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DEVELOPMENT AND PERFORMANCE EVALUATION OF THERMAL CONDUCTIVITY EQUIPMENT FOR LABORATORY USES

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ABSTRACT: *In this study, thermal conductivity test equipment was designed and fabricated for the determination of thermal conductivity values of non-metallic materials only. The energy balance equation for the equipment was based on the transient method analysis. Three specimens, cut to uniform area of* $0.002m^2$ *were used for the experiment, to validate the performance of the test equipment. These materials were cork, cardboard and asbestos. The following values of thermal conductivity 0.088, 0.20 and 0.122* $w/m^{o}k$ *were obtained respectively for them. The values were compared to their respective reference values and a correcting factor of 0.02 was obtained.*

KEYWORDS: *conductivity, material, temperature, thermal*

INTRODUCTION

Our world is filled with vast assortment of both natural and artificial temperature differences. Thus an immerse variety of heat transfer equipment has been created to deal with these differences: - boiler, condensers, solar collectors, radiators, insulators, refrigerators stores – the list is almost endless (Frank, 1991). This temperature difference can best be explained under the subject "heat transfer" which cuts across many disciplines, from metallurgy, chemical processes to nuclear fusion. The problem posed in designing heat transfer related equipment is the ability of designer to judge rightly the material to be selected for a given design. For instance, when the required temperature in a particular design for a specific condition is required to be high and should be maintained as such, the material selected for the design should provide such effect. If however, practical result of the design show a low temperature record, the design is said to have failed. The inside temperature of a boiler in an industry will reach an equilibrium temperature with its surrounding, if wrong judgment of material selection was made during material selection process. In the selection of material for heat transfer applications, the amount of heat conducted through the material with respect to time is considered very important as it is a determinant factor. For example, heat exchanger plates, insulators etc are selected based on their thermal conductivity value. Knowing the thermal conductivity of a material can be a key to obtaining the optimum performance of a particular design or can lead to an accurate measurement of its overall thermo physical properties. This thermal conductivity value is a numerical value that gives the designer the idea of the heat conduction of a material – which in other words, will enable the designer select appropriately material that will fit into a particular purpose and condition. Hence, it is important to have a data bank of the thermal conductivity values of materials as they are developed and to do this requires some equipment that is not easy to come by most especially in developing countries like Nigeria. It is in a bid to address this short coming that the thermal conductivity equipment was designed and fabricated locally for laboratory use. So many types have been developed for example, heat flow meter, guarded heat flow meters, guarded hot plate instrument, flash diffusivity methods etc (Jurgen, 2004). But the need for local availability of thermal conductivity meter as submitted by Ighodalo and Okoebor (1996) will provide for more research into local materials development and various uses that such materials can be put into. It was therefore, the need to make this thermal conductivity equipment available locally that this work was carried out.

DESIGN ANALYSIS AND CALCULATION

Thermal conductivity meter is laboratory test equipment based on the principle of heat conduction. The early development of heat conduction is largely due to the effort of a French Mathematical physicist, Joseph Fourier (1822), who first proposed the law that is known today as Fourier's Law of Heat Conduction, which is expressed in equation (1)

$$Q_x = \frac{KA\Delta T}{\Delta_x} \qquad (1)$$

where K is the thermal conductivity and has a unit w/m^{o}k. The step by step design of each components of the thermal conductivity is detailed below.

Boiler Design: *The boiler heater was designed to boil a minimum water of 4 litres capacity in 10 minutes and the heat output of the electric heater (coil) was calculated from*

$$Q = \frac{Q^1}{\tau} (watt) \qquad (2)$$

where $Q^1 = MC\Delta T$, *heat output from heater (1176000J),* Q *= heat transfer rate (1960W), M= mass of water (kg), C = specific heat capacity of water (KJ/kg^{o}K), t = time (s) and* ΔT *= temperature difference (^{o}C). The heat capacity adopted for the design was 2000W*

Condensation Rate: *The average condensation rate of steam during the heating period was calculated from equation (3), (Northcroft and Barber, 1979)*

$$q = \frac{M \times C \times \Delta T}{H_{fg} \times H \times 3600} (kg/s) \qquad (3)$$

where m = mass of water heated (kg), C = specific heat capacity of water (KJ/kg^{o}C), H = recovery time (hour) ΔT *= temperature rise* $(T_2 - T_1)^o C$ *,* H_{fg} *= specific enthalpy of evaporation of steam at working pressure (KJ/kg). Condensation rate, (q) = 2.89 x 10^{-4} (kg/s),*

Volume of Boiler: *The volume of boiler was calculated from equations (4a & 4b)*

$$V_w = \frac{m}{\rho} \qquad (4a)$$

$$V_T = V_w + V_{gx} \qquad (4b)$$

But $$V_T = \pi r^2 h$$

where V_T *= total volume,* V_w *= volume of water,* V_{gx} *= volume of steam,* ρ *= density of water. The height obtained was 314.34mm, but 316mm was adopted*

Boiler Shell Design: *The circumferential stress value was adopted for design of boiler shell, because it has a higher value for pressure vessel having closed ends as both longitudinal and circumference stresses were induced (Khurmi and Gupta, 2003).*

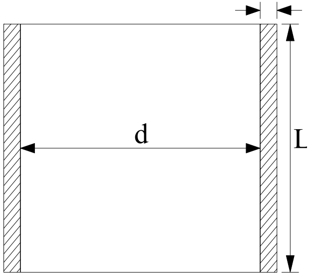

Figure 1: Boiler shell

$$\sigma_1 = \frac{pd}{2t} \qquad (5a);$$

but $$\sigma_1 = \frac{[\sigma_1]}{f}$$

$$t = \frac{pd}{2\sigma_1} \qquad (5b),$$

$$t_D = \frac{pd}{2\sigma_1} + 1mm \qquad (5c)$$

where σ_1 *= circumferential stress (allowable stress),* $[\sigma_1]$ *= Yield stress of boiler material, f = factor of safety, d = internal diameter of the pressure, t = thickness of the boiler material, design thickness (* t_D *) = 1.1697mm but 1.5mm was adopted.*

Cover Plate Design: *The cover plate was a circular flat plate with uniformly distributed load and the thickness of the plate is determined from*

$$t_1 = K_1 . d \sqrt{\frac{p}{\sigma_1}} \qquad (6)$$

where K$_1$ is a value which depends upon the material of the plate and the method of holding the edges, p = pressure, d = diameter and σ_1 *= allowable stress. t$_1$ = 2.74mm but t$_1$ = 4mm was adopted.*

Bolt Requirement: *The upward force acting on the cylinder used was given by*

$$F = 2\pi rhp \qquad (7a)$$

The resisting force offered by number of bolts was given by

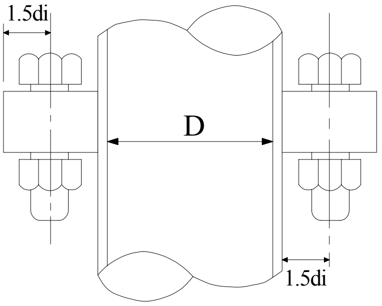

Figure 2: Bolt Arrangement

$$F=\frac{\pi}{4}(d_c)^2\sigma_{tb}\times n \qquad (7b)$$

From equations 7a and 7b, equation (8) was obtained

$$2\pi rhp=F=\frac{\pi}{4}(d_c)^2\sigma_{tb}\times n \qquad (8)$$

where r = radius of cylinder, h = height of cylinder, p = pressure of cylinder, d_1 = diameter of hole, σ_{tb} = minimum yield strength of bolt. The number of bolts obtained was 6.87 and 8 was used. The volume of plate material for insulation surface was obtained using equation 9

$$V=\pi r^2 h \qquad (9),$$

but $r=r_3$, where r = radius of the insulation surface, h = height of cylinder.

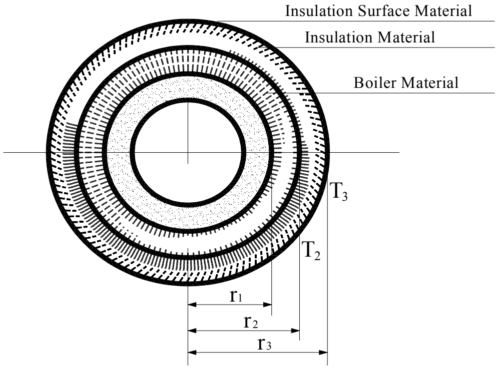

Figure 3: Boiler Insulation Thickness

Boiler Insulation Thickness: The minimum thickness required for insulation was r_2-r_1 as shown in equation 10.

$$\frac{Q}{L}=\frac{2\pi(Tl_1-T_3)}{\frac{\ln\left(\frac{r_2}{r_1}\right)}{k_a}+\frac{\ln\left(\frac{r_3}{r_2}\right)}{k_b}} \qquad (10)$$

where T_1 = temperature of steam inside the vessel, T_2 = temperature of boiler material, T_3 = temperature of the insulator surface, K_a = coefficient of thermal conductivity of boiler material, K_b = coefficient of thermal conductivity of insulator, $\frac{Q}{L}$ heat transfer rate per unit length. The value of T_3 = 39.7°C, shows that the assumed value for r_2 was satisfactory.

Steam Pipe Design at an Inclined Angle: According to Croft, Davison and Hargreaves (1995), using the relation

$$\tan\theta=\frac{opp}{adj}=\frac{x}{y} \qquad (11)$$

and "z" can be determined from Pythagoras theorem $z^2=x^2+y^2$

$$T_L=W+Z \qquad (12)$$

where,

θ=pipe angle(69.5°), W=height of pipe from boiler, L=boiler height, i=boiler height, T_L=1061mm

Pipe Volume: The pipe volume was obtained using equation (13) ((Khurmi and Gupta, 2003)

$$V_2=\pi r L_T \qquad (13)$$

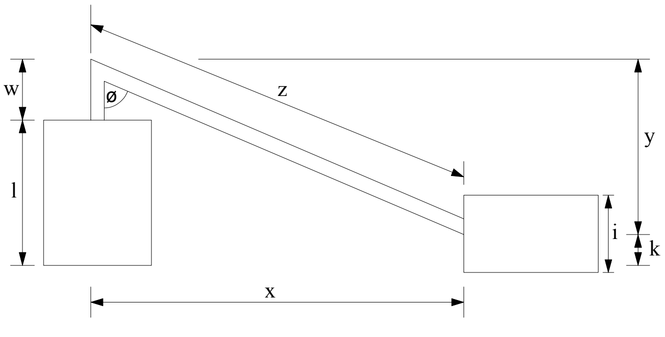

Figure 4: Pipe Inclination Angle

where r = radius of pipe, V_2 = volume of pipe (333366.2mm^2).

Pipe Pressure: Using Boyle's law (Rogers & Mayhew, 1992), the pipe pressure was calculated

$$P_1V_1=P_2V_2 \qquad (14)$$

where P_1 = boiler pressure (atmospheric pressure), V_1= total volume of boiler, V_2 = volume of pipe. P_2 = pressure in pipe, (1.216N/mm^2)

Pipe Insulation: The pipe was treated as a composite hollow cylinder and like the boiler unit, equation 10 holds according to Rajput (2003)

The Size of Insulator Surface Material (Plate) Required: - The size of insulator surface for plate as shown in figure5 was obtained using equation (15)

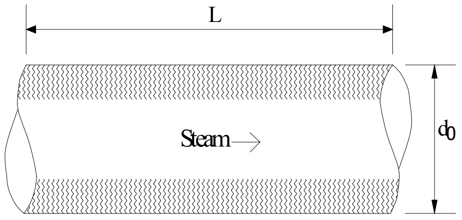

Figure 5: Size of Insulator Surface Material

$$\text{Size of plate (area)} = \pi d_o \times L \tag{15}$$

But $d_o = 2r_3$, *where* d_0 *= diameter of the pipe + the insulation, L = length of pipe. The size obtained was 201.08 x 1061*

Heat Exchanger Unit (Steam Jacket Design): *The pressure in steam jacket was determined using Boyle's law*

$$P_2V_2 = P_3V_3 \tag{16a}$$

$$P_3 = \frac{P_2V_2}{V_3} \tag{16b}$$

where V_3 *= volume of steam jacket,* P_3 *= pressure in steam jacket (0.1013N/mm*^{2}*),*

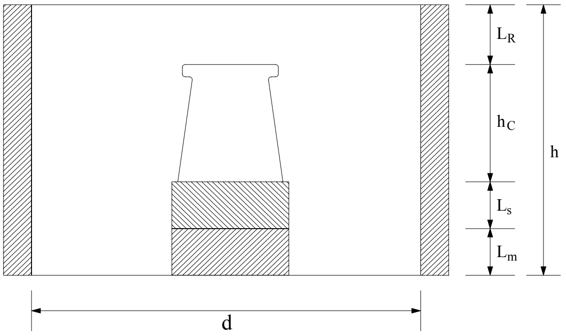

Figure 6: Design of Volume of Test Section

The steam jacket shell design value obtained from the boiler design was adopted and the steam jacket insulation size was equally adopted to for the design.

Test Section Design: *The shell, cover plate thickness were obtained as in equations 5c and 6*

Design of Volume of Test Section: *According to Anthony and Martin (1995) and using equation 17, when*

$$h = L_m + L_s + h_c L_R \tag{17}$$

$$V = 2\pi r h \tag{18}$$

where V = volume of test section (5825.7mm^3*), h = height of test section,* L_m *= Thickness of metal sheet (mild steel),* L_s *= Thickness of specimen,* L_R *= tolerance,* h_C *= height of conical flask*

FABRICATION AND PERFORMANCE EVALUATION

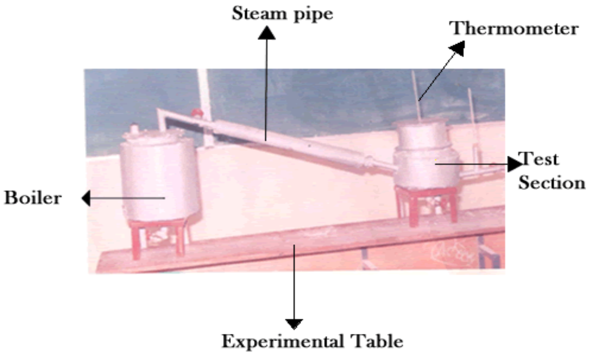

Plate 1. Thermal Conductivity Test Equipment

The numerical values obtained from the design procedure were used in fabrication of the thermal conductivity equipment. Cutting process using hacksaw and welding process were some production processes that were involved in the fabrication of the equipment. Table 3 show all the materials involved in the fabrication of the equipment. Plate 1 shows the photograph of the fabricated conductivity test equipment.

The performance of the test equipment was obtained by comparing values of thermal conductivities obtained from the test equipment with the documented thermal conductivity values as shown in table 1. This was achieved by using the equipment to carry out experiment using three specimens of non-metallic materials i.e. cork, cardboard and asbestos. Each of these specimens was cut to an area of 0.002m^2 *and was placed in the test section at a position which it fit into. A conical flask containing 50ml of water was placed directly on the specimen and a cork having a thermometer passing through it was used to cork the conical flask. The thermometer measured the temperature changes of the water in the flask. Cotton wool was used to insulate the specimen and the conical flask. The test section was then closed and the initial water temperature was noted. A second thermometer was inserted into the steam outlet pipe with the aid of a cork to monitor the steam temperature so as to ensure that a base temperature of 100*^{o}*C was maintained. The boiler water outlet valve was closed and then the water inlet cover was opened. Five litres of water was filled into the boiler, while the steam inlet valve, outlet valve and condensate outlet valve were all closed. With the boiler water inlet cover remaining open, the boiler was switched on. Immediately the water started boiling, the boiler water inlet cover was closed, while the steam inlet valve was fully opened with all other valves remaining closed. Timing commenced with the aid of stop watch immediately the steam inlet valve was opened. The experiment was timed in each case for 10 minutes. Temperature and time records were taken. Each specimen was experimented twice and mean temperature values were obtained as shown in table 2.*

Table 1: Result Obtained Compared with Reference

S/No	Material	Reference Thermal conductivity Kr (w/m^{o}k)	Calculated Thermal Conductivity Kc (w/m^{o}k)	Difference (Kr –Kc)	Corrected Thermal conductivity Kc (w/m^{o}k)
1	Cork	0.1	0.088	0.012	0.108
2	Cardboard	0.21	0.20	0.01	0.22
3	Asbestos	0.16	0.122	0.038	0.142

Table 2: Experimental Result

S/No	Material	Thickness (m) l	Mean initial Temp (T_i°C)	Mean Final Temp (T_4 °C)	$T_1 - T_i$ (0i°C)	T_1-T_4 (0_2°C)
1	Cork	0.009	45	48	55	52
2	Cardboard	0.003	40	59	60	41
3	Asbestos	0.003	42	54	58	46

At the end of each experiment the steam outlet valve was opened to release steam. The water in the boiler was also topped to maintain the five litres. The thermal conductivity of the material was determined by adopting the energy balance equation using the lumped heat capacity approach of the transient state using Fourier's law as shown in equation (19) (Rajput, 2003)

$$K = \frac{\frac{2.303MCL}{A}\log\left(\frac{\theta_1}{\theta_2}\right)}{\tau} \tag{19}$$

where K = thermal conductivity of material to be determined; T_1 = temperature of steam; T_i = initial water temperature in conical flask; $\theta_{1,};\theta_2$ temperature differences at the beginning and at the end of the experiment; time (s), A = specimen area; M = mass of water in conical, C = specific heat capacity of water in conical flask, L = thickness of specimen.

MATERIALS AND COST ESTIMATE

Galvanized steel was used for the fabrication of the boiler shell based on its properties like melting point of 1510°C, a moderate thermal conductivity value of 50.2w/m°C and high density 7850kg/m^3, which meet the condition of service required for boiler. Mild steel was used for cover plate, steam pipe and bolts, while insulation material used was cotton wool of 0.063w/m°C. The material cost was based on the cost of materials used for the construction of the thermal conductivity equipment under current market price and the factors considered in costing are as follows (a) material cost, (b) labour cost and (c) Overhead cost. Labour cost was determined by assuming a direct labour cost of 20% of the material cost, while Overhead cost which includes other expenses incurred apart from direct material and direct labour cost was determined by assuming a 10% of the cost of material and the total cost is the sum of material, labour and overhead costs (Johnson, 1982). The cost of production of the thermal conductivity equipment was NGN1, 625:00. (Where NGN stand for Naira, which is Nigeria currency). Table 3 show the materials cost and specification.

Table 3: Material Cost and Specification

S/No	Component's Name	Material	Dimension	Qty	Standard price / unit (NGN)	Total cost (NGN)
1.	Boiler / heat exchanger	Galvanized steel	4 x 4mm	1	2750	2750
	Cover plate					
2.	Stand	Mild steel	2 x 8mm	1	2000	2000
3.	Heater	Mild steel	1" x 10mm	1	800	800
4.	Welding	-	2000W	1	1400	1400
5.	Insulator	Oxy- acetylene	1bar	1	1000	1000
		Cotton				
6.	Insulator surface cover	Aluminum	4kg	1	100	100
7.	Steam pipe		2 x 4mm	1	1000	1000
		Galvanized steel				
8.	Coupler	Galvanized steel	OD(25mm)	1	50	50
		Galvanized steel				
9	Nipples	Cast iron	OD(25mm)	2	50	100
		Brass				
10	Plunge / socket	Mercury – in- glass	OD(25mm)	2	80	160
	Gate valves	Mild steel	OD(25mm)	4	250	1000
11	Thermometer	Mild steel	OD(25mm)	2	600	1200
12		Aluminum colour	30cm	2	80	160
13	Bolts & nuts	Pyrex glass	M4 short	8	60	480
14	Screws		M4 short	8	30	240
15	Paint		1litre	1	300	300
16	Conical flask		50ml	1	500	500
17	**Total cost**					**12,030**

RESULTS AND CONCLUSION

The thermal conductivity test equipment for the determination of the co-efficient of thermal conductivity of non-metallic materials has been successfully designed and fabricated. The equipment performance was evaluated during the experiment conducted on the three samples of cork, cardboard and asbestos. The thermal conductivity co-efficient for each sample was discovered to have a correcting factor of 0.02 when compared with the documented value. The cost of producing the equipment locally is not too high compared to imported equipment. Therefore, with this equipment, research institution laboratories can use it to study the thermal conductivity values of non-metallic.

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