An Apparatus for Measuring Heat Transfer Rate and Thermal Conductivity of Tubes جهاز لقياس معدل الانتقال الحرارى والتوصيلية الحرارية للمواسير

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الملخص

ان معدل انتقال الحرارة والتوصيلية الحرارية هما من أكثر الخصائص المباشرة والعملية لتقييم أداء المواد لنقل الحرارة ولا توجد طريقة واحدة يمكن اعتمادها لقياس الخواص الحرارية للمواد ولكن تقتصر كل طريقة قياس لتحديد التوصيلية الحرارية على نطاق محدد من قيم التوصيلية الحرارية ودرجات الحرارة وأنواع معينة من المواد ولا يتم تطبيق طرق قياس التوصيلية الحرارية على عينات عشوائية ولكن لكل طريقة يلزم وجود عينة قياسية لها بتصميم وأبعاد محددة ومثال على ذلك يتم استخدام عينة دائرية بقطر نصف بوصة مغطاة بطبقة من الجرافيت لتكون معتمة تماماً في طريقة القياس من نوعية **Flash Laser**. ولكن في طريقة **Guarded Hot Plate** يتم استخدام لوح على شكل متوازى مستطيلات ذو دقة تصنيع عالية و بأبعاد محددة.

بالإضافة إلى القيود السابقة ، تتطلب بعض التجارب معادلات رياضية خاصة بالإضافة إلى معرفة تامة بالخواص الفيزيائية للمواد وقاعدة معلومات تتطلب فى بعض الطرق جهاز حاسوب وتناقش هذه الورقة تحديد معدل نقل الحرارة والتوصيلية الحرارية للمواسير فى صورتها التجارية باستخدام جهاز بسيط جديد يستخدم معادلة فوريير للأشكال الاسطوانية فى الاتجاه القطرى لتعيين التوصيلية الحرارية للمواسير

وتم فى هذه الدراسة قياس معدل التدفق الحرارى عبر عينات مواسير من الكربون استيل ثم تحديد التوصيلية الحرارية لهذه العينات وكانت القيم التى تم قياسها مقاربة لتلك الموجودة بالمراجع المعتمدة والموصفة لهذه المواد فعلى سبيل المثال تم تعيين التوصيلية الحرارية لعينة من الكربون استيل **SA 53 B** بقطر داخلى 39.5 مم وقطر خارجى 44.5مم وبطول 38.5 مم وكانت قيمة التوصيلية الحرارية 15,2 وات /متر.كلفن بحيود - 5% عن القيمة المذكورة بالمرجع الأمريكى (**American Power Research Institute EPRI**) وهى 16 وات /متر.كلفن. وتم أيضا قياس التغير فى معدل التدفق الحرارى لعينات مواسير عليها رواسب وكان الفارق فى معدل التدفق الحرارى للعينات قبل وبعد التنظيف واضحا باستخدام الجهاز حيث كانت الزيادة فى معدل التدفق الحرارى بعد التنظيف حوالى 0,8 وات مما يعنى أن الجهاز له حساسية وأدائية عالية تسمح بالمقارنة بين عينات المواسير للحصول على أعلى المراجل كفاءة

***Abstract-*The heat transfer rate and thermal conductivity are the most direct and realistic properties for evaluating the performance of materials to transfer heat. Each measuring method for determining the thermal conductivity is limited for specific range of thermal conductivities, temperatures and specific types of materials. Thermal conductivity measuring methods are applied to standard samples. Those samples are supplied in a specific design with defined dimensions i.e. are not similar to the forms used in the industry. For example, a circular specimen of half inch finished with a layer of graphite to be completely opaque is used in the Flash Laser Method. But in Guarded Hot Plate method a highly precision plate with definite dimensions is used.**

In addition to previous limits, some experiments require certain mathematical equations as well as advanced knowledge of physical properties of materials. This paper discusses the determination of heat transfer rate and thermal conductivity of industrial pipes in its commercial configuration using a new simple apparatus which uses the known Fourier equation for radial direction heat transfer in cylindrical pipe.

In this study, the rate of heat transfer was measured for samples of carbon steel tubes and then the thermal conductivity of these samples was determined. The values measured were similar to those found in the approved and standard references For these materials, for example, the thermal conductivity of a sample of carbon SA 53B was determined with an internal diameter of 39.5 mm and an outer diameter of 44.5 mm and a length of 38.5 mm. The thermal conductivity value was 15.2 W / m2. It was 5% - the value indicated by the American reference Power Research Institute EPRI (16 W / m).in addition to that the difference between the heat transfer rate of three samples before and after cleaning were studied, the difference was about 0.8 Watt which means that the device has high sensitivity and performance.

I. INTRODUCTION

Steam boilers are the most important equipment used in many industries for example fertilizers, food, refining, paper, and petrochemicals in addition to generating electricity. Steam boilers can be classified into two types' fire tube boilers and water tube boilers. Purchasing any equipment for heat exchanging as a new boiler at maximum possible efficiency is a difficult task since there is no a practical assessment available; actually the post-operation experience is the only possible evaluation tool.

In addition to that, deposits continuously accumulate (fouling phenomenon) as a result of various factors on the surface of the heat transfer in both water tube and fire tube boilers. The components of sediment layeres are complex in most cases and their properties cannot be precisely defined due to the difference and multiplicity of conditions in which the sediment layers are formed. Epstein [1] classified fouling into five categories:

a. Crystallization fouling which means solidification or precipitation of salts from supersaturated solutions.

b. Particulate fouling: Deposition of suspended solid particles (dirt, silt, clay, rust).

c. Chemical reaction fouling: Deposition resulting from chemical reactions between reactants.

d. Corrosion fouling: Deposition produced by reactions between reactants and the metal surface.

e. Biological fouling: Formation of microorganism's layers.

Louis and Schikorr [2] explained the forces between deposit particles in Table 1.

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TABLE 1: DIFFERENT ADHESIVE FORCES BETWEEN FOULING PARTICLES[2]

Adhesive Force	Description
Vander Waals force or specific adhesion (side group reactions)	Caused by effects of polarization and by electrostatic force between substratum and layer-material .The adhesion may be of middle strength.
Chemosorption (dissociation-force)	Due to the emission of free electrons activated from substrate surface before a chemical reaction to the coating material (cross-linking) during the coating process. The determined adhesion strength are very high.
Mechanical adhesion (gravity, hooked force)	The layer is mechanically fixed in kerf, pores and roughness of the substratum. The rougher the effective surface is, the higher is the degree of adhesion to the layer. The possible adhesion strength reached is relatively low.

There are two sides of fouling in steam boilers; water side fouling and fire side fouling. Groysman [3] classified the two sides as following:

Water side fouling composed of many chemicals. The deposits may consist of carbonate hardness, sulfates, silicates, phosphates, hydroxides, oxides, sulfides, silica and mud.

Fire side fouling is formed from the burning of fuel oil and diesel fuel in furnaces and the smoke tubes in boilers. Due to the presence of sulfur compounds and metals in fuel oil, fouling of combustion products is severely corrosive to carbon steel and fuel ash corrosion can occur.

Cleaning the fire side surface is an easier mission if it is compared by cleaning the water side which is harder to be reached due to the manufacturers tendency toward the compact design Kohan[4].

Fouling can decrease the efficiency of heat transfer surfaces, whereas American National Institute of Standards and Technology [5] tabled a relationship between the scale thickness and fuel loss as shown in Table 2.

TABLE 2: SCALE DEPOSITS THICKNESS VS. FUEL LOSS [5]

Scale Thickness, inches	Fuel Loss, % of Total Use		
	Scale Type		
	"Normal"	High Iron	Iron Plus Silica
1/64	1.0	1.6	3.5
1/32	2.0	3.1	7.0
3/64	3.0	4.7	-
1/16	3.9	6.2	-

Mitigation of fouling layers includes decreasing or removal of the fouling layers. Steinhagen et al.[6]classified the main methodologies for the mitigation of fouling in industrial heat exchangers in order of their applicability into:

i) Chemical
ii) Mechanical
iii)Physical

Determination of the effect of various factors on the cleaning depth of the sediment layer is the point of research most discussed by previous studies which did not include mostly the effect of cleaning on the rate of heat transfer or thermal conductivity. Most of the studies were done on laboratory samples of a specific form which is not compatible with the specimen requirement in the different measuring methods of thermal conductivity.

One of the main objectives in this paper is to find a simple and high precision method to evaluate the effect of cleaning on the rate of heat transfer. It is necessary after the cleaning process and before the purchase of a new boiler or any other heat exchanger to evaluate the rate of heat transfer and thermal conductivity to evaluate the performance of heat transfer surfaces.

As a consequence of the wide range of thermal properties there is no single measuring method which can be used for all thermal conductivity measurements. Desired temperature range, sample size, required accuracy and thermal conductivity range all need to be considered when designing a measurement as declared by F.E.Camilla [7].

II. MEASURING METHODS OF THERMAL PROPERTIES

The measuring methods can be classified into two main groups Steady State Direct Methods and Transient Methods.

A. Steady state direct methods

These methods include two important measurements firstly the Guarded Hot Plate instrument is one of the most popular and most widely used methods which has been standardized in several countries for example in the United States of America under the code ASTM C177-63, in England under the English code B.S.874:1965 and in Germany DIN52612 [8]. In short, the idea is based on placing the sample between two layers where the bottom layer is cooled and the upper layer is heated until the equilibrium temperatures are reached. Knowing the amount of heat passed through the sample and thickness of sample, then applying Fourier equation for slides in the horizontal direction the thermal conductivity of the sample can be set [9]. This method is suitable for determination of thermal properties of nonmetals such as glass, ceramics, polymers and insulation materials. Even though this method is effective for many practical conductivity tests but it is defective for the length of time required for the experiment, not applicable to fluids or materials with high thermal conductivity and it is difficult to carry out tests of powders.
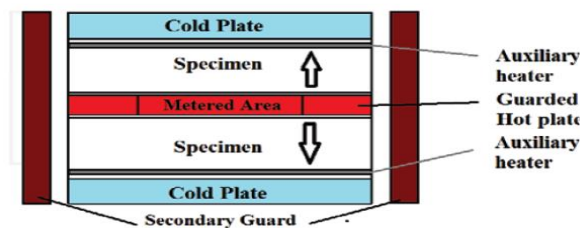

Figure 1. Schematic drawing for guarded hot plate method [5].

Secondly the Direct Heating Method which avoided the defects of the first group methods in terms of the length of time required for the test as well as the possibility of using them to specify the thermal properties of metals and not only for insulation materials [10]. The sample shall be a wire or a solid cylindrical tube positioned between two heaters. Sample shall be heated to an average temperature of 127 to

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272 CO, temperature and voltage of specified points shall be set on the sample body as shown in figure 2.

By applying the following relationship, the thermal conductivity, k as well as the thermal properties of the sample can be determined from the following formula:

$$k \frac{V_h A}{I_h l} = \frac{(V_3 - V_1)^2}{4\left[2T_2 - (T_1 + T_3)\right]}$$
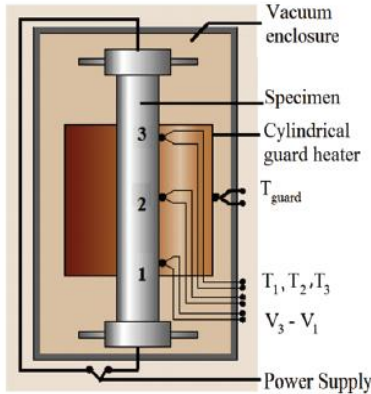

Figure 2. Schematic diagram of direct heating method [5].

B. Transient Methods

This group of measurement is more advantageous than steady state measuring methods as declared in table 4, and includes many of most common widely used methods.
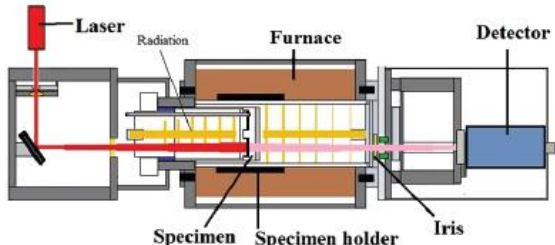

Figure 3. Schematic diagram of Laser Flash Method [5].

Firstly, the Laser Flash Method One of the most important and most commonly used methods is [11,12] which is based on the heating a sample of 1-inch diameter and 1 mm thickness with a laser beam illuminated on the upper face and then set the height in the temperature of the lower face of the sample using an infrared thermal sensor and drawing the increase in the temperature of the lower face as a relationship with time Figure [4] The thermal diffusion can be set.
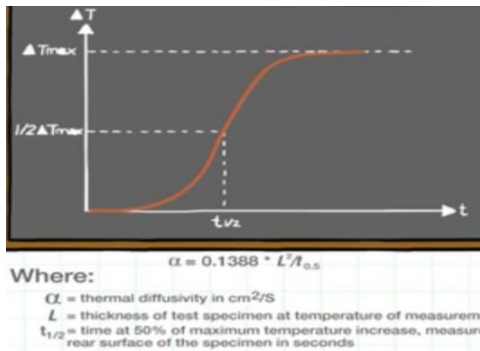

Figure 4. Relationship between temperature increase and time.

By applying the following equation, thermal conductivity can be determined:

$$\alpha = 0.138 d^2 / t 0.5$$
$$\alpha = k / \rho\, cp$$

Where α Thermal Diffusivity, K Thermal Conductivity, ρ Density, Cp Specific Heat Secondly, the Transient Plane Method, where a flat thermal sensor made from nickel supported with a layer of heat-resistant Kapton, Mica or Teflon the system is also applied as a heater. The system is placed between two identical layers of the sample drawing a relationship between temperature and time and applying a mathematical equation, thermal conductivity of the sample can be determined [13].


Figure 5. Single sided and two sided experimental sample setup [14].

International Organization for Standardization [15] described Transient Plane Source Method as utilizing a plane sensor combined with electronics and using a special mathematical model describing the heat conductivity to measure thermal transport properties. It covers a thermal conductivity range of at least 0.01-500 W/m.K and can be used for measuring various kinds of materials, such as solids, liquid, paste and thin films etc. Using an equation that relates the change in temperature with time then the thermal conductivity can be calculated. Each specimen configuration has its modified equation and corrections as shown table 3 which declares a summary of some recommended experimental parameters for a range of materials with different thermal conductivities

Table (4) compares between the two different groups of thermal conductivity measuring methods, the first group included steady-state methods in which the temperature at each point of the sample is not a function of time and kept constant. On contrast the transient methods were used to

record measurements during the process of heating up or cooling down a material or fluid. Transient methods had the advantage of giving quicker measurements than the steady state methods.

Based on what has been presented briefly for the most common methods, it is clear that there is no a uniform method by which the thermal properties of all materials can be measured but for each method there are limits and special specifications [16,17].By using the new measurement method described in this paper it will be easy to measure the heat transfer properties including the heat flow rate across the pipe surfaces in their cylindrical commercial form, in addition to thermal conductivity which can be set by applying Fourier equation for thermal conductivity in the cylindrical direction of cylindrical shapes.

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1-Upper Flange

2- Water

3- Heater

4-Thermometer

5-Hex Head Holder

6-Insulator
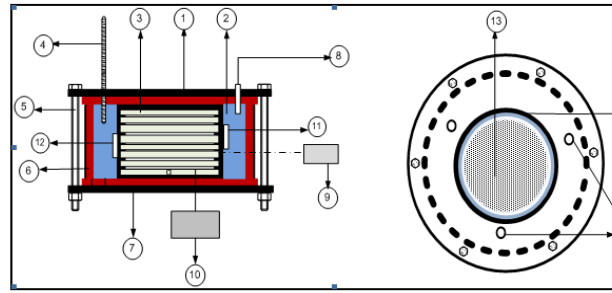
7-lower flange

8- Thermocouple with a digital monitor(water)

9- Thermocouple with an electrical switch(heater)

10- AC Automatic Voltage Regulator

11,12- Thermocouple (inner surface temperature)

13- Insulation around heater

14- Specimen

15- Thermocouple hatches

Figure 7b. Schematic diagram of the new measuring device.

Table 3: International organization for Standardization[13] .

	Metal alloy	Dense ceramic	Steel	Ceramic	Polymer	Insulating material
Thermal conductivity [W/(m·K)]	170	40	14	1,5	0,19	0,028
Thermal diffusivity (mm²/s)	69	11	3,7	0,96	0,11	0,75
Temperature increase (K)	0,3	0,5	1,0	0,8	1,3	2,5
Probe radius (mm)	15	6,4	6,4	6,4	6,4	15
Specimen thickness (mm)	30	10	10	10	15	30
Specimen diameter (mm)	90	40	40	40	40	90
Measurement time (s)	5	10	10	40	160	160
Power output (W)	4	3	2	0,5	0,25	0,1

III. DESCRIPTION OF EXPERIMENTAL SETUP

The device consists of an external carbon steel cylindrical vessel with an outer diameter of 12.5 cm and an inner diameter of 11.5 cm, the vessel is internally insulated with a 0.4 cm polyurethane layer to prevent any thermal leakage to or from surrounding environment. The vessel is closed with an upper and bottom flange made from carbon steel and insulated with a thickness of 0.4 cm polyurethane these flanges are fixed to the vessel by three screws M6 of 20 cm length, an 80 Watt heater is connected to a DC voltage regulator so that the temperature rise is uniform for all specimens and to avoid the rise and fall of voltage through the experiment time. Thermal cotton insulation is placed around the heater to isolate the surface and make the thermal flow in the radial direction so that the Fourier equation can be applied and thermal conductivity can be set.

The top cover is fitted with three holes of 1 cm diameter to set the two thermocouples and a mercury thermometer to measure the temperature increase of water which is injected around the external surface of the sample. Water is the storing material for thermal energy in this device, it is safe

and provides a typical simulation environment similar to that of fire tube boilers. A thermocouple with a digital screen is installed on the internal surface of the specimen to measure rate temperature increase of the specimen. Another thermocouple is installed on the internal surface of the sample connected to a control system to disconnect the electric current from the heater; figure (7a, b) shows the components of the device.

Figure 7a. Photography of the new measuring device.

IV. STEPS OF THE EXPERIMENT

The electric heater is wrapped around the inner surface of the sample then the sample is installed between the top and bottom covers and closing of the system with the screws is done. The thermocouple is installed on the inside surface of the sample and the thermocouples are switched on to determine the increase of water temperature. Heating rate of the internal surface shall be as constant as possible to decrease the errors resulted from the heating rate deviation. Water temperature difference as well as the experiment time is recorded to set the following calculations.

A. Calculation of heat transfer rate
Composition using the following empirical. The amount of heat passing through the surface of sample and stored in water can be determined from the following relationship:

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Table 4: Evaluation of thermal conductivity measuring methods[9]

Method	Temperature range	Un-certainty	Materials	Merit	Demerit
Guarded hot Plate	-193:527 ∘C	2%	Insulation materials, plastics, glasses	High accuracy	Long measurement time , large specimen size
Cylinder	-269:727 ∘C	2%	Metals	Temperature range, Simultaneous determination of electrical conductivity	Long measurement time
Heat flow meter	−100:200 C∘	3–10%	Insulation materials	Simple construction and operation	Measurement uncertainty
Comparative	20:1300 ∘ C	10–20%	Metals, ceramics plastics	Simple construction and operation	Measurement uncertainty
Pipe method	20:2500 ∘ C	3–20%	Solids	Temperature range	Specimen preparation, long measurement time
Direct heating	127:2727 ∘C	2–10%	Metals	Simple and fast measurements	only electrically conducting materials

$$Q = m\ C_p\ \Delta T$$

Where Q the quantity of heat (joule) , experiment time (seconds) ,the water temperature difference ΔT(∘C) and Cp specific heat of water (J/kg. ∘C). Dividing the amount of heat by the time of the experiment the heat transfer rate can be calculated in (watt).

B. *Thermal conductivity calculation by applying Fourier equation in radial direction*

$K = Q\ ln\ (r_2/r_1) \div 2\pi h\ (T_1 - T_2)$

Where the *h* is the specimen length (m), T_1 and T_2 are the inner and outer surface temperatures (∘C) and (r_1), (r_2) are the inner and outer diameters of the specimen (mm).

Heat Transfer Rate Passing Through Sample Surface

Sample was installed in the device and then the heater was wrapped around the inside surface of the specimen. 40 g of water was injected at a temperature of 28 ∘ C and the temperature of the internal surface of the sample increased according to table 5.

C. *Measured Samples by the new device Carbon steel SA53B sample.*

Note that after the experiment time the temperature of the outer side of the specimen (water side) reached 44 °C

Figure 8 a Photography of carbon steel SA53B sample.

Table 5: Rate of temperature increase of carbon steel SA53B sample (inner surface)

Temperature (∘C)	Time (Sec)
56	102
68	140
74	160
80	187
86	213
92	248
98	269
100	296

Water temperature T_2 was set at the end of the experiment and measured at 37 °C and the amount of heat transferred through the sample was stored in water isolated from the surrounding environment well through the relationship

$Q = m\ C_p\ \Delta T$=0.04 x 4178 x 9 = 1504 J.

By dividing the output on the experimental time by 296 seconds, the heat transfer rate is 5.08 J/s (watts).

Calculating thermal conductivity of SA53B carbon steel sample

Assuming that heat transfer was directed in the radial direction due to insulation around the electric heater. And by applying Fourier equation as following the thermal conductivity of the sample can be set

$$K = Q\ ln\ (r_2/r_1) \div 2\pi h\ (T_1 - T_2)$$

$$K = \frac{1504 \text{ x } ln\ (44.5 / 39.5)}{2\text{x}3.14\text{x } (0.0385\text{-}0.005) \text{ x}56}$$

So the calculated value of thermal conductivity = 15.6 W/m.°C

Subtract the value of 0.005 from the length of the specimen, this value expresses the thickness of polyurethane in both upper and lower layers. Reviewing the value of the thermal conductivity measured by the new device with the value of thermal conductivity mentioned in the reference American

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Power Research Institute [18]. which referred to the thermal conductivity of the same carbon steel grade as 16 W/m.C°. With a deviation of -5% giving good indications about the device accuracy.

D. Determination of heat transfer rate of ASME SA-179 pipe samples before and after cleaning

In this experiment, the increase in the heat transfer rate of three samples of ASME SA-179 pipes used in a fire tube steam boiler of 12 ton/h. capacity was determined. The thermal flow rate of the pipes was measured before cleaning and after cleaning as shown in Figures 9a and b.

Figures 9a. Three samples of ASME SA-179 pipes before cleaning.

Figures 9b. Three samples of ASME SA-179 pipes after cleaning

The experimental steps were applied to the samples before and after cleaning and by heating the internal surface of the samples at the rate indicated in the following drawings, figures10-12(a, b).
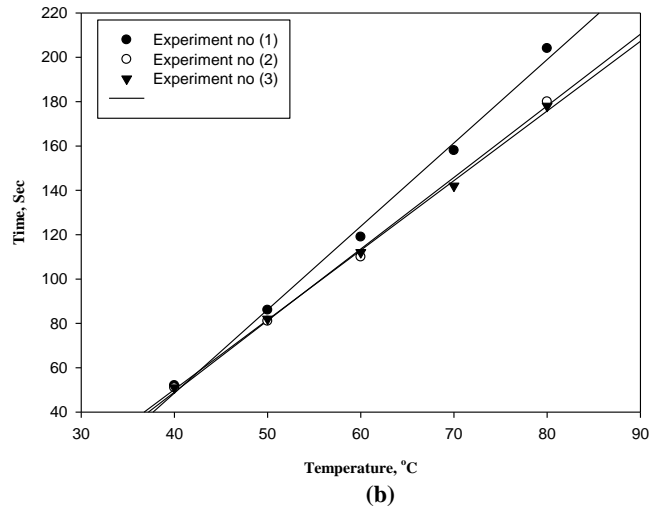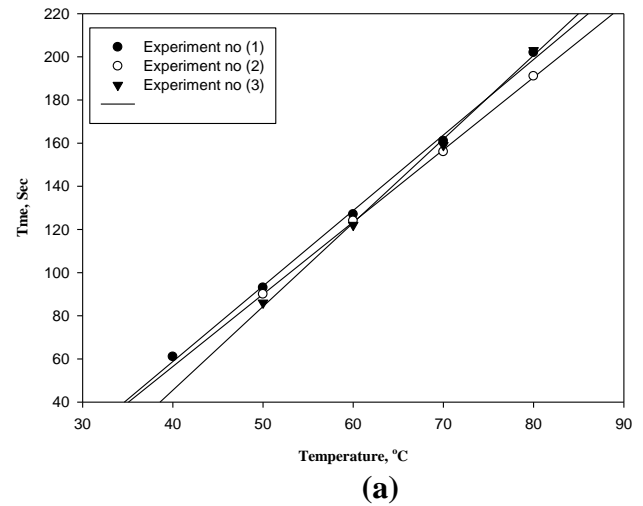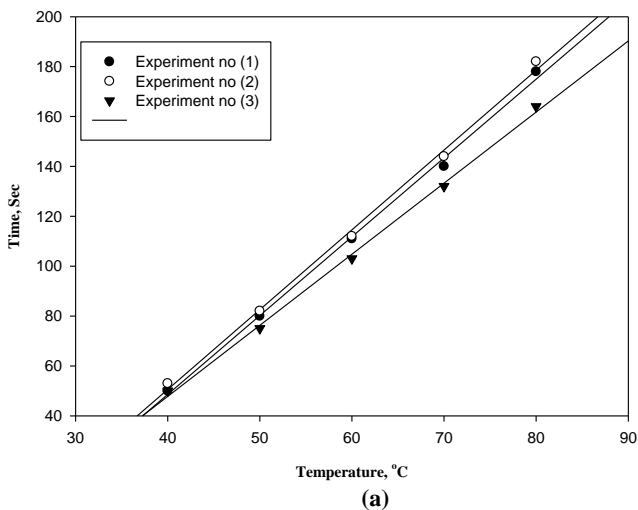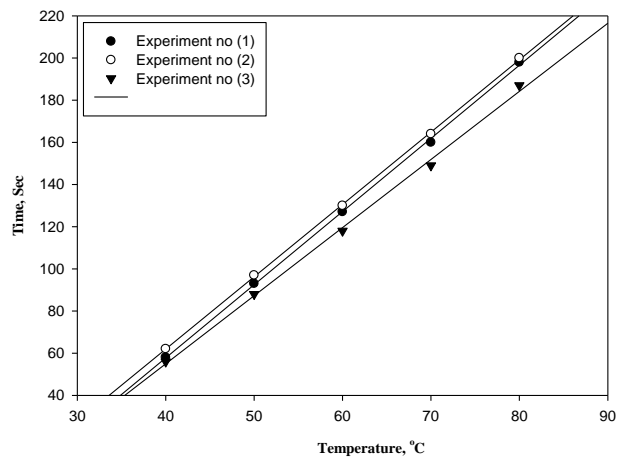

(a)

(b)

Figure 10. a & b Before and after cleaning for sample no 1.

(a)

(b)

Figure 11. Before and after cleaning for sample no 2.

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(a)

Figure 13. The average amount of heat transferred before and after cleaning.
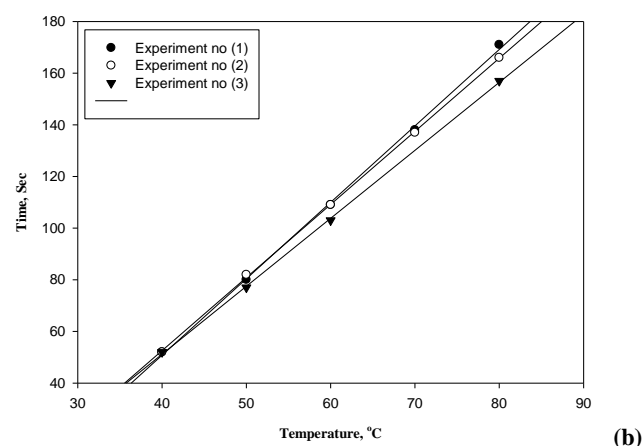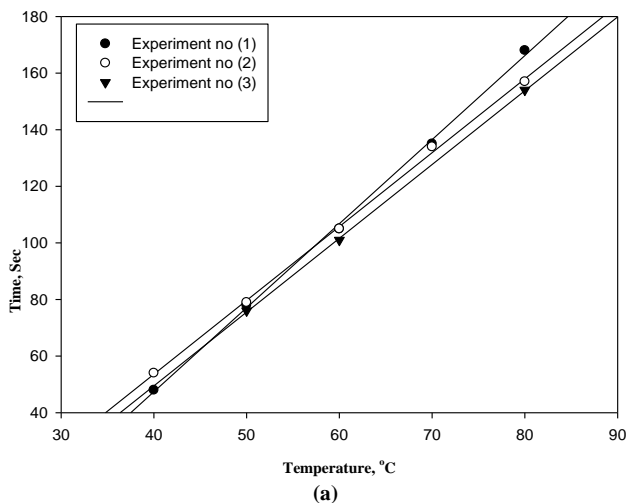

(b)

Figure 12. Before and after cleaning for sample no 3.

V. Results and Discussion

The results distinguish the increase in water temperature difference range is 0.47 °C for the three samples after cleaning.

As a result of temperature difference increase of samples resulting from the cleaning process, the increase in the amount of heat transferred through the sample surfaces, which is 150 J, is clearly shown in figure13.

VI. Conclusions

Heat transfer rate of pipes in its industrial configuration can be evaluated and heat exchanging equipment such as fire tube boilers can be practically examined before purchasing to obtain the highest efficient equipment; There is no need for samples of special dimensions for measurements or treatment of the surfaces of samples before measurement which means reducing the cost of conducting experiments.
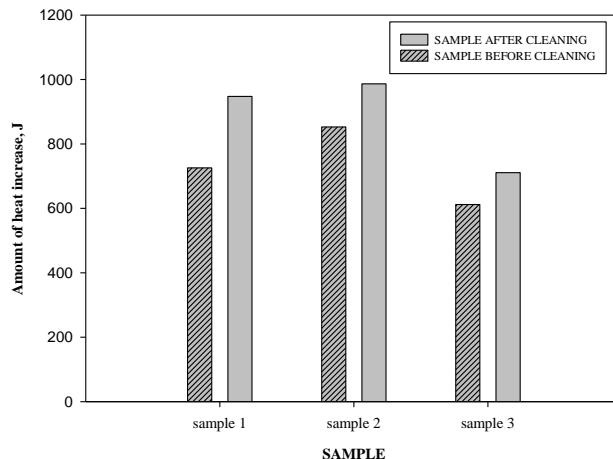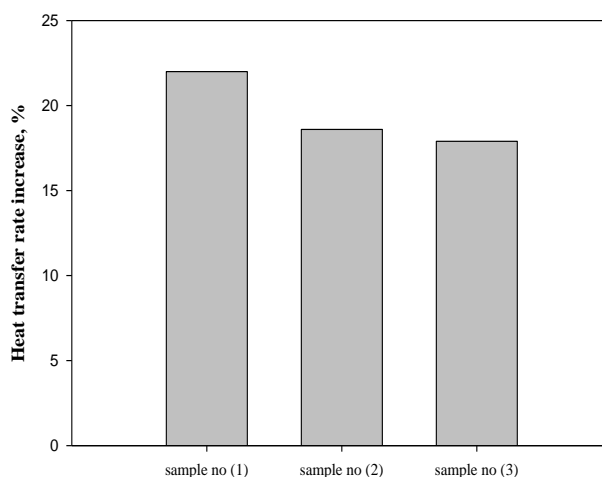

Ease of mathematical equations model and no need for large database as in most measuring methods. The use of water as a heat absorbent material which is safe to use with known properties under all circumstances, and also provides laboratory simulation of the medium surrounding boiler pipes. High sensitivity of the device because each increase of 0.1 °C in the temperature of water gives an increase of about 34 times in the calculated energy value considering the amount of water (m Cp) constant value (80x 4.18) = 334.4 which increases the possibility of monitoring any slight change of heat transfer rate. Finally, the increase of heat transfer after cleaning is about 20% which necessitates the need to think of finding innovative solutions and effective cleaning methods for water side fouling in fire tube boilers which decreases boiler efficiency and heat transfer rate of pipes.

Table 5: Averages of the experimental results.

SAMPLE NuMBER	Sample no(1)		Sample no(2)		Sample no(3)	
	Before cleaning	After cleaning	Before cleaning	After cleaning	Before cleaning	After cleaning
ΔT of water	2.2	2.8	2.6	3.00	1.8	2.2
The amount heat	725.7	947.5	852.7	986.5	612	711
The heat transfer rate	4.1	5.00	4.3	5.1	3.9	4.6

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