysis is that heat transfer coefficients for the medium of interest vary by orders of magnitude due to the nature of test or service and the material properties may be a function of temperature [9]. It needs to be emphasized that only valid heat transfer coefficient is with the actual component in the conditions encountered in service.

Any other simplified estimation can be misleading and can only be used as a relative comparison between different materials.

Most probably Bi number is smaller than unity for small sizes even with high heat transfer rate, so Lumped Analysis is convenient with the study of the present work. Unless this condition is justified, other proper conduction equations are applied.

The energy equation of heat transfer with Lumped Analysis in the solid may be stated as:

(Rate of heat flow into the solid of volume through boundary surface A) = (Rate of increase internal energy of the solid of volume, V)

$$Q = A h (T_\infty - T(t)) = \rho C_p V dt(t) / d(t) \qquad (10)$$

T (t): Temperature of solid at time (t).

dt (t): Difference between solid temperature at time (t) and initial temperature.

d (t): Change in time from T_0 to T(t).

T_∞ : Fluid temperature.

ρ : Solid density

C_p : Specific heat of solid

V and A: Volume and area of solid

Applying mathematical integration on eq. (10):

$$T(t) = T_\infty - e^{-mt} (T_\infty - T_0) \qquad ....(11)$$

Where,

$$m = A h / \rho C_p v$$

Then the temperature of the solid as a function of time can be estimated from equation (11). Figure (2) expresses temperature distribution in transient heat conduction at different times, surface temperature is the most critical one [9] at a particular time, so studied thermal fatigue is based on surface temperature value.

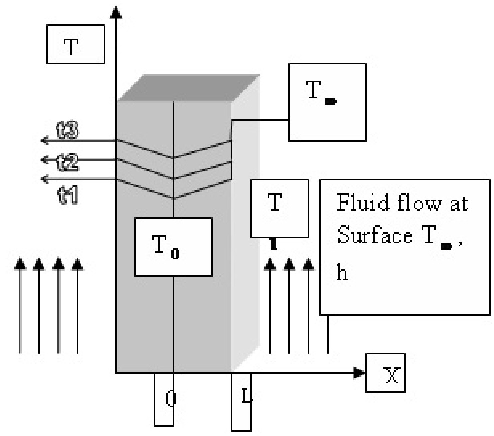


Figure 2: Temperature distribution in transient heat conduction at different times

3-2-Cooling process

Determination of cooling process factors does not need complicated analysis as heating one. It has just required estimation rate of cooling fluid as cooling time is constrained according to construction design. In other words, the speed of the samples which are linked to chain is constant during the same thermal cycle, so cooling process is controllable by cold fluid rate only. Water fluid is selected for cooling solid. Rate of fluidity is achieved using eq. (12).

$$Q = \dot{m} C_p \Delta T \qquad .... (12)$$

$$\dot{m} = \dot{V} \rho, \qquad \vartheta = \dot{V} / A$$

Q: Rate of heat loss

ΔT: Temperature diffidence wanted to be lost

C_p : Specific heat of cooling fluid (water)

$\dot{m}$: Rate of water currency

$\dot{V}$: Volume of water per time

ϑ : Water speed

A: Cross section of water tube

4-Fitting of thermal analysis with setup apparatus

From analytical description, it can be concluded that raising solid temperature to certain value (T) in a particular thermal test, major parameters included are as;

T=f (heat energy, material properties and period of time) …… (13)

When the apparatus is used to test a specific material with certain properties and working with the maximum energy particularly in a case of rapid heating process, it is indicated that the period of time is the only variable factor in function (13) that control the a solid temperature (T).

Accommodation of the parameters of function (13) with the apparatus design factors will be discussed as following;

Factors of design affecting function (13); rotation speed (r.p.m), conveyor length (L) and size of furnace camber are the factors that control the solid temperature. Both second and third factors are design constrains and the changeable one is the rotation speed.

Heating energy: a resistance furnace is the source of heat energy; it is designed to provide seven kw electrical power as states before. Temperature inside furnace can be adjusted at specific value ranges from room temperature to maximum value of 900 ^{0}C. So maximum temperature of hot air (T_∞) is considered as a constant factor and so are the material properties, therefore, when carrying out a specific thermal test at the maximum power capacity, surface temperature changes only with time; T= (t). Therefore time is one of the essential issues for the basic design concepts.

As discussed before, samples are linked to a movable chain are heated while moving inside the furnace. Actually, the time that samples spend inside the furnace could be controlled by change the linear chain speed (V) and the covered distance inside furnace (L). If the required temperature is not reached by the minimum chain drive speed and maximum electrical power (Q). The latter (L and Q) are design constrains while the first one (V) is controllable. Therefore, leaving the chain inside the furnace for certain time is unavoidable matter. Open loop control of chain speed up, dwell, deceleration and stop via digital inverter to control motor motion is possible [8] as shown in figure (3). Figure 3 shows examples of motion cycles. Despite these control facilities, the programmable inverter fails to fulfill a motion cycle required to accomplish a thermal cycle in an accurate manner. Nature of digital control leads to execute control actions at discrete equal intervals. Thus, stopping at definite position in each cycle is difficult unless the chain length matches the integration of integer interval counts, otherwise there will be a fraction difference each cycle. This fraction difference accumulates to increase the error of each cycle than its previous cycle, produces dissimilar specific thermal fatigue cycles and leads to inaccurate evaluation of material thermal properties. This is because samples shifting outside furnace in some number of cycles during dwelling for heating up is an inevitable matter and of course failure of heating process. To tackle this problem, it was the necessity to construct an auxiliary circuit to eliminate this error. So, the programmable inverter is used only for motor speed control. Figure (4) shows the modified control diagrams of apparatus.

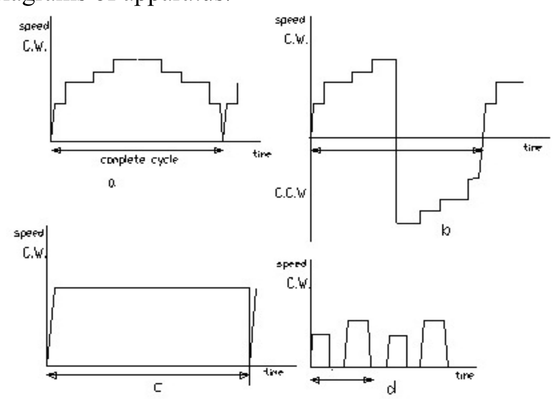
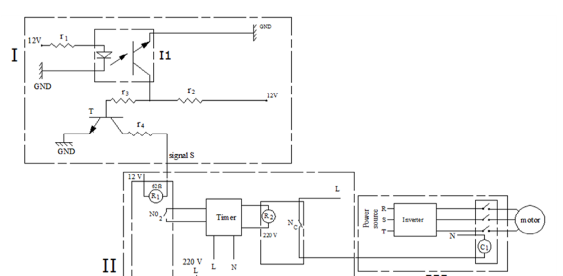


Figure 3: Examples of motion cycles [8]



Item	Description	Item	Description
I	Module1	r_1	100Ω
II	Module2	r_2	2 kΩ
III	Control system	r_3	2.2 kΩ
I_1	Photo coupler	r_4	100Ω
R_1	5V DC relay	C_1	Contactor
R_2	220V AC relay	T	Transistor

Figure 4: Modification of mechanical control system

The thermal cyclic test conducted with the mechanical control system minimizes the error of sample temperature measures. Sample temperature is measured with external infra red gun, its reading range is from zero to 600 ^{0}C with accuracy $\pm$ 0.01 ^{0}C in responding time = 1 sec, measurement process is applied when sample just out the furnace. Because of difficulty of measuring the hold samples temperature during the rotation process, an insulated thermo couple is inserted inside the hole punched in a dummy specimen to certain depth as described by Sobczak *et al.* [10]. This allowed the measure of the specimen temperature while in the furnace to reach the required temperature. By this way the specimen temperature will be defined through the cycle.

The evaluation of the material damage can be measured by means of the designed apparatus shown in figure (5).Therefore, thermal shock resistance, oxidation, and the other mechanical properties can be investigated.

Figure 5: Thermal tester photograph

5- Evaluation of material properties degradation due to cycling thermal

5.1-Thermal shock resistance (σ_c);

Thermal shock is a stress induced in a material because of temperature differences between the surface and the interior or between different regions of the component. These stresses can be high enough to cause failure of the component thus caution must be exercised when selecting materials, designs and operating conditions [9]. To determine the ability of material to resist thermal shock, Thermal fatigue test is carried out on samples; sample specification might be taken from [9]. Estimation is as;

In case of high heat transfer rate, (Bi = $\frac{h.\ell_s}{k}$ > 1),

$$\sigma_c = \frac{E.\alpha.\Delta T}{(1-\upsilon)}, \qquad \text{……….(14)}$$

In case of low heat transfer rate, (Bi = $\frac{h.\ell_s}{k}$ < 1)

$$\sigma_c = \left(\frac{E.\alpha.\Delta T}{(1-\upsilon)}\right)\left(\frac{l_s h}{k}\right), \qquad \text{……..... (15)}$$

Where;

σ_c is the thermal stress, α is the coefficient of thermal expansion , ν is the Poisson's ratio,
E is the modulus of elasticity, and ΔT is the temperature difference between heating and cooling the surface of solid.

The thermal stress (σ_c) is compared with yield strength of material, if σ_c exceed material strength, therefore damaged is unavoidable matter; it occurred due to giving rise cracks to cause stress relief. The value of total crack length appearing on the surface is an experimental approach to evaluate and compare thermal resistance of materials. Hence, theoretical thermal shock resistance of solids is estimated quantitatively not quantitatively [10] and confirmed experimentally by the present method. Measuring of crack length at sample surface after the total number of thermal cycles is obtained by microscopic magnifier (±0.1 mm accuracy). **Blatt and Hartman** [3] adopt two independent methods for measuring crack length fit to the installed apparatus in his study; (1) direct-current electric potential (DCEP) and (2) optical inspection. The description detail of DCEP method is explained in [3].

5.2-Mechanical properties affected by thermal cycles;

In most of mechanical engineering applications, material subjected to both thermal and mechanical stresses simultaneously. There is a shortage of information about influence of thermal stress on the mechanical properties; (tensile, compression, impact, wear, ect.). Studying the dramatic effects of thermal stress on mechanical properties by the assembled system is possible. Where; standard specimens having various geometries (relevant to different mechanical tests) could be mounted onto the conveyor and subjected to thermal stress by applying cyclic test. After a certain number of cycles they are mechanically tested. Comparing the results with the standard values of those mechanical properties is a measure of the deterioration magnitude. Also gradual degradation of such properties can be estimated by conducting the revelant test after each stage of thermal cycles

5.3-Oxidation behavior of materials;

As materials in many applications are exposed to high temperature environments, the materials used should have sufficient stability both mechanically and chemically, the latter referring to its resistance to oxidation [11]. Oxidation analysis is handled in many investigations and information in this concern is available. In this light, a trial to study the oxidation behavior of material with thermal cyclic approach is experimented. The method is summarized in; subjecting samples to specific number of thermal cycles with heating them to certain temperature followed with rapid cooling in running water as the apparatus works. Cyclic test is repeated at different heating temperatures. Results and discussion can be conducted according to related investigations.

Adopting the present technique simulates many practical applications in automotive industry, where some mechanical parts in automotive section (piston, cylinder area, ect) undergo oxidation attack due to subjection to elevated temperatures followed or simultaneously with cold fluid (air, water or oil).

6- Conclusion:

The designed thermal fatigue tester has several benefits which can be listed follows:

1-Durability of a the set-up for conducting thousands of thermal cycles on solids in an intermediate time with heating up by convection process that simulates wide sector in engineering applications considering reliability and cost effective.

2- Validity of the designed thermal tester has been achieved, as dwelling during heating process and obtaining different thermal cycle profiles is possible.

3- Flexibility of design aides in determining the deterioration in many material properties.

4- Capability of testing a large batch of samples globally with aid of chain length and continuity of rotation is a beneficial contribution as a time reduction merit.

5- Different kinds of cooling fluid (liquid or gas) can be selected referring to cyclic test conditions.

6- Unfortunately Sub-zeros temperature is unavailable in cooling process. However the circulating cold fluid is recommended to keep up with the problem.

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