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TECHNIQUE FOR THE DIRECT MEASUREMENT OF THERMAL CONDUCTIVITY AT HIGH TEMPERATURES BY THE USE OF A HEAT PIPE

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ABSTRACT

An experimental technique for accurately measuring thermal conductivity in the temperature range of 800° to 1500° C is presented. The procedure is capable of making a direct measurement of the heat flux and temperature drop across a sample by the use of a heat pipe to transport the heat flux. The technique eliminates many of the uncertainties associated with current methods presently employed to measure thermal conductivity at these high temperatures. Other applications of the method are also discussed.

INTRODUCTION

By definition, the thermal conductivity of a sample with a known geometry is determined by measuring the temperature gradient across the sample for a given measured heat flow through the sample. Relatively simple techniques exist for doing this at low temperatures. However, at high temperatures, where radiation losses are appreciable, it becomes very difficult to make such direct measurements because of the uncertainty in evaluating the heat flow through the sample. A number of methods have been developed at high temperatures to minimize this difficulty and they consist of (a) steady state techniques[1] (b) transient thermal techniques.[2] Although the former method employs "guard" principles to evaluate the linear or radial heat flow through the sample, practical considerations, with respect to transverse heat losses, limit the effectiveness and accuracy of this mode of measurement. The latter method avoids the problem of measuring the heat flux directly by using a time dependent thermal flux and measuring indirect parameters such as the temperature variations with time. This permits the experimenter to determine thermal diffusivity which is directly related to thermal conductivity. Both methods are limited by practical experimental problems and the difficulties increase with an increasing temperature range.

The purpose of this report is to suggest an experimental procedure which is felt to be superior to those presently employed for making high temperature thermal conductivity measurements. The technique discussed for the range 800° to 1500° C in this paper, employs a high temperature lithium filled heat pipe. The heat pipe is an engineering device which exhibits extremely high thermal conductance and was first described by Grover.[3] The characteristics of the device are achieved by containing a fluid inside an envelope, evaporating the fluid as a liquid at one end, transport of the vapor to the other end where it is condensed and returned to the original evaporator end through a wick of suitable capillary structure. Since the latent heat of vaporization and condensation of the fluids employed is very high, it is possible to transmit high heat flux down the heat pipe and still maintain a relatively minute temperature drop along the device. It behaves like an ideal isothermal heat conductor. This permits one to linearize a measured heat flux down a heat pipe through a sample and still maintain a constant temperature across any one face of the sample. The property can be exploited as an ideal experimental technique for making high temperature thermal conductivity measurements.

EXPERIMENTAL PROCEDURE

One procedure for using a heat pipe to measure thermal conductivity at high temperatures is illustrated by the details of Fig. 1. The furnace used to establish the steady state high temperature is shown as 1. It consists of two half cylinders of tantalum sheet, joined at the bottom by a heavier tantalum strap shown as 2. The a.c. currents, used to heat the furnace, are supplied through the two tantalum strips, shown as 3, which are connected to each half cylinder of the furnace. The tantalum furnace is radiation shielded by the tantalum shields shown as 4. The heat pipe illustrated in Fig. 1 as 5 is a lithium filled tantalum pipe 4 inches long, 1/2 inch diameter. It is supported by a tantalum pin 6 on a tantalum base 7. The top end cap 8 of the heat pipe is a heat transfer unit which will be described later (Fig. 2). The sample being tested is shown as 9 and a tantalum disk, which is in contact with one end of the sample and also in thermal contact with the furnace, is shown as 10. This is a relatively massive electrode used to insure good thermal contact to the sample. A high temperature thoriated tungsten filament, used for electron bombardment heating is shown as 11. A beryllium oxide insulator, 12, inside furnace 1 confines the electron bombardment heating to pipe 5 and prevents it from being dissipated in the furnace walls 1.

The heat transfer unit, 8, between the heat pipe and sample is amplified and illustrated in Fig. 2. The heat transfer unit, in this instance, is part of heat pipe A. The tantalum pieces B and C are separated by a gap D which can be either evacuated or filled with a rare gas through outlet E. The thickness of the tantalum cylinder F is small so that the heat losses across the gap are minimized. The sample to be tested is placed on C as illustrated in Fig. 1. The heat transfer unit concept has a unique property which makes it useful for thermal conductivity measurements. The heat flux through the sample can be accurately controlled by varying the environmental gas in gap D.

To determine the thermal conductivity of a sample at a given temperature, T_0, the following procedure is followed. The furnace in Fig. 1 is heated to the operating temperature T_0 by a high current a.c. source. With gap D (Fig. 2) evacuated, the heat pipe is heated by electron bombardment to a uniform temperature T_1, which in a typical case may be 25° to 50° C higher than T_0. Figure 3(a) illustrates the temperature profile attained with vacuum in the gap. If the heat transfer unit, with vacuum in the gap, is designed to have a higher thermal resistance than the sample, the temperature drop $T_2 - T_0$, across the sample will be small compared to $T_1 - T_0$. The next step in the procedure is to introduce helium, at approximately atmospheric pressure, into the gas gap. This decreases the thermal resistance of the heat transfer unit and permits more heat to travel through sample 9 of Fig. 1. If the electron bombardment power is held constant, this will result in a drop in heat pipe temperature when helium is introduced. To bring the heat pipe back up to a temperature T_1 requires additional electron bombardment power ΔW. When this is accomplished the new temperature profile shown in Fig. 3(b) is attained where $T_3 > T_2$. The thermal conductivity is then given, to a first order approximation, by the relation

$$k_s = \frac{t}{A} \frac{\Delta W}{(T_3 - T_2)} \tag{1}$$

where k_s is the thermal conductivity, t the thickness, and A the cross sectional area of the sample. Equation (1) neglects the decrease in radiation loss from the heat transfer unit in Fig. 1 when helium replaces vacuum in the gap. Since the temperature drop across this unit decreases, radiation losses decrease and ΔW would have to be corrected for this radiation loss change. The correction term can be theoretically evaluated to a good approximation by analyzing the heat problem, illustrated in Fig. 3, by the procedure described in the appendix. The final result is

$$k_s = \frac{t}{A} \frac{\Delta W}{T_3 - T_2} + \frac{t}{A} \left\{ \frac{2\pi a}{\alpha} \frac{(\cosh \alpha \ell - 1)}{\sinh \alpha \ell} S_1 + A_1 S_3 \right\} \tag{2}$$

which is a transcription of equation XV of the appendix. The symbols not previously identified have the following meaning. a is the radius of the heat transfer cylinder, α is an expression defined by equation VIII(a) of the appendix, ℓ is the length of the heat transfer unit, S_1 and S_3 are radiation terms defined in the appendix and A_1 is the area of the top of the heat transfer unit not in contact with the sample. The latter term on the right of equation (2) is obviously the correction term for equation (1).

Since the values of S_1 and S_3 depend on the total emissivity values of the given radiating surfaces and these values are generally not known too accurately, the correction term in equation (2) may, in some cases, limit the absolute accuracy of the measurement. To avoid, this difficulty, one can devise a possible alternative experiment which eliminates the radiation term. This consists of making two consecutive measurements, one with a sample of thickness t, the other with one of thickness $2t$. In both measurements helium is maintained in the gap. In the first experiment the heat flow given by appendix equation XIII results in the temperature profile shown in Fig. 3(b) as before. If the thicker sample is then tested and a mixture of He and Ar is put into the gas gap so that the temperature profile shown in Fig. 3(b) is again attained, one can determine the new heat input, as given by

$$W_M = W_{HP} + \frac{k_s A}{2t}(T_3 - T_0) + \frac{2\pi a}{\alpha}\frac{(\cosh \alpha\ell - 1)}{\sinh \alpha\ell} S_1 \left\{(T_1 - T_0) + (T_3 - T_0)\right\} + A_1(T_3 - T_0) S_3 \qquad (3)$$

which is obtained from appendix relation equation XIII. The difference in power input for both measurements is given by

$$\Delta W_1 = \frac{k_s A}{2t}(T_3 - T_0) \qquad (4)$$

or

$$k_s = \frac{2t}{A}\frac{\Delta W_1}{(T_3 - T_0)} \qquad (5)$$

ANALYSIS OF A PROPOSED THERMAL CONDUCTIVITY EXPERIMENT

In order to evaluate the proposed experiment, a specific design for the equipment shown in Fig. 1 has been analyzed. The purpose of this analysis is to determine the power requirements of the measurement, applicability of the method to materials of interest and its limits on accuracy.

The proposed furnace (1 of Fig. 1) is 7 inches high and 2 inches in diameter. The two half cylinders are made of 0.005-inch-thick tantalum. The heat pipe envelope is tantalum, filled with lithium, and is 0.5 inch in diameter and 4 inches long. The heat transfer unit is made of tantalum and is 5/8 inch in diameter and 3/4 inch long. The gas gap in the device is 0.005 inch.

From the published value for the resistivity of tantalum as a function of temperature[4] one can evaluate the resistance of the furnace at 1500° C as 24×10^{-3} ohms. Assuming a total emissivity of 0.3[4] and sufficient radiation shielding to reduce the radiation to about 1/6 of its unshielded value, one finds that it takes about 400 watts to heat the furnace up to 1500° C. This would require a high current power supply that delivers about 130 amps at approximately 3.1 volts.

The electrical circuit used for electron bombardment heating is illustrated in Fig. 4. The filament is heated with a 60 cycle a.c. source V_1 and V_0 is a d.c. power supply between the filament and the grounded heat pipe. The purpose of power source V_2, an audio source whose frequency differs from V_1, is to be able to add accurately measured incremental power to the heat pipe when a rare gas is substituted for vacuum in the gas gap.

If the electron bombardment filament is about 1 inch in diameter and operated in the space charge mode, it would take a d.c. voltage (V_0) of about 300 volts and d.c. current to 80 ma to attain a heat pipe temperature of 1525° C if the furnace temperature is 1500° C. The space charge mode is necessary if one wants to use the a.c. source V_2 for incremental heating.

An analysis of the total thermal resistance to heat flow, from the heat pipe through the sample under vacuum gap conditions, shows that

$$R^{v}_{1000} = 22 + \frac{t}{k_s A} \quad {}^{\circ}\mathrm{C}/\mathrm{watt} \quad \text{at } 1000^{\circ}\ \mathrm{C} \tag{6(a)}$$

$$R^{v}_{1500} = 19 + \frac{t}{k_s A} \quad {}^{\circ}\mathrm{C}/\mathrm{watt} \quad \text{at } 1500^{\circ}\ \mathrm{C} \tag{6(b)}$$

Helium in the gap of the heat transfer unit leads to the following relations

$$R^{H_e}_{1000} = 3.9 + \frac{t}{k_s A} \quad {}^{\circ}\mathrm{C}/\mathrm{watt} \quad \text{at } 1000^{\circ}\ \mathrm{C} \tag{7(a)}$$

$$R^{H_e}_{1500} = 3.3 + \frac{t}{k_s A} \quad {}^{\circ}\mathrm{C}/\mathrm{watt} \quad \text{at } 1500^{\circ}\ \mathrm{C} \tag{7(b)}$$

The above figures were obtained from the dimensions of the heat transfer unit, the thermal conductivity of tantalum[4] and the thermal conductivity of helium. Radiation effects were neglected.

The proposed method can best be evaluated by its applicability to insulators. From a practical point of view the thermal conductivity of insulators has always been most difficult to measure because one has to work with relatively small heat fluxes. Since the accurate measurement of low heat flux at high temperatures has always been experimentally difficult in the past and the proposed new method claims to eliminate some of these difficulties, it would seem appropriate to apply the scheme to a high temperature insulator, such as aluminum oxide and determine where the problem areas are. The best available data on high purity alumina[6] gives probable values of k as

$$k_{1000^\circ C}(Al_2O_3) = 0.063 \frac{\text{watts}}{\text{cm}^\circ\ C}, \qquad k_{1500^\circ C}(Al_2O_3) = 0.058 \frac{\text{watts}}{\text{cm}^\circ\ C}$$

Using these values of k and an arbitrary value of $A = 1\ cm^2$ and $t = 0.2$ cm, one finds from equation 6(a) that, at an ambient temperature of 1000° C and a $(T_1 - T_0)$ of 25° C, the temperature drop across the Al_2O_3 sample is 3.2° C with vacuum in the gap. When helium is inserted into the gap, 2.5 watts have to be introduced by power source V_2 (equivalent to about 80 volts rms at 30 ma rms) to raise the heat pipe temperature back up to 1025° C. The resulting temperature drop across the Al_2O_3 sample is now 11.1° C. A similar analysis at 1500° C ambient shows that the temperature changes from 4° to 11° C in going from a vacuum to a helium filled gap and the ΔW becomes about 2.1 watts.

The limits or accuracy of this proposed experiment can now be examined. Measuring ΔW of about 2.5 watts to a few percent accuracy should be no problem with the proposed method but this precision is probably not obtainable in the temperature measurements. A temperature difference of 10° C at 1000° C in a tungsten (5% Re) - tungsten (26% Re) thermocouple corresponds to 180 microvolts. Measuring this voltage to a few percent can be done if it remains stable and reproducible. However, stability and reproducibility of these temperature measurements would probably be the major difficulty and the prime source of error in the accuracy of the measurement. An accuracy of 5-10% should be possible. One could also decrease the error by working with a larger temperature difference between the heat pipe and furnace (e.g. $T_1 - T_0 = 50^\circ$ C) or a thicker sample.

The above arguments show that the proposed technique is capable of making relatively accurate thermal conduction measurements at high temperatures on insulators. From the thesis presented earlier it follows that measurements on materials with a higher conductivity would be less difficult. In this category materials having a possible application to high temperature thermoelectrics are the most interesting. Silicon carbide is a possible example of such a substance. Extrapolating the one reported thermal conductivity measurement[6] on dense SiC to higher temperatures, a value of about 0.13 watts/cm° C can be obtained at 1500° C. If equations 6(b) and 7(b) are applied to a sample with a cross sectional area of one cm^2 and a thickness of 0.2 cm, one finds that the measures ΔW of equation (1) would be 4.0 watts and the measured $(T_3 - T_2)$ would be 6° C at 1500° C. The accuracy arguments discussed previously apply in an identical manner to this case.

All the preceding computations for SiC and Al_2O_3 have neglected radiation losses from the heat transfer unit as described by equation 2. This was deliberately done to obtain order of magnitude information on the measured parameters in order to evaluate the experimental difficulties. The radiation correction term of equation (2) is evaluated in the appendix (Eq. XVIId) and its value is given as 0.11 watts/°K. If this is compared to the $\Delta W/T_3 - T_2$ value for SiC, measured at 1500° C, we find that the radiation correction would be a 16 percent correction to the uncorrected value. At lower temperatures the correction would be less because radiation becomes less important. The employment of the two sample techniques, described earlier, would eliminate this problem entirely. The only problem still present in the two sample techniques is maintaining good thermal contact but this is an inherent problem in any thermal conductivity measurement especially at elevated temperatures.

ADDITIONAL APPLICATIONS OF THE EXPERIMENTAL PROCEDURE

An obvious extension is its application to measuring thermoelectric power and electrical resistivity of thermoelectric materials. These additional measurements could easily be made in the setup of Fig. 1 by adding voltage probe leads to the equipment. In this manner figure of merit information on high temperature thermoelectrics could readily be obtained.

Since the equipment of Fig. 1 can be made relatively simple, it could be used for on-site thermal conductivity measurements on materials used in nuclear reactor applications. If one wanted to measure the change in thermal conductivity of nuclear materials with radiation dose, it could be done by designing the equipment for a test hole in a nuclear reactor system. The sample could be irradiated for a time, removed from the irradiated area, tested and then reinserted for increased dosage.

The proposed experiment could also be used to accurately measure total emissivity of high temperature materials. The only change needed in the procedure would be to make the sample long and narrow so that the radiation losses from the surface are large compared to the heat flow by conduction.

APPENDIX

The radiation loss from the heat transfer unit can be calculated from a consideration of Fig. 2. The temperature variation of its length occurs along tantalum cylinder F of Fig. 2. Heat is thermally conducted down this cylinder and also being radiated from it. We assume the temperature to the bottom of cylinder F is at the heat pipe temperature T_1 and at the top is at temperature T_2. The heat flow through the heat transfer unit is

$$W_V = W_{HP} + \frac{kA}{t}(T_2 - T_0) + W_1 + W_2 + W_3 \qquad \text{(I)}$$

where W_{HP} is the radiation and conduction losses from the heat pipe and bottom of heat transfer unit at temperature T_1. k, A, and t are respectively the thermal conductivity, cross sectional area and thickness of the sample. W_1, W_2, and W_3 are the radiation losses from the lower half of Ta cylinder F, the upper half of F, and the top part of the heat transfer unit at a temperature T_2 respectively. To evaluate W_1 and W_2 the temperature profile on the tantalum cylinder F has to be determined. This can be done to a good approximation by considering the following model. Heat is being conducted down the cylinder and being radiated to the furnace wall (assumed to be at a temperature T_0) and to the internal surfaces B and C of Fig. 2. If we take an infinitesimal element of height dz of this cylinder, we obtain for the energy balance from the lower half of the cylinder.

$$2\pi a\ kd\ \frac{d^2T_L}{dZ^2}\, dZ = 2\pi a dZ \left[S_1(T_L - T_0) - S_2(T_1 - T_L)\right] \qquad \text{(II)}$$

where a, k, d, and T_L are respectively the radius, thermal conductivity thickness of the cylinder and temperature respectively, and $a \gg d$. S_1 is the radiation term for the outside of the cylinder radiating to the furnace and S_2 is the term for the internal radiation from surface B at temperature T_1. They are a function of the relative emissivities, T_0, T_1 and the relative geometry of the surfaces with respect to each other. The resulting differential equation is

$$\frac{d^2T_L}{dZ^2} - \frac{(S_1 + S_2)}{kd} T_L + \frac{S_1T_0 + S_2T_1}{kd} = 0 \qquad \text{(III)}$$

Similarly for the upper part of the heat transfer unit, we find the differential equation for the upper temperature profile is given by

$$\frac{d^2T_u}{dZ^2} - \frac{(S_1 + S_2)}{kd} T_u + \frac{S_1T_0 + S_2T_2}{kd} = 0 \qquad \text{(IV)}$$

where we again assume there is no temperature drop through the cylinder C of Fig. 2 and it is at a constant temperature T_2. The radiation coefficient S_2 is also assumed to apply for the internal radiation term in the upper part. The two equations can be solved with the boundary condition

$$\begin{aligned} &T_L = T_1 \text{ at } Z = 0 \\ &T_u = T_2 \text{ at } Z = \ell \\ &\left.\begin{aligned} T_L &= T_u \\ \frac{dT_L}{dZ} &= \frac{dT_u}{dZ} \end{aligned}\right\} \text{at } \quad Z = \frac{\ell}{2} \end{aligned} \qquad \text{(V)}$$

and give the following result

$$T_L = B \sinh \alpha Z + C \cosh \alpha Z + \frac{S_1T_0 + S_2T_1}{S_1 + S_2} \qquad \text{(VI)}$$

$$T_u = D \sinh \alpha Z + E \cosh \alpha Z + \frac{S_1T_0 + S_2T_2}{S_1 + S_2} \qquad \text{(VII)}$$

where

$$\alpha^2 = \frac{S_1 + S_2}{kd} \qquad \text{(VIIIa)}$$

$$B = \frac{1}{S_1 + S_2}\left[\frac{S_1(T_2 - T_0)}{\sinh \alpha\ell} - \frac{S_1(T_1 - T_0)}{\tanh \alpha\ell} - \frac{S_2(T_1 - T_2)}{2 \sinh \frac{\alpha\ell}{2}}\right] \qquad \text{(VIIIb)}$$

$$C = \frac{S_1(T_1 - T_0)}{(S_1 + S_2)} \qquad \text{(VIIIc)}$$

$$D = \frac{1}{S_1 + S_2}\left[\frac{S_1(T_2 - T_0)}{\sinh \alpha\ell} - \frac{S_1(T_1 - T_0)}{\tanh \alpha\ell} - \frac{S_2(T_1 - T_2)\cosh\frac{\alpha\ell}{2}}{\tanh \alpha\ell}\right] \qquad \text{(VIIId)}$$

$$E = \frac{1}{S_1 + S_2}\left[S_1(T_1 - T_0) + S_2(T_1 - T_2)\cosh\frac{\alpha\ell}{2}\right] \qquad \text{(VIIIe)}$$

From the temperature distribution along tantalum cylinder F of Fig. 2, one can now calculate quantities W_1 and W_2 from the formula

$$W_1 + W_2 = 2\pi a \int_0^{\ell/2}\left[S_1(T_L - T_0) - S_2(T_1 - T_L)\right] dZ$$

$$+ 2\pi a \int_{\ell/2}^{\ell}\left[S_1(T_u - T_0) + S_2(T_u - T_2)\right] dZ \qquad \text{(IX)}$$

Equation IX can be solved and becomes the relatively simple expression

$$W_1 + W_2 = \frac{2\pi a}{\alpha}\,\frac{(\cosh \alpha\ell - 1)}{\sinh \alpha\ell}\, S_1\left\{(T_1 - T_0) + (T_2 - T_0)\right\} \qquad \text{(X)}$$

The expression for W_3 in equation (I) is given by

$$W_3 = A_1(T_2 - T_0)S_3 \qquad \text{(XI)}$$

where S_3 is the radiation constant for the top of the heat transfer unit radiating to the furnace at temperature T_0 and A_1 is the area of the top of the heat transfer unit not in contact with the sample. Inserting the values of W_1, W_2, and W_3 into equation I, one obtains the following expression

$$w_v = W_{HP} + \frac{kA}{t}(T_2 - T_0) + \frac{2\pi a}{\alpha}\,\frac{(\cosh \alpha\ell - 1)}{\sinh \alpha\ell}\,S_1\left\{(T_1 - T_0) + (T_2 - T_0)\right\}$$

$$+ A_1(T_2 - T_0)\,S_3 \qquad \text{(XII)}$$

for the heat loss from the heat transfer unit with vacuum in the gap.

The heat flow through the heat transfer unit with helium in the gap, w_{He}, can be similarly evaluated from the temperature profile in Fig. 3(b) to be

$$w_{He} = W_{HP} + \frac{kA}{t}(T_3 - T_0) + \frac{2\pi a}{\alpha}\,\frac{(\cosh \alpha\ell - 1)}{\sinh \alpha\ell}\,S_1\left\{(T_1 - T_0) + (T_3 - T_0)\right\}$$

$$+ A_1(T_3 - T_0)\,S_3 \qquad \text{(XIII)}$$

The difference in electron bombardment power ΔW of equation (1), is then given to a much better approximation by

$$\Delta W = w_{He} - w_v = \frac{kA}{t}(T_3 - T_2) + \frac{2\pi a}{\alpha}\,\frac{(\cosh \alpha\ell - 1)}{\sinh \alpha\ell}\,S_1(T_3 - T_2)$$

$$+ A_1(T_3 - T_2)\,S_3 \qquad \text{(XIV)}$$

or

$$k = \frac{t}{A}\,\frac{\Delta W}{(T_3 - T_2)} + \frac{t}{A}\left\{\frac{2\pi a}{\alpha}\,\frac{(\cosh \alpha\ell - 1)}{\sinh \alpha\ell}\,S_1 + A_1 S_3\right\} \qquad \text{(XV)}$$

The radiation correction will be evaluated for the case of the tantalum heat transfer unit discussed in the text, where $a = 5/16$ inch and $\ell = 3/4$ inch. The values of S_1, S_2, and S_3 are given to a reasonable approximation by

$$S_1 = \frac{5.67\text{x}10^{-12}}{\frac{1}{\mathcal{E}_1} + \frac{1}{\mathcal{E}_2} - 1} \text{ x } 4\ T_0^{\ 3} \text{ watts/cm}^2\ {}^o\text{K} \tag{XVIa}$$

$$S_2 = S_3 = \frac{5.67\text{x}10^{-12} \text{ x } 4T_0^{\ 3}}{\frac{2}{\mathcal{E}_1} - 1} \text{ watts/cm}^2\ {}^o\text{K} \tag{XVIb}$$

where $\mathcal{E}_1$, $\mathcal{E}_2$ are the total emissivity of tantalum and BeO respectively. We assume here that the top of the heat transfer unit (S_3) radiates mainly to the tantalum cap 10 of Fig. 1. Inserting the following values for parameters a, ℓ, $\mathcal{E}_1$,[4] $\mathcal{E}_2$,[6] k,[4] d, T_0, and A_1

$$a = 0.79 \text{ cm};\ \ell = 1.91 \text{ cm};\ \mathcal{E}_1 = 0.3;\ \mathcal{E}_2 = 0.5$$

$$k = 0.79 \frac{\text{watts}}{\text{cm}^o \text{ K}};\ d = 2.54\text{x}10^{-2} \text{ cm};\ T_0 = 1773^o \text{ K};\ A_1 = 1.4 \text{ cm}^2$$

into equation (VIII(a)), (XVI), and the last term on the right of equation (XV) shows that

$$S_1 = 29.2\text{x}10^{-3} \text{ watts/cm}^2\ {}^o\text{K} \tag{XVIIa}$$

$$S_2 = S_3 = 22.3\text{x}10^{-3} \text{ watts/cm}^2\ {}^o\text{K} \tag{XVIb}$$

$$\alpha = 1.60 \text{ cm}^{-1} \tag{XVIIc}$$

$$\frac{2\pi a}{\alpha} \frac{(\cosh \alpha\ell - 1)}{\sinh \alpha\ell} S_1 + A_1 S_3 = 0.11 \frac{\text{watts}}{{}^o\text{K}} \tag{XVIId}$$

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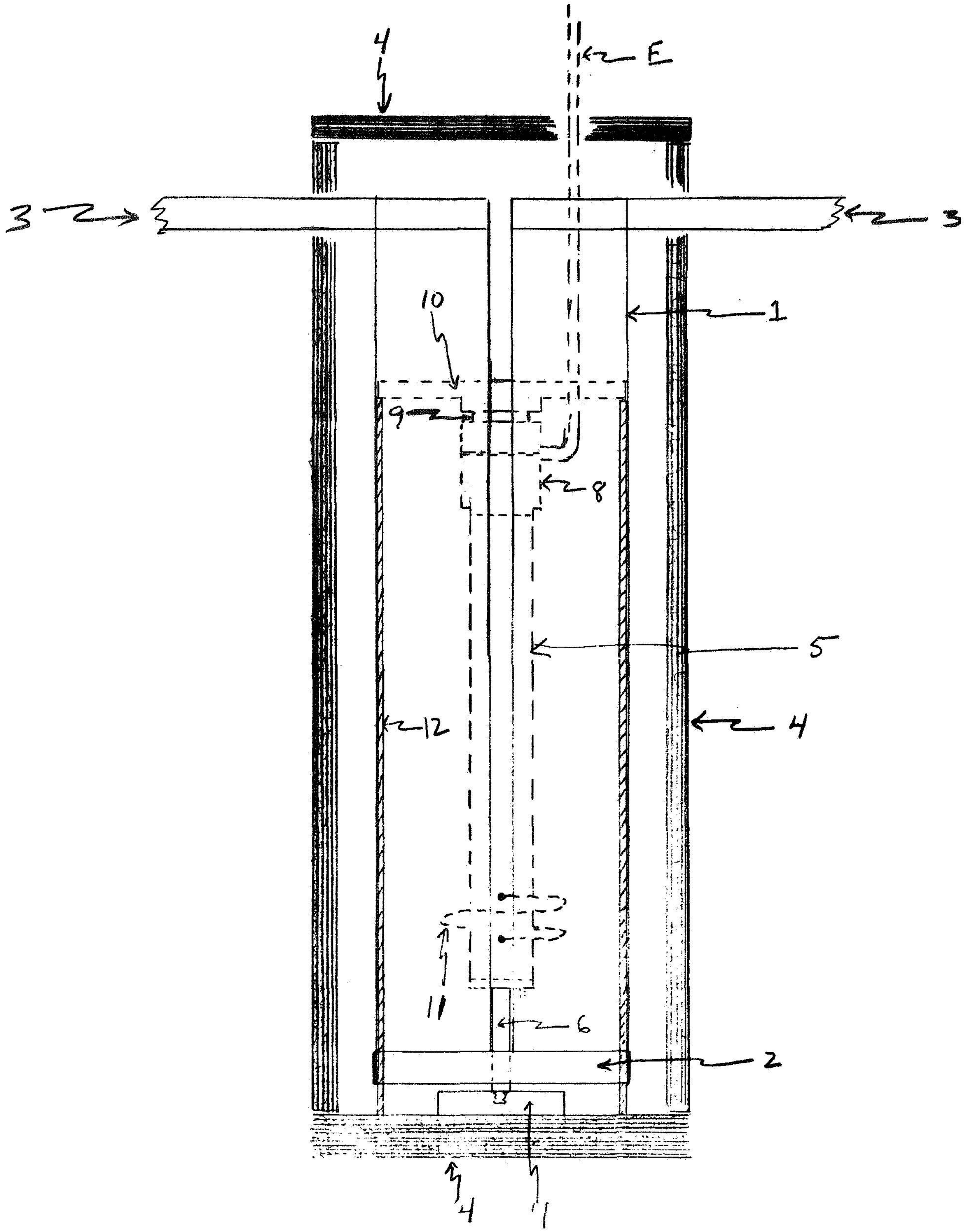


Figure 1. - Equipment for measuring thermal conductivity using a high temperature heat pipe

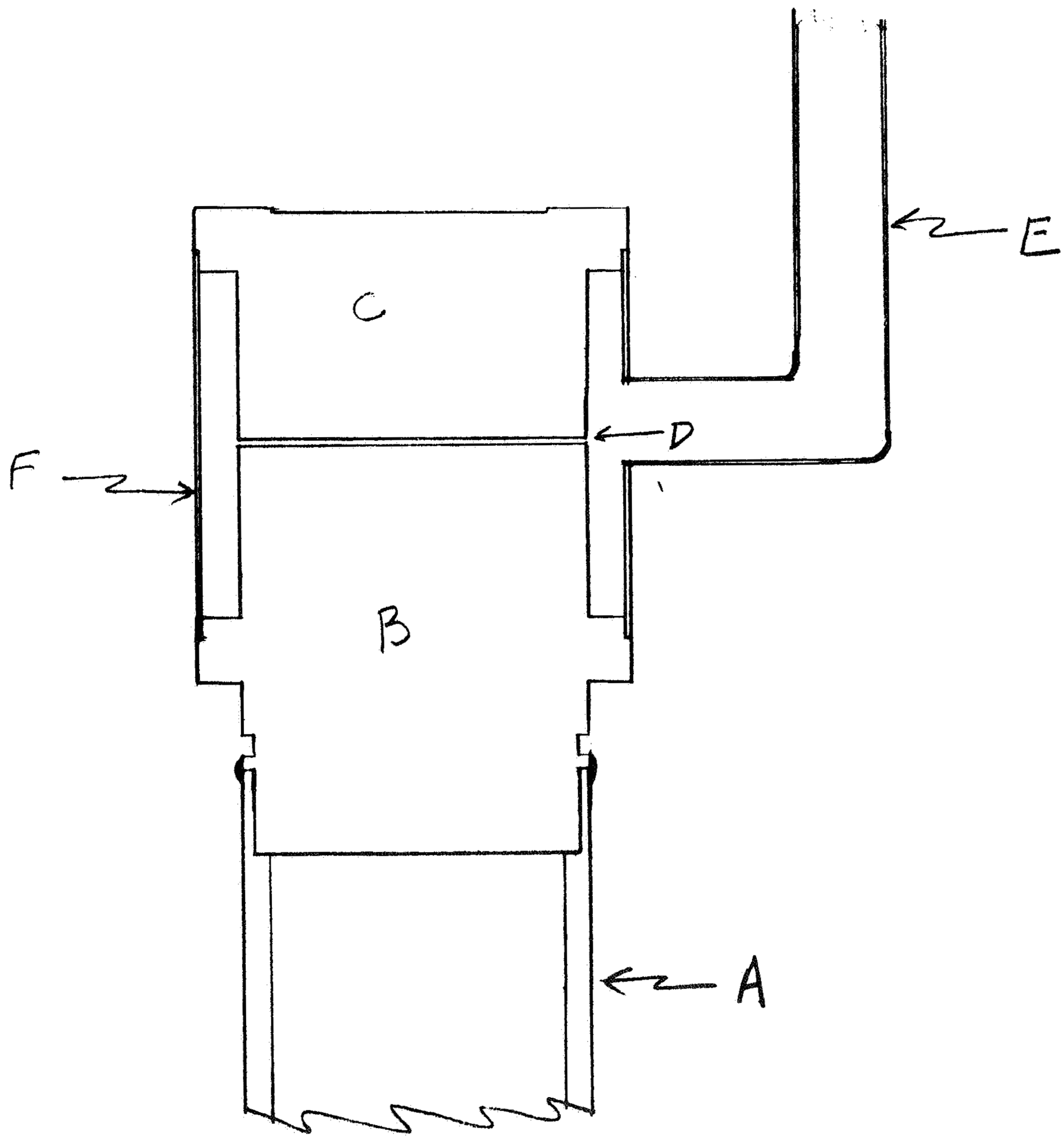
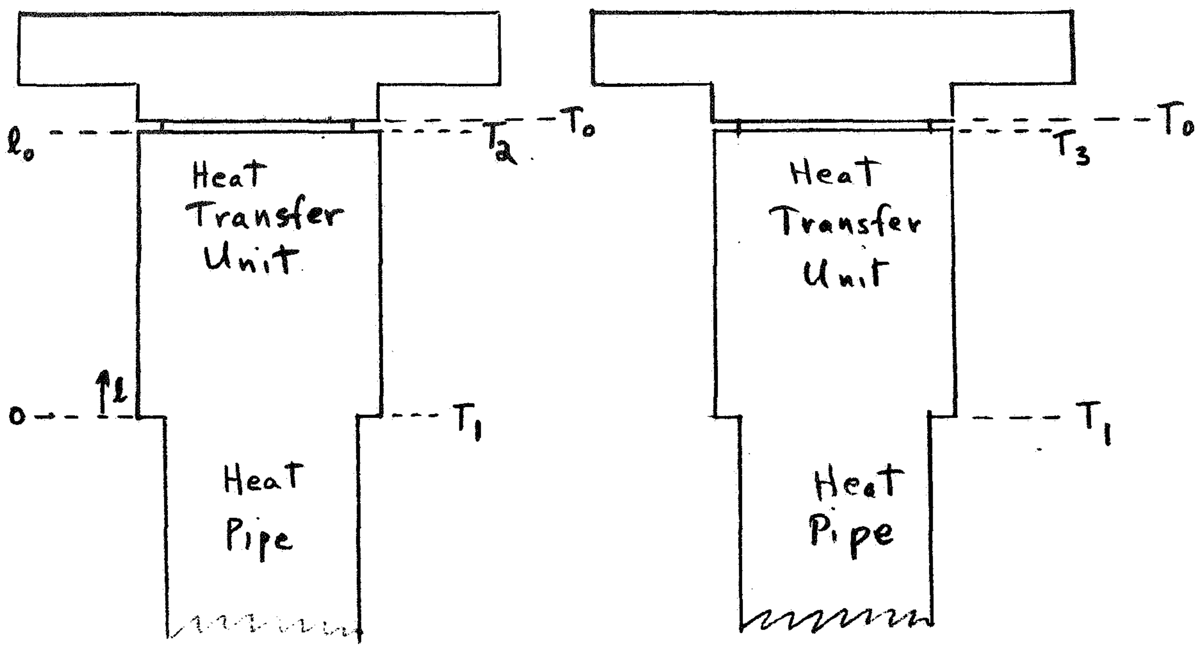


Figure 2. - Details of heat transfer unit.



(a) Gap is evacuated. (b) Gap is filled with He.

Figure 3. - Temperature profile on heat transfer.

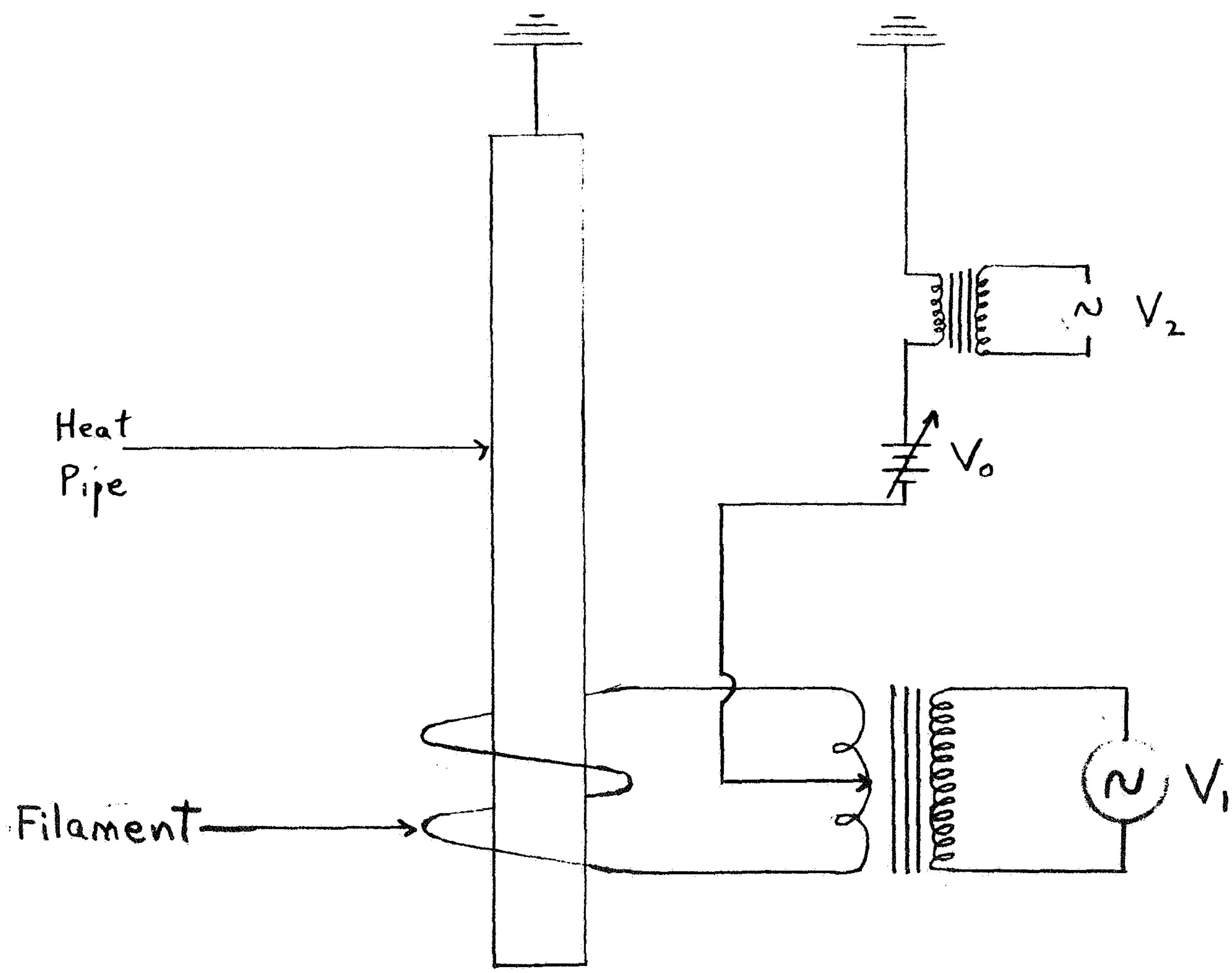


Figure 4. - Electrical circuit for heat ing heat pipe.