Evaluation of Thermal Conductivity of Fiber glass Composite by using Experimental Set-up

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ABSTRACT

The paper describes a method for measuring the thermal conductivity of fiber glass composite having a low thermal conductivity. The apparatus is rather simple and low-cost, being therefore suitable in a laboratory for students of engineering, where several set-ups are often required. A numerical approach solves the thermal field in the specimen, which is depending on the thermal diffusivity of its material. The numerical method requires the temperature data from two different positions in the specimen, measured by two thermocouples connected to a temperature meter/controller /logger. After calculate thermal diffusivity, calculate thermal conductivity of specimen. By Fourier's law of heat conduction, calculated thermal conductivity of fiber glass composite and compared it with other 3 metals. This paper shows the experimental set-up and result details.

KEYWORD: - thermal diffusivity, thermal conductivity, fiber glass composite, copper, stainless steel, aluminum, thermocouple.

LIST OF SYMBOLS: - *q_l heat transfer rate (in watt), α = thermal diffusivity, k = thermal conductivity, ρ = density.*

1. INTRODUCTION

The evaluation of thermal properties of new materials is quite important. For several of their engineering applications in microscopic or macroscopic structures for instance, we need to know how they are able to dissipate heat. The same is true for those systems suitable for the recover or storage of energy. Besides this necessity of measuring the thermal properties of new component materials, the study and development of relevant experimental methods is quite important for researchers and students of engineering too. Here then, we propose a method that allows the students to have an experimental approach to the problem of thermal transport.

New methods to measure the thermal diffusivity has published by the author. Some measures reported in the references were based on modeling the thermal field inside a specimen after the measure of its thermal expansion. This method is able to reduce strongly the experimental errors, which are derived from thermal leaks, but requires a capacitive system to record the thermal expansion. It is therefore not suitable to be used in a laboratory for engineering students. Moreover, the instruments are quite expensive.

Other methods, known as the flash methods, to determine the thermal diffusivity exist. They are based on the use of a laser for heating the specimen. A high-intensity short-duration light pulse is absorbed in the front surface of the specimen and the resulting temperature history of the rear surface is measured, usually by a thermocouple. To cancel the problem of the thermal leaks through the thermocouple wires, the thermal diffusivity can be measured using a noncontact experimental configuration based on infrared photo thermal radiometry. This technique reduces the thermal leaks, but, as in the previous case of methods, requires a sophisticate set-up.

The aim is to improve a laboratory for students with a measure of the thermal diffusivity, without increasing the overalls cost of the structure, we describe here an experimental procedure based on the use of thermocouples, adapting the numerical methods of determining the thermal. The method of solution is simplified for engineering students. In the following, the experimental set-up is proposed for materials having low thermal conductivity. As we will see, the method provides good results in agreement with previous measurements.

2. EXPERIMENTAL SET-UP: -

Fig shows the experimental set-up. This setup is to be used in very simple way. We need two thermocouples and a two temperature controller/meter. I used for students an old device having two large displays, quite useful during room demonstrations, because everybody can see directly the variations of temperature. A cylindrical specimen of commercial fiber glass composite, 15mm diameter and 6mm long, is placed on a metal grid, as shown in Figure 1. Around the cylinder, a layer a few millimeters thick of grey plasticine is used to avoid convective flows. The heat source is applied at the lower base. The heater is an electric resistive coil under an insulating disk having 10watt. Some students simply used a lighter during the experiments.

For what concerns the specimen, to reduce the dispersion of heat from its lateral surface, a thermal guard is use of the same material (Fig.3). The temperature is measured at two different positions in the specimen. One thermocouple is placed at two millimeters from the lower base, in a small diameter hole drilled parallel to the base, through the thermal guard to the axis of the specimen. Since the wires of thermocouple are heated, as the specimen and the thermal guards are, we can consider negligible any thermal leak due to their presence. We can see from Figure 3 how the lower part of the specimen / thermal guard cylinder had been properly shaped.

The proposed set-up is used for measurements of fiber glass composite materials of low thermal conductivity. The actual length of the specimen that we will consider in the calculation of the thermal field is 6mm.

The second thermocouple is placed at the top of the specimen. Of course, a computer could record the temperatures. In the case that we use a device as in Fig.1, a stopwatch allows to directly read and record the temperatures with a suitable time interval (we used an interval of 10 seconds). The data analysis is done with a numerical program, which is quite simple, as we discuss in the next section.

3. THEORETICAL MODEL: -

We can use to solve the thermal transport in the cylindrical specimen by numerical calculation. It is based on a recurrence relation, which uses the temperature measured by the thermocouple at the lower base. After imposing a value of the thermal diffusivity, the temperature field in the cylinder is obtained. Evaluating with the recurrence relation the field at the upper base, we can compare its time behaviour with the temperature recorded by the second thermocouple. The actual thermal diffusivity of the sample is that providing the best agreement between theoretical and experimental values.

Let us remember that the thermal diffusivity α is the physical quantity, which appears in the equation of heat:

$$\frac{1}{\alpha} \cdot \frac{\partial T}{\partial t} = \nabla^2 T \qquad (1)$$

To determine the thermal diffusivity, we measure the temperature as a function of time, using at least two thermocouples, as shown in the sketch (Fig.3) of the cylindrical specimen. As previously discussed, the lower base is heated by means of a suitable heat source: we assume that the lower base is uniformly heated. Using the two thermocouples, the temperature is measured at two different positions. As previously told, one of the thermocouples is inserted laterally at the lower base, passing through the thermal guard. The wires of this thermocouple, having practically the same temperature of the specimen and of the thermal guard, have a negligible pertubative effects on the temperature field.

The other thermocouple is inserted on the upper base of the specimen. The thermal guard is a hollow cylinder made of the stainless steel grade 202. The radial distance between the points AB and DE is of 0.5 millimetres and the outer diameter of 3.8 cm. The diameter of inner cylinder is 1.6 cm. The total length is 5 cm. The distance of the two thermocouples is 6mm to 1cm (see Fig.3).

Since the material under measurement has a low thermal conductivity, we consider its thermal field depending only on *z*, not on the radial coordinate. Considering only a dependence on the *z*-coordinate, this means that each section of the cylinder is reached in a uniform manner by the heat coming from below, and that there is not any radial propagation of heat. If the two cylinders are of the same material, positions at the same distance from the base (for example, A, B, C, D, E in Fig.3) will have the same temperature.

We assume that this is true, because of the presence of the thermal guard. Admitting that the heat spreads along the longitudinal axis *z*, and calling *T* the thermal field in the specimen:

$$\frac{\partial T}{\partial x} = \frac{\partial T}{\partial y} = 0 \qquad (2)$$

Therefore, the thermal equation 1st can be written as:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} \qquad (3)$$

Where $\alpha = K/(c\rho)$ is the thermal diffusivity, *K* the thermal conductivity, *c* the specific heat and ρ the density. To solve this last equation it is necessary to have the thermal field at the initial time of measurements and the boundary conditions. At the initial time condition, we imagine that the cylinder is at the same temperature, the room temperature, $T(t = 0) = T0$. Since the problem is one-dimensional, we need two conditions: one at the lower base, $z = 0$, and at the top of the cylinder, $z = L$, where *L* is the length of the specimen. At the lower base, the temperature is known, because measured by the lower thermocouple. At the top of the specimen we assume a non dispersive boundary condition. From the lateral surfaces, the irradiation of heat is negligible. The thermal exchange with the environment exists for sure, but it can be neglected because air is not flowing between the sample and the thermal guard and the difference between the temperatures of specimen and environment is quite small. In any case, the aim of this method is the use of it for students, and therefore, with some suitable remarks, a non-dispersive condition can be assumed.

By using **Fourier's law** of conduction we calculate the thermal conductivity of materials.

$$Q = -KA\,(T_2 - T_1) / L \qquad (4)$$

$$Q = KA\,(T_1 - T_2) / L \qquad (5)$$

$$K = Q.L / A\,(T_1 - T_2) \qquad (6)$$

By electrical analogy for calculate rate of heat transfer, we consider 3 min (approx.) time of heating of specimen and the heating coil resistance by measurement 3.5 k-ohm. And supplying voltage 220v, 50 Hz. by relation,

$Q = I^{2} \cdot R.\ t = 42$ watt/m

Where: I = current flowing in coil, R = resistance of heating coil, t = Time of heating specimen.

By **ohm's law** we can calculate I current in ampere,

V = RI

I = V/R = 220/ 3.5* 1000 = 0.06285 amp

$Q = (0.06285)^2 * 3.5 * 1000 * 3 = 42$ watt/m,

4. TEMPERATURE RESULT OF FOUR MATERIALS AT CONSTANT TEMPERATURE: -

s. no.	**Aluminum 6061**		**Stainless steel 302**		**Copper**		**Fiber glass composite**	
	T_1 ºC	**T_2 ºC**	**T_1 ºC**	**T_2 ºC**	**T_1 ºC**	**T_2 ºC**	**T_1 ºC**	**T_2 ºC**
1.	87	77	87	58	87	79	87	42

4.1 Aluminum alloy 6061 T4 annealed,

Take the density $\rho = 2.7$ g/cm^3, c = 0.896 J/g-K room temp. (By material science book)

Steady state method (one dimensional) to find out thermal conductivity by **Fourier's law**

$Q = KA\,(T_1 - T_2) / L$

$K = QL / A\,(T_1 - T_2)$

The result obtained by this setup are T_1 = 87 ºC, T_2 = 77 ºC, and rate of heat transfer Q = 42 watt/m, area of specimen, $A = \pi/4 * (15\text{x}10^{-3})^2$, = 0 .0001769 square meter, L = 6mm = 0.006 meter

K = 42* 0.006 / .0001769* (87- 77) = 142.5 W/m-k,

The actual value of thermal conductivity of pure aluminum alloy 6061 annealed, K =180 W/ m-k, T4 temper K= 154 W/m-k

4.2 Stainless steel 405 alloy

Take the density $\rho = 7.8$ g/cm^3, c = 0.5 J/g-K room temp. (By material science book)

$Q = KA\,(T_1 - T_2) / L$

$K = QL / A\,(T_1 - T_2)$

The result obtained by this setup are T_1 = 87 ºC, T_2 = 58 ºC, and rate of heat transfer Q = 42 watt/ m, area of specimen, $A = \pi/4 * (15\text{x}10^{-3})^2$, = 0 .0001769 square meter, L = 6mm = 0.006 meter,

K = 42* 0.006 / .0001769* (87- 58) = 49 W/m-k

Actual thermal conductivity of pure stainless steel 405 grade lies between 27-50 W/m-k,

4.3 90-10 bronze, (copper alloy)

Take the density ρ = 8.8 g/cm^3, c = 0.376 J/g-K room temp. (By material science book)

$K = QL / A (T_1 - T_2)$

$Q = KA (T_1 - T_2) / L$

The result obtained by this setup are T_1 = 87 ºC, T_2 = 79 ºC, and rate of heat transfer Q = 42 watt/m, area of specimen, A = $\pi/4 * (15x10^{-3})^2$, = 0 .0001769 square meter, L = 6mm = 0.006 meter,

K = 42* 0.006 / .0001769* (87- 79) = 178.1 W/m-k,

The actual value of thermal conductivity of pure bronze (90%copper, 10%Zn), T4 temper K= 189 W/m-k,

4.3 Fiber glass composite

Take the density ρ = 2.57 g/cm^3, c = 0.81 J/g-K room temp. (By material science book)

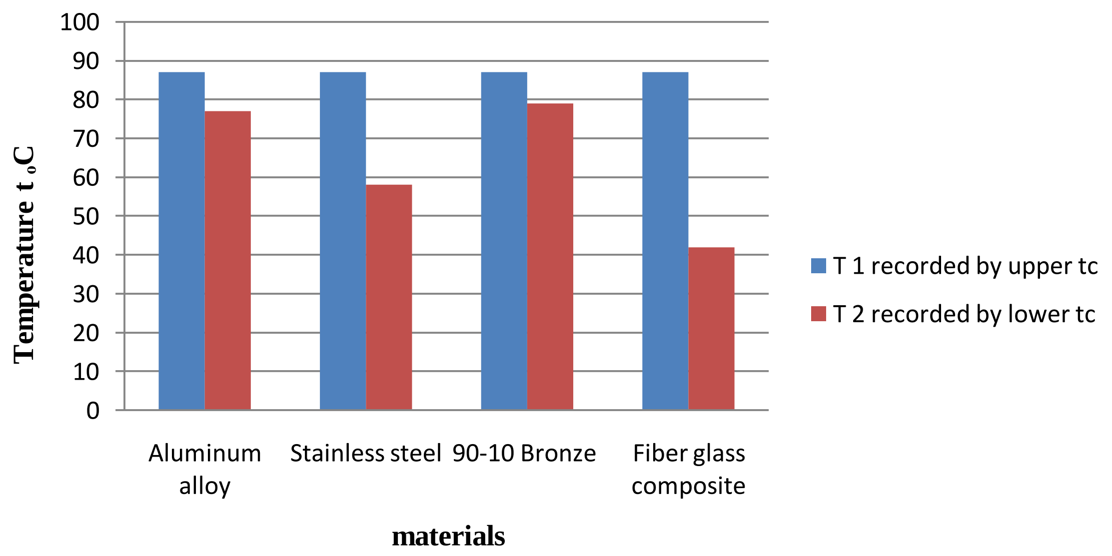
$K = QL / A (T_1 - T_2)$

The result obtained by this setup are T_1 = 87 ºC, T_2 = 42 ºC, and rate of heat transfer Q = 42 watt/m, area of specimen, A = $\pi/4 * (15x10^{-3})^2$, = 0 .0001769 square meter, L = 6mm = 0.006 meter,

K = 42* 0.006 / .0001769* (87- 42) = 31.6W/m-k,

The actual value of thermal conductivity of E fiber glass composite, K =0.01 W/ m-k, -35W/m-k.

Fig 1.a Temperature graph



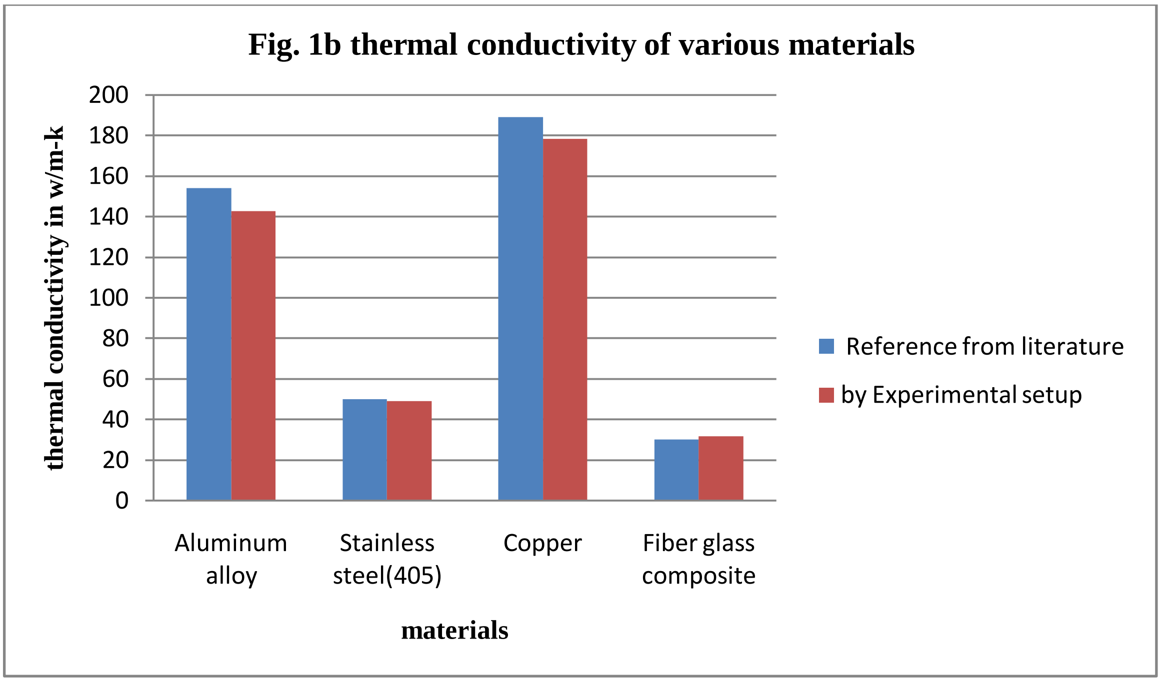


Figure 2. EXPERIMENTAL SET-UP

Fig shows the Experimental set-up for measuring the thermal diffusivity, thermal conductivity of any material by Fourier's law of heat conduction we see the cylinder on the left, which is composed by the specimen and its thermal guard, placed on a metallic grid.

Near the base of the cylinder, a small amount of insulating material (grey plasticine) is used to avoid convective currents about the cylinder, when the specimen is heated at its lower base. We can simply use a lighter to heat it. but this setup attach heater with a range 27 ºC to

100 ºC On the right we see the data logger/temperature controller for thermocouples, having two displays to visualize the temperatures. We can also see the wires of thermocouples and k type of testing probe.

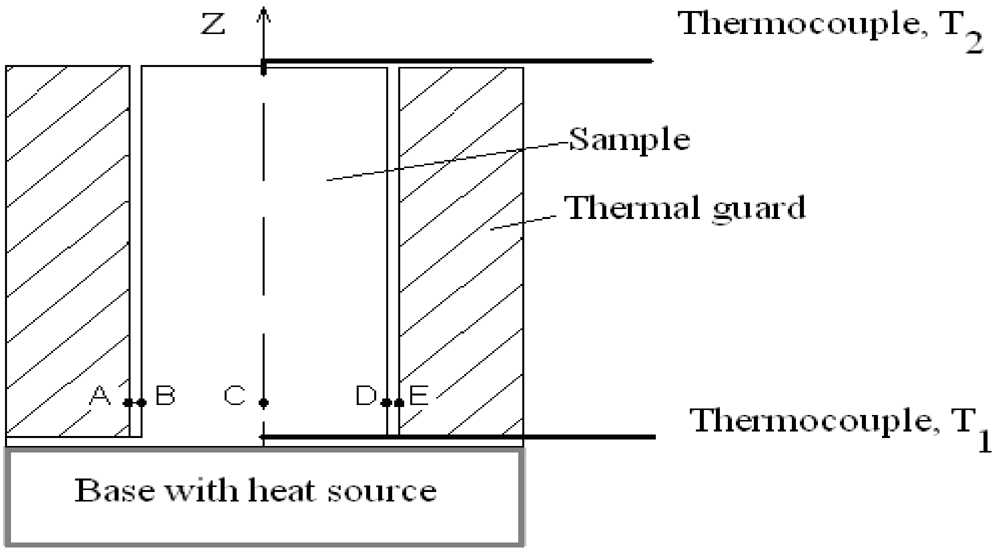


Fig.3. Sketch of specimen and thermal guard.

5. COMPARISON AND VALIDATION OF THERMAL CONDUCTIVITY DATA

This setup is simple and used by Engineering Student PG/UG. The result obtained by this setup is nearly previous data we can calculate approx. thermal conductivity of materials by applying steady state method. The result is shown in fig 1a, 1b the value of thermal conductivity obtained by setup are 142.5 w/m-k and actual 154 w/m-k so this setup is valid for evaluate thermal conductivity of materials we can validate this value from actual value. We performs thermal conductivity test on the other specimen such as copper and stainless steel too. The value of thermal conductivity of fiber glass is not nearly the actual value but it differs from matrix and density of fiber and epoxy. So the variation occurs on the specimen. This set-up is simple setup, cast effectiveness, and easy made, not require flash method. But the result obtains accurate by using vacuum thermal guard, in this set-up used gray plasticine used to avoid thermal convection. The cost of this setup nearly 5k-6k and there are other limitations of this setup are not accurate result. By using flash method arrangement the result obtained quite accurate with thermal diffusivity. The table shows the thermal conductivity of four materials.

s. no.	Materials	Thermal conductivity w/ m-k By Experimental set-up	Thermal conductivity by literature data w/m/k
1.	Aluminum 6061 t4 annealed	142.5	154-180
2.	Stainless steel 405 grade	49	27-50
3.	90-10 bronze copper	178.1	189
4.	Fiber glass composite sheet	31.6	1.1-30

6. CONCLUSION

Heating the specimen for five minutes approximately and recording the two temperatures each ten seconds, two curves as in Fig.1a,b are obtained. Applying the numerical procedure to find out the thermal conductivity is obtained. The behaviour of this function for the data of Fig.1a is given in Fig.1b. This function has a well defined minimum. The outcome value is near the existing value.

The value of the thermal conductivity giving the best agreement with experimental data of Fig.1b is therefore K = 31.5 w/m-k, Repeating some measurements on the same specimen, we obtained a value of the thermal conductivity of K = 30 w/m-k. This measure is in good agreement with the values obtained in a more controlled environment (27 ºC). The dispersion of the values is larger, but this is not surprising, because it is difficult to repeat the measures in the same conditions. Moreover, there is the possibility that convective heat flows exist during the heating of the specimen.

Of course, the method can be improved preparing a small box for the set-up and create the vacuum in it with a relative pump, but this is beyond the aim of the proposed approach, which is the use of it in a student laboratory. For what concerns the calculation, the numerical recurrence is quite simple to be implemented by an Engineering student on a personal computer. Moreover, the apparatus has a low-cost, and therefore several replicas can be prepared without being their cost exceedingly large for the financial support of the laboratory.

7. REFERENCES

1) Sparavigna A.C., S. Giurdanella, M. Patrucco Behaviour of Thermodynamic Models with Phase Change Materials under Periodic Conditions. Energy and Power Engineering, **3**, 150- 157, 2011..

2) Sparavigna A., Nuovo metodo dilatometrico di misura della diffusivita' termica dei solidi, Ph:D. Dissertation, 1990.

3) Sparavigna A., Omini M., Pasquarelli A. and Strigazzi A., Thermal diffusivity of amorphous plastic materials, High Temp - High Press. **24,** 175, 1992.

4) Sparavigna A., Omini M, Pasquarelli A; Strigazzi A, Thermal diffusivity and conductivity in low-conducting materials: a new technique, Int. J. of Thermophysics, **13**, 351, 1992.

5) Omini M., Sparavigna A. and Strigazzi A., Thermal diffusivity of solids with low expansion coefficient: a dilatometric technique, Int. J. of Thermophysics, **13**, 711, 1992.

6) Giachello G., Omini M., Sparavigna A. and Strigazzi A., Thermal diffusivity in low conducting solids: a capacitive method, Physica Scripta, **42**, 439, 1990.

7) Sparavigna A., Giachello G., Omini M. and Strigazzi A., High- sensitivity capacitance method for measuring thermal diffusivity and thermal expansion: results on aluminum and copper, Int. J. of Thermophysics, **11**, 1111, 1990.

8) Omini M, Sparavigna A. and Strigazzi A, Thermal diffusivity and Biot number: a new experimental technique, Appl. Phys. A., **50**, 35, 1990.

9) Omini M., Sparavigna A., Strigazzi A. and Teppati G., A ring-source method to measure the thermal diffusivity of a conducting specimen in forced air flow: study on aluminum,
Nuovo Cimento D, **12**, 79,1990.

10) Omini M., Sparavigna A. and Strigazzi A., Dilatometric determination of thermal diffusivity in low conducting materials, Measurement Science & Technology, **1**, 166, 1990.

11) Omini M., Sparavigna A., and Strigazzi A., Calibration of capacitive cells for dilatometric measurements of thermal diffusivity, Measurement Science & Technology, **1**, 1228, 1990.

12) Omini M., Sparavigna A. and Strigazzi A., Thermal diffusivity and thermal expansion in high-conducting materials: a capacitance method, Europhysics Letters, **10**, 129, 1989.

13) Parker W.J., Jenkins R.J., Butler, C.P. and Abbott, G.L., Flash Method of Determining Thermal Diffusivity, Heat Capacity, and Thermal Conductivity, Journal of Applied Physics, **32**, 1679, 1961.

14) Cape J.A. and Lehman G. W., Temperature and Finite Pulse-Time Effects in the Flash Method for Measuring Thermal Diffusivity, Journal of Applied Physics, **34**, 1909, 1963.

15) E. MacCormack, A. Mandelis, M. Munidasa, B. Farahbakhsh and H. Sang, Measurements of the Thermal Diffusivity of Aluminium Using Frequency-Scanned, Transient, and Rate Window Photo-thermal Radiometry. Theory and Experiment, Int. J. of Thermo-physics, **18**, 221, 1997.

16) HEAT TRANSFER by J.P. Holman book published by McGraw hills companies new Delhi. 2010

17) MATERIAL SCIENCE AND ENGINEERING written by William F Smith, Javed Hasemi, Ravi Prakash.