



## On the Modification of Lee – Charlton’s Disc Apparatus Technique for Thermal Conductivity Determination

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### Abstract

In recent years, the demand for thermal insulation has been very high. Consequently, assorted new heat-insulating materials are being developed in order to meet the needs for thermal insulation in buildings, power engineering, refrigeration, spacecraft, mechanical systems, firemanship, installations, and industrial facilities among others. Enhancement of effective thermal conductivity investigation for such materials requires the use of a device that is inexpensive, time-saving, easy-to-use, and capable of rendering reliable/accurate results for a wide range of the materials.

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If not that the traditional Lee – Charlton’s Disc (TLD) apparatus set-up usually requires a long-time duration to attain thermal balance, it would be the best fit for the task, thus warranting the design of a modified Lee – Charlton’s Disc (MLD) apparatus set-up to solve this problem. Achievement of time-saving in this new approach was feasible by using two metallic discs with electric hotplate or bunsen burner (instead of water) for heating purpose. The present study sought to proffer the possibility of analysing samples that are significantly smaller than the size of the heating element of an available electric hotplate and also compare the MLD apparatus set-up with that of TLD. Steady-state durations were measured. Also, the total weight of components in each set-up was determined and compared for appraisal of portability. It was observed that measurement (steady- state) durations were reduced by about 66.2 % to 66.7 % when using MLD apparatus technique over TLD technique to analyse samples of same dimensions prepared from a particular material. Aside being simple and about 56.69 % to 92.91 % more portable, the MLD apparatus set-up technique rendered more accurate thermal

conductivity results than those obtained by employing the TLD apparatus technique. Generally, it was noticed that the MLD apparatus technique could satisfy the above-mentioned conditions with uncertainty better than 1.5 % if applied for determination of thermal conductivity of thermal insulation materials having thickness of up to about 9.0mm.

**Keywords:** Accuracy; Fourier's law; Measurement duration; Portability; Rate of cooling; Thermal insulant

## 1.0 Introduction

The concept of thermal insulation is associated with control of heat transfer. In Al- Homoud's (2005) view, thermal insulation is a material or combination of materials that, when properly applied, retard the rate of heat flow by conduction, convection, and radiation. Materials in the same state of matter may differ in their heat-retarding tendencies thus warranting consideration of thermal conductivity for any application as far as heat transmission is concerned. Basically, thermal conductivity is a transport property that expresses the intrinsic ability of a material to allow transfer of heat. As such, materials of relatively low heat conductivity are regarded as good thermal insulators because they have the ability to significantly reduce heat transfer in order to minimise changes in the temperature of a system or space. Such heat-insulating materials may be porous, non - porous, composite or non - composite.

Nowadays, thermal conductivities of thermal insulation materials can be determined in a laboratory situation by means of devices designed to be absolute (used without calibration) or relative (used only after being calibrated) and also for application on either transient (unsteady-state) or steady-state basis. For example, the Transient hot wire (THW) proposed by Stalhane and Pyk in 1931 operates

on unsteady-state principle and after several decades of development, has become one of the most accurate techniques for measuring thermal conductivities on absolute basis. When employed to test solids, it is vital to ensure that contact resistance between the test materials and heating wire is sufficiently low (Czichos *et al.*, 2006). Also, Transient plane source is another transient-based device for probing thermal conductivities of heat insulators (Log and Gustafsson, 1995; Malinarič, 2013; Krupa and Malinarič, 2014; Laskowski *et al.*, 2016). If properly used, its precision can be improved (Li *et al.*, 2014; Jayachandran *et al.*, 2017; Elkholy *et al.*, 2019). Again, KD2-Pro meter (Rubio, 2014; Saadie, 2016) is a handheld, battery-operated, menu-driven, and portable thermal properties analyser with replaceable sensors and thermal data storage capabilities designed for ease of use and maximum functionality after calibration. It operates on unsteady-state principle as outlined in ASTM D5334 (2022). However, application of these devices has diverse drawbacks characterised by many factors among which are expensiveness (like in the case of KD2-Pro meter), limited suitability for use, and difficult operational procedure (like in the cases of Transient hot wire and Transient plane source). Lei *et al.* (2010) observed that Transient hot wire is unsuitable for testing inter-linked pore structures. These factors contribute in no small measures to scarcity of the said devices in laboratories.

Guarded hot plate (GHP) apparatus operates on steady-state principle (Kobari *et al.*, 2015; ASTM C177, 2019) and can be employed for determination of thermal conductivity of thermal insulants as documented in ASTM C1045 (2019). Terzić *et al.* (2016) developed a single-sided GHP and applied it to determine thermal conductivity of ceramics, polymers, rubbers, and glasses. But no matter how successful its application is, establishing steady-state temperature gradient through a test

material is time-consuming and the apparatus is not suitable for use on heterogeneous materials. Traditional Lee – Charlton’s Disc (TLD) apparatus also relies on steady-state principle (Gesa *et al.*, 2014; Mohapatra *et al.*, 2014) and has a simple experimental set-up for determining thermal conductivity of assorted heat-insulating materials like wood (Etuk *et al.*, 2005), soil samples (Akpabio *et al.*, 2010), composites (Ochang *et al.*, 2018; Kharshiduzzaman *et al.*, 2019), fibres and synthetic materials (Alausa *et al.*, 2011; González-Domínguez *et al.*, 2019), and so on. Though the apparatus is commonly found in many laboratories due to cheapness, durability, and availability of its components, its use is time-consuming. In contrast, a Heat flow meter saves time. If applied as stated in the standard protocol that governs its operation (ASTM C518, 2021), this easy-to-use but rather expensive research instrument can render highly accurate and reliable results of thermal conductivity measurements on a wide range of thermal insulation materials, including those that are composites (Hoseini *et al.*, 2016; Robert *et al.*, 2019a). The use of approach that involves a combination of Heat flow meter and GHP (Tleoubaev and Brzezinski, 2003) can render absolute accurate results with confidence on various materials like glasses, ceramics, rocks, plastics, composites, polymers and fireproofs. Nevertheless, the expensiveness of Heat flow meter is still an inevitable drawback associated with the method. Even the Heat flow plate approach that Flori *et al.* (2017) used to determine thermal conductivity of a building material sample of Rohacell consists of costly components and appears cumbersome.

In recent years, the demand for thermal insulation has been very high. This gives rise to development of assorted new heat-insulating materials in order to meet the needs for thermal insulation in buildings, power engineering, refrigeration, spacecraft, mechanical systems,

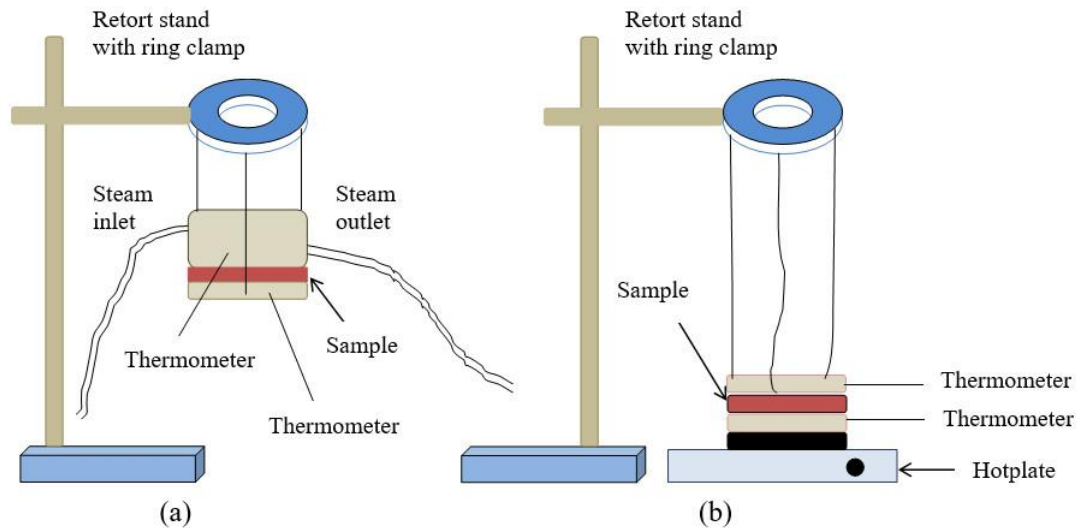
firemanship, installations and industrial facilities among others. To develop insulation materials in an economically and environmentally friendly manner, it is essential to have knowledge and control over their thermal conductivities. Keeping that in mind, there is no doubt that enhancement of effective thermal conductivity investigation for such materials requires the use of a device (an apparatus) that is inexpensive, time-saving, easy-to-use, suitable for analysing a wide range of thermal insulation materials, and capable of rendering accurate/reliable results. Considering the drawbacks in the above-mentioned cases, it is obvious that the TLD apparatus set-up has more advantages than other devices in this regard. Hence, it became necessary to choose it for modification and then design a modified Lee – Charlton’s Disc (MLD) apparatus technique which ensures quick determination of thermal conductivity for a wide range of dry thermal insulation materials and with low uncertainty in the results (Robert *et al.*, 2021a). The time-saving achievement (reduction of duration for attainment of steady state/thermal balance) in this new approach is feasible due to utilisation of two metallic discs with electric hotplate or bunsen burner (instead of water) for heating purpose. The present study aims at proffering the possibility of adopting the MLD technique to analyse thermal insulation samples using discs that are smaller in diameter than the heating element of an available hotplate. In addition to validation of results, the approach will be appraised and compared with TLD in terms of portability. These proposed assessments are vital because the size of heating element of most electric hotplates available in laboratories is large. Also, some devices that can render satisfactory results for thermal conductivity test may be too cumbersome to carry to various places for use.

## 2.0 Design and Operation of the TLD apparatus and MLD apparatus set-ups

## 2.1 Features of each set-up

Figure 1 shows the features and their arrangements in the designs of the two Lee – Charlton's Disc apparatus set-ups. It is worthy of note that any sample to be analysed should be absolutely uniform in thickness and same in cross-sectional area (or simply, diameter) as the

discs. Also, the sample's thickness must be made smaller, compared to the diameter, so as to ensure negligible losses of heat from the side of the sample. In both set-ups, one test sample is analysed at a time and the apparatus components between which the sample is inserted are made using the same type of metal.



**Fig. 1:** Set-ups of (a) TLD apparatus (b) MLD apparatus (with small heating element)

## 2.2 The heating process

In the case of TLD apparatus set-up, the sample is inserted between the steam chamber and a disc. Also, water is heated in a boiler to produce steam which is passed via a rubber hose into the chamber for the purpose of heating the sample. The steam chamber and disc, each, has one radial hole meant for insertion of thermometer sensor/probe for simultaneous monitoring of temperature. While the steam is being supplied to the chamber, heat gained by the sample is conducted downwardly by the disc. But in the MLD apparatus set-up, an electric hotplate is used as the heat source and heat flow is upward from one disc to the other through the sample. In both cases, the temperatures are monitored and noted until a steady state is reached.

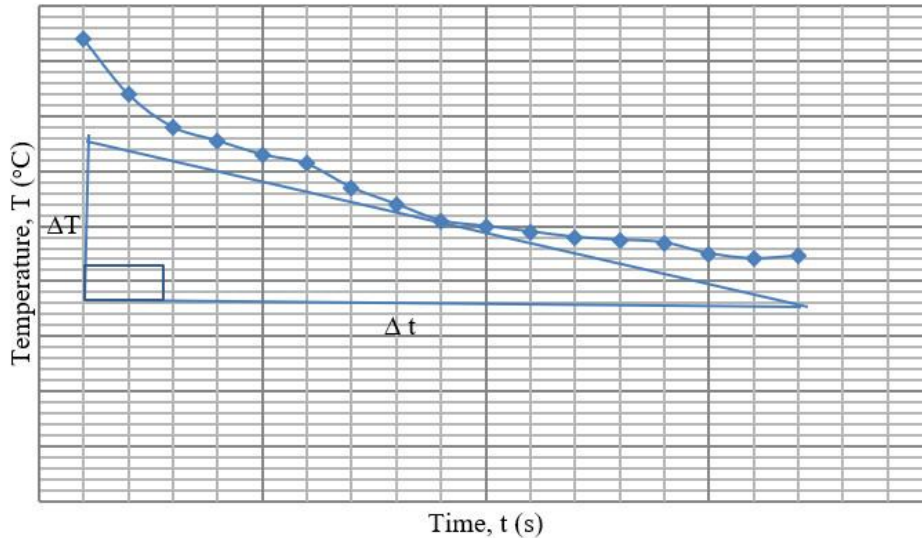
## 2.2 Determination of rate of cooling of the disc

Usually, the heat supplied to the system is conducted from the sample by a disc and a steady state is assumed to be reached if the rise in temperature of the disc is observed to be less than  $0.5^{\circ}\text{C}$  for 10 minutes. When the steady state is established, the sample is removed from the assembly and the disc is heated until its temperature rises to about  $10^{\circ}\text{C}$  above the value obtained at the steady state. After that, the heating is discontinued and the heat source is removed. The disc is suspended in air and the sample is placed on it. Also, the temperature - time data are taken while the disc cools until its temperature falls to about  $10^{\circ}\text{C}$  below the value obtained at the steady state. Next, the data gathered are used to plot cooling curve (a graph of cooling temperature against time). The required rate of cooling is same as the slope of the cooling curve obtained from the gradient of a tangent drawn to the curve.

In the TLD procedure, cooling rate of the disc

is usually determined by graphical method (Alam *et al.*, 2012; Gesa *et al.*, 2014). This technique involves drawing a tangent to the curve at the steady state temperature value of

the disc and then forming a right-angled triangle with the tangent as its hypotenuse. For the purpose of explanation, it is assumed here that such analysis is as illustrated in figure 2.



**Fig. 2:** A typical cooling curve

Two temperature values and two time values are then read from the graph to obtain  $\Delta T$  and  $\Delta t$  respectively. Based on the values got, the rate of cooling (slope),  $\frac{dT}{dt}$  is calculated as:

$$\frac{dT}{dt} = \frac{\Delta T}{\Delta t} \quad 1$$

But in the case of the approach proposed for the MLD technique, no right-angled triangle is used. Instead, a model of temperature as a function of time is generated from the plot before the rate of cooling (slope of the cooling curve) is determined by differentiation (Robert *et al.*, 2021a). Either Microsoft Excel or Origin Graphing and Analysis Software can be employed for modelling of the required function(s). It is important to note that when finding the slope, the difference between two temperature values is calculated. As such, the result obtained on Celsius scale is same in magnitude as the one that can be rendered on Kelvin scale (*For example, the difference between 90 °C and 40 °C is 50 °C. On Kelvin scale, it means the same as the difference between 363K and 313K, which is 50K*). Thus,

it is needless to convert  $T$  to Kelvin before plotting the cooling curve (since the value of  $\frac{dT}{dt}$  will be the same even in the S.I unit, which is Kelvin per second).

### 2.3 Computation of thermal conductivity value

At macroscopic level, the equation that governs a sample's thermal conductivity,  $k$  in the direction of its thickness,  $x$  is premised on Fourier's law (Rajput, 2015; González-Domínguez *et al.*, 2019) thus:

$$Q_x = -kA \frac{\partial T}{\partial x} \quad 2$$

where  $Q_x$  is the quantity of heat transferred,  $A$  is the cross-sectional area of the sample, and  $\frac{\partial T}{\partial x}$  is the temperature gradient in the direction of heat flow. The minus sign shows that temperature gradient is always negative along the positive direction of heat flow (and this situation is taken care of by the existence of negative sign in the computed value of  $\frac{dT}{dt}$ , thus making  $Q_x$  value become positive).



Now, if heat losses from the sample's side are negligible and  $Q$  is the amount of heat conducted per second through the sample at steady state of one-dimensional heat conduction, then

$$Q = kA\left(\frac{\Delta\theta}{x}\right) \quad 3$$

where  $\Delta\theta$  is the temperature difference across the thickness,  $x$  of the sample. At that instant, this quantity of heat is same as the amount radiated per second from the exposed surface of the disc. That is,

$$Q = Mc\left(\frac{dT}{dt}\right) \quad 4$$

where  $M$  and  $c$  are, respectively, the mass and specific heat capacity of the disc. So, under steady-state boundary conditions, it implies from eqs. (3) and (4) that (Robert *et al.*, 2021a)

$$k = \left(\frac{Mcx}{A\Delta\theta}\right) \frac{dT}{dt} \quad 5$$

### 3.0 Materials and Methods

One of the major materials used in this study was a standard reference material known as Extruded polystyrene (XPS) foam. It was carefully cut into several square pieces each measuring 240 mm x 240 mm but with varied thicknesses. The mass of each piece was determined by means of a weighing balance (SCOUT-PRO SERIES, Model SPU2001). Also, the thickness of each piece was measured using digital vernier callipers. After that, bulk volume was determined as the product of length, width, and thickness before the corresponding bulk density was computed based on the relation (George *et al.*, 2010; Okorie *et al.*, 2020; Etuk *et al.*, 2021; Robert *et al.*, 2021b)

$$\rho = \frac{M}{V} \quad 6$$

where  $\rho$  is the bulk density,  $M$  is mass, and  $V$  is bulk volume. For each of the thickness sizes considered, one piece was selected to get a total of five pieces, all having the same bulk density value (31.0 kgm<sup>-3</sup>). The selected pieces were

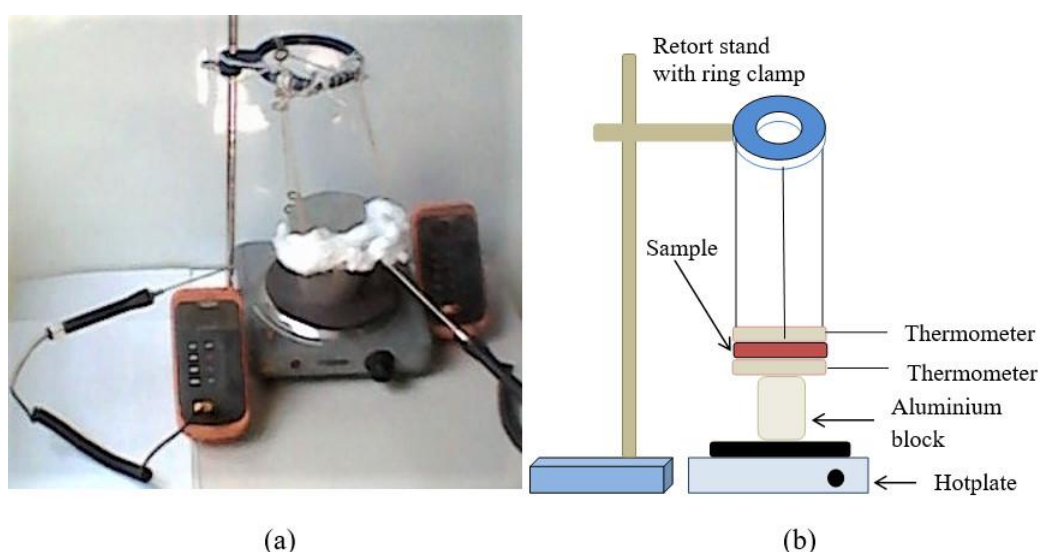
coded (with thickness values for ease of identification) and used as test samples. In this study, two categories of reference value were used for assessment of error level. For one category, the thermal conductivity value reported in the literature and also declared at the same bulk density value (that is, 31.0 kgm<sup>-3</sup>) for the standard reference material (XPS) was chosen. The reason for desiring similarity in bulk density arises from the fact that heat shunting errors may occur during the measurement process if the materials have drastically different thermal conductivities due to significant differences in their bulk densities.

Another category consisted of thermal conductivity values obtained by analysing the test samples using a calibrated Heat flow meter (HFM 100 series) as gold standard. Heat flow meter is recommended in standard protocols, including ISO/IEC 8301 (2019), for such purpose (determination of reference values) and Jannot *et al.* (2017) employed it to obtain reference values for validation of a new apparatus. It is interesting to also note that operation of a Heat flow meter is backed by a fully established theory of Fourier's law as clearly stated in ASTM C518 (2021) and applied by Clarke (2017), thereby substantiating its fitness into one of the target aspects of this work. The Heat flow meter was employed to obtain reference thermal conductivity values for two trial runs and the average value was computed per thickness of the test samples used. Then after, disc-shaped samples were prepared from all the test samples analysed by means of the Heat flow meter. The disc-shaped samples were of same bulk density and thickness as the ones from which they were made. As such, two replicate samples were obtained per thickness as before. Five TLD apparatus set-ups were arranged for experimentation. Each of them consisted of a steam chamber (of thickness 45 mm) and a disc (of thickness 10 mm), both made from nickel.

In addition, each set-up was provided with digital stopwatch, ring clamp (with strings for suspension of the disc), laboratory stand, two digital thermometers (Model 305, calibrated and equipped with type-K probe for temperature measurement), and steam generator (with facility of steam passage to steam chamber) containing 1540 cm<sup>3</sup> of water at 28 °C. Five disc-shaped samples of different thicknesses were selected and used in such a way that one was accommodated in a set-up at a time. This enabled all of them to be analysed simultaneously during each trial run. Immediately the steam generator for a particular set-up was turned on, timing of the process was commenced and the temperature of the disc was noted after every minute until a steady state was attained. The difference in temperature across each sample's thickness at the steady state was noted and the cooling

temperature – time data were gathered. These procedures were adopted for all the set-ups. Prior to repetition of the measurements for another trial run, the discs, steam chambers, steam generators, and test samples were allowed to cool completely. During the second trial run, the same water volume was used but a particular set-up was not applied to analyse a particular test sample twice.

Five MLD apparatus set-ups were then arranged for analysis involving the same disc-shaped samples but considering the use of an electric hotplate with a larger heating element compared to the disc/sample size. Each experimental set-up in this case was provided with an electric hotplate (having heating element of diameter 170 mm) and a cylindrical aluminium block (of height 80 mm and diameter 75 mm weighing 992.3 g). Figure 3 shows the features of the set-up.



**Fig. 3:** MLD apparatus set-up employing hotplate with larger heating element  
(a) Experimental (b) Diagrammatic

The control dial of the hotplate was adjusted and maintained at a point the temperature reading of the lower disc was same as that of the steam chamber used in the TLD assembly. Also, it was ensured that all the discs used had not been utilised in the previously-arranged set-ups. The thickness of each test sample and that

of the upper disc were properly lagged with cotton wool. Measurements were taken for two trial runs. All the discs and steam chambers used were of diameter 110 mm. The discs were carefully selected and those used in the experiments were of approximately the same mass. In all the set-ups, a little metal-based

thermal grease was used to improve interfacial heat conduction in the interface areas. Also, steady state duration was noted for each method applied and per thickness of the sample. The cooling rates were determined by graphical method in the case of adopting the TLD apparatus technique. For the MLD approach,

$$\frac{u(k)}{k} = \sqrt{\left[\frac{u(M)}{M}\right]^2 + \left[\frac{u(c)}{c}\right]^2 + \left[\frac{u(x)}{x}\right]^2 + \left[u\left(\frac{dT}{dt}\right)/\frac{dT}{dt}\right]^2 + \left[\frac{u(A)}{A}\right]^2 + \left[\frac{u(\Delta\theta)}{\Delta\theta}\right]^2} \quad 7$$

All the experiments were conducted at room temperature and computation of statistical parameters was done with the aid of SPSS (Statistical Package for the Social Sciences) Software.

#### 4.0 Results and Discussion

The weight of each component used in the TLD apparatus and MLD apparatus set-ups is presented in Table 1. It can be deduced that the total weight of all the components in the MLD apparatus set-up is less by 92.91 % (or 56.69 % on considering mass of the cylindrical aluminium block) compared to the case for the TLD apparatus set-up. Observably, Lee –

differentiation was applied to determine the rate of cooling of the disc (Robert *et al.*, 2021). In accordance with ISO/IEC Guide (2008), uncertainty in the measurement results was assessed based on the following functional model derived from eq. 5 above:

Charlton's discs and steam chambers available in the market are made from nickel or brass. Nickel has density of 8908 kgm<sup>-3</sup> while brass has density of 8400 kgm<sup>-3</sup> to 8700 kgm<sup>-3</sup> (Engineering Toolbox, 2004), showing that it is lighter than nickel. Also, the weight of a Heat flow meter or standardised GHP is far greater than that of the TLD apparatus. Since portability correlates inversely with weight of a device, the net weights obtained in this work show that the MLD apparatus is the most portable among the steady-state-based devices used on heat-insulating slabs for thermal conductivity determination.

**Table 1:** Particulars of the Lee –Charlton's Disc Apparatus set-ups

Parameters Set-up component	Weight (g)	Statistics of components in a set-up per method		Total mean weight (g)	
		TLD Method	MLD Method	TLD Method	MLD Method
Disc	846.2 ± 0.1	1	2	846.2	1692.4
Steam chamber	913.7 ± 0.2	1	-	913.7	-
Steam generator (containing 1540 cm <sup>3</sup> of water)	4910.8 ± 0.1	1	-	4910.8	-
Laboratory stand (rod with base)	1251.8 ± 0.2	1	1	1251.8	1251.8
Ring clamp	118.9 ± 0.1	1	1	118.9	118.9
Rubber hose	120.3 ± 0.3	2	-	240.6	-
Electric hot plate	1230.4 ± 0.1	-	1	-	1230.1
Overall mean weight of components per set-up				8282.0	4293.2

Table 2 shows summary of the measurement durations for each method employed in this

study. Irrespective of the measurement method adopted, it is observed that steady state duration



varies with thickness of the test sample. The shortest measurement time is obtained in the case of HFM method, while the use of the MLD method is more time-saving than application of the TLD method. Statistically, the steady state durations between the use of the TLD method and HFM method correlate by 97.86% whereas 98.11% agreement is obtained in the case involving the MLD method and HFM method. These results show strong positive relationship but with the MLD method being more effective than the TLD method in terms of quick thermal conductivity determination. Except in the case involving the results rendered by the MLD method and HFM method, other ANOVA results show that the calculated F-values are greater than the critical F-value (5.318). The implication is that the steady state durations for the TLD method significantly differ from those associated with the use of either the HFM method or MLD method. This may be attributed to utilisation of water in the design of the TLD apparatus set-up. Broadly speaking, thermal grease was applied in the assemblies of both techniques to ensure effective heat transfer across the interface areas. Also, the source through which heat propagates to the test sample in the MLD apparatus set-up was maintained at the same temperature as the one in the case of the TLD apparatus set-up. It therefore becomes obvious that the use of water to produce steam for heating purpose is responsible for the delay in attainment of thermal balance as observed in the case of the TLD apparatus set-up.

Figure 4 shows the graphical illustration of the said relationships in steady state durations. With respect to measurement duration by the HFM method, the slope angle produced when correlating the steady state durations due to the use of the MLD method is  $16.9^\circ$  less than the

slope angle of  $79.9^\circ$  obtained as a result of employing the TLD method. Usually, a slope angle of  $45.0^\circ$  signifies a perfect agreement between two measurement methods in a linear plot (Robert *et al.*, 2019b). So, as the value obtained for the MLD method is closer to  $45.0^\circ$  in this case, it simply supports the above submission that the MLD method exhibits a better agreement with the HFM method compared to the TLD method as far as enhancement of quick thermal conductivity determination is concerned. In fact, among the three substances (water, nickel, and brass) that could be used in Lee –Charlton’s disc experimental set-up for heat transfer from the source, water is the poorest thermal conductor. For instance, water has specific heat capacity and thermal conductivity of  $4200 \text{ Jkg}^{-1}\text{K}^{-1}$  and  $0.62 \text{ Wm}^{-1}\text{K}^{-1}$  respectively (Mgbenu *et al.*, 1999) whereas nickel has  $445 \text{ J kg}^{-1}\text{K}^{-1}$  and  $90.7 \text{ Wm}^{-1}\text{K}^{-1}$  as its specific heat capacity and thermal conductivity respectively (Lide, 2005). Also, as noted by Mgbenu *et al.* (1999), brass has thermal conductivity of  $109.0 \text{ Wm}^{-1}\text{K}^{-1}$  and specific heat capacity of  $380 \text{ Jkg}^{-1}\text{K}^{-1}$ . By comparison, it can be deciphered that, ordinarily, nickel or brass is capable of transferring more heat and also at a faster rate than water, let alone being in direct contact with the heat source like in the case of the MLD apparatus set-up design. Thus, it is appropriate to posit that the significant reduction observed in measurement time due to the use of MLD apparatus set-up over application of the TLD apparatus set-up is as a result of excluding water in the heating process. This finding portrays that a material of higher thermal conductivity and lower specific heat capacity is a better conductor than the one with contrariwise tendencies.

**Table 2:** Measured steady state duration per test method

<i>x</i> (mm)	<i>t<sub>s</sub></i> (min)									PPMCC between the mean values of <i>t<sub>s</sub></i>	Calculated F-value for one-way ANOVA in the mean values of <i>t<sub>s</sub></i> at <i>p</i> < 0.05
	Trial 1			Trial 2			Mean value				
	TLD Method	MLD Method	Reference (HFM)	TLD Method	MLD Method	Reference (HFM)	TLD Method	MLD Method	Reference (HFM)		
5.02	65.0	22.0	20.0	65.0	20.0	20.0	65.0	21.0	20.0		
6.71	80.0	27.0	22.0	79.0	26.0	22.0	79.5	26.5	22.0	0.9786 <sup>a</sup>	39.27 <sup>a</sup>
7.13	87.0	29.0	25.0	86.0	28.0	25.0	86.5	28.5	25.0		1.98 <sup>b</sup>
8.26	106.0	36.0	28.0	105.0	36.0	28.0	105.5	36.0	28.0	0.9811 <sup>b</sup>	30.16 <sup>m</sup>
9.14	126.0	42.0	30.0	126.0	42.0	30.0	126.0	42.0	30.0		

*ANOVA = Analysis of variance; PPMCC = Pearson's Product - Moment Correlation Coefficient*

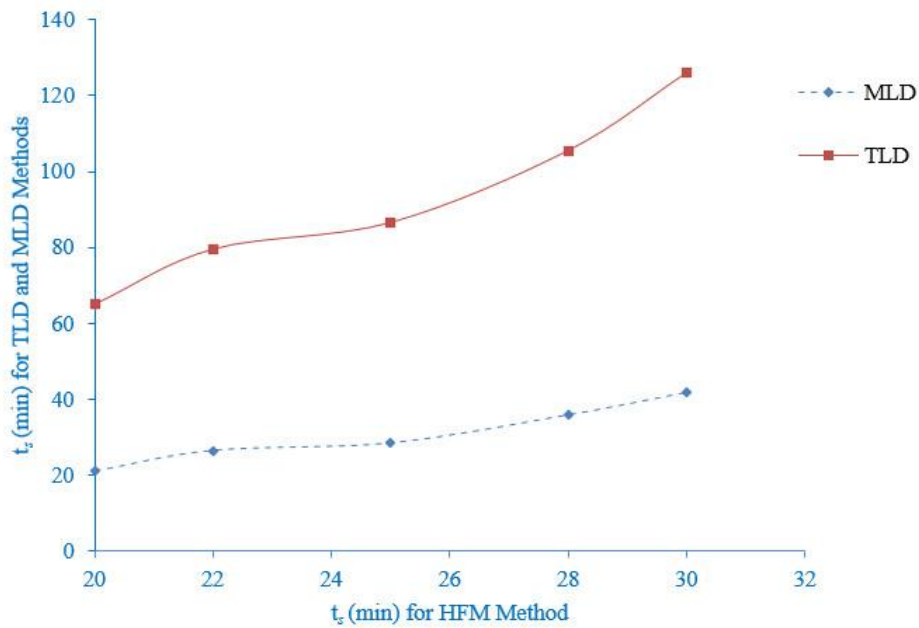
*a: value obtained between the results rendered by TLD Method and HFM Method*

*b: value obtained between the results rendered by MLD Method and HFM Method*

*m: value obtained between the results rendered by TLD Method and MLD Method*

*t<sub>s</sub>: Steady state duration*

*x: Thickness of the sample*



**Fig. 4:** Comparison of steady state durations for the TLD and MLD set-ups with HFM

From the results (of the sample's thermal conductivity measurements) recorded in Table 3, it can be inferred that unlike in the case of using the TLD method, the MLD method produces thermal conductivity values that compare very well with the reference values. Based on the remark by Etuk *et al.* (2020) that a new measurement approach is reliable if the values obtained by it compare well with reference values, it can be submitted that such remarkable agreement is an indication that the MLD apparatus has the needed reliability for its design purpose. Table 4 contains the results obtained from uncertainty assessment and validation test.

It can be observed that the MLD apparatus technique is capable of rendering results satisfactorily with uncertainty better than 1.5%. Greater percentage errors characterise the results rendered by the TLD method, thus showing that the MLD method is more efficient when comparing the two

techniques. The disparity in the error values is due to the differences in the approaches adopted in determining the rates of cooling of the discs. In other words, the procedure applied in this study ensured that when employing the TLD method and MLD method, the temperature difference across the test sample remained the same and also, the steady state temperature was the same for a particular thickness. Thus, the application of differentiation (as adopted for the MLD method) successfully and effectively minimised the negative influence exercised by the outliers (odd plotted points) which the graphical approach (usually adopted for the TLD method) cannot address. By considering the fact that in all measurements of physical quantities, low percentage error indicates high accuracy, it can be remarked that the thermal conductivity results obtained by using the MLD apparatus technique are more accurate than the values rendered by employing the TLD apparatus technique.

**Table 3:** Thermal conductivity values of the test sample and associated errors in the measurements

$x$ (mm)	Measured thermal conductivity, $k$ (in $Wm^{-1}K^{-1}$ )								
	Trial 1			Trial 2			Mean values for the trial runs		
	TLD Method	MLD Method	Reference (HFM)	TLD Method	MLD Method	Reference (HFM)	TLD Method	MLD Method	Reference (HFM)
5.02	0.0321	0.0319	0.0320	0.0322	0.0317	0.0319	0.0322	0.0318	0.0320
6.71	0.0321	0.0316	0.0320	0.0321	0.0318	0.0320	0.0321	0.0317	0.0320
7.13	0.0323	0.0318	0.0319	0.0322	0.0319	0.0318	0.0323	0.0319	0.0319
8.26	0.0321	0.0317	0.0318	0.0321	0.0316	0.0318	0.0321	0.0317	0.0318
9.14	0.0322	0.0316	0.0317	0.0322	0.0317	0.0318	0.0322	0.0317	0.0318

**Table 4:** Results of MLD apparatus validation and uncertainty assessment

$x$ (mm)	Combined standard uncertainty (%)	Average $k$ - value per method				Computed error with respect to the reference values	
		TLD Method	MLD Method	Reference (HFM)	Reference (Literature)	TLD Method	MLD Method
5.02	1.43						
6.71	1.39					0.94% <sup>a</sup>	0.31% <sup>b</sup>
7.13	1.47	0.0322	0.0318	0.0319	0.0317		
8.26	1.39					1.58% <sup>l</sup>	0.32% <sup>l</sup>
9.14	1.39						

\* Source of the Literature reference value: Dominguez-Muñoz (2010)

*l*: value obtained with respect to the reference value declared in the literature

## 5.0 Conclusion

Findings from this work revealed that the MLD apparatus set-up is more portable compared to TLD apparatus set-up. Measurement durations were found to be shorter in the case of using the MLD apparatus set-up than when employing the TLD apparatus set-up for determination of thermal conductivity of heat-insulating materials. Again, computation of thermal conductivity by applying the rate of cooling obtained using differentiation was found to reduce uncertainty, thus yielding results with greater accuracy for the MLD apparatus technique compared to the graphical method usually adopted in the case of TLD apparatus technique. Statistically, unlike in the case

with the TLD method, no significant difference was revealed by one-way analysis of variance between the experimental data generated using Heat flow meter and those produced by means of the MLD apparatus technique. For sample thickness of about 9.0 mm, steady state duration ranged from 21.0 minutes to 42.0 minutes in the case of using the MLD apparatus set-up whereas by using the TLD apparatus set-up, it ranged from 65.0 minutes to 126.0 minutes. In addition to being cost-effective and easy-to-use, the MLD apparatus technique was found to be suitable for effective, fast, and accurate determination of thermal conductivity with uncertainty better than 1.5 %.

### Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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