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SUMMARY

A simple siphon method is described for determining the resistivities of thin heat-pipe wicks as a function of the pressure difference between the liquid in the wick and the vapor above it. The method was applied to wicks of one layer and two layers of 100-mesh (40 per centimeter) stainless-steel screens diffusion bonded to stainless-steel substrates. Some possible improvements in the method are suggested.

INTRODUCTION

In the usual method of determining the resistivity of a heat-pipe wick, a test specimen is inserted into a tightly fitting passageway and a liquid is forced through it. From the pressure drop across the specimen, the volume flow rate, the dimensions of the specimen, and the viscosity of the liquid, the wick resistivity is then readily determined. For a very thin wick such as a single layer of screen bonded to its substrate, however, this method is not applicable, because when the pressure within the wick is appreciably less than that of the vapor phase above it (as in the evaporator of a heat pipe), the recessed menisci within the interstices reduce the flow cross section and thereby increase the resistivity (sketch (a)). For such a wick, the resistivity is a function of this pressure difference and of the surface tension of the liquid. Any resistivity determination in which such a thin wick is enclosed in a tightly fitting passageway would have to be invalid, since the menisci would be thereby eliminated and the measured resistivity would then be not only independent of internal pressure, but also not representative of any operating condition.

Thin wick with internal pressure almost equal to external pressure

Thin wick with low internal pressure

Sketch (a)

Another type of wick for which resistivity depends on internal pressure is the soft wick, such as blotting paper. With such a wick, an excess of external pressure over internal pressure compresses the wick, reducing its total cross section and the cross sections of the internal passages and thereby increasing the resistivity.

The present note describes a simple method of determining the resistivity of a thin wick or a soft wick as a function of the internal pressure. The method uses a small specimen of the wick in a siphon-type arrangement in which the wick is inclined so that gravity causes the liquid to flow down the wick against the wick's internal resistance. The arrangement is such that the internal pressure is uniform all along the wick.

The method was verified by tests of wicks of two different constructions, namely, a single layer and a double layer of 100-mesh (40 per centimeter) stainless-steel screen diffusion bonded to a stainless-steel substrate. Two different test lengths, 2.5 and 5.0 cm, were used for each of these two wick constructions.

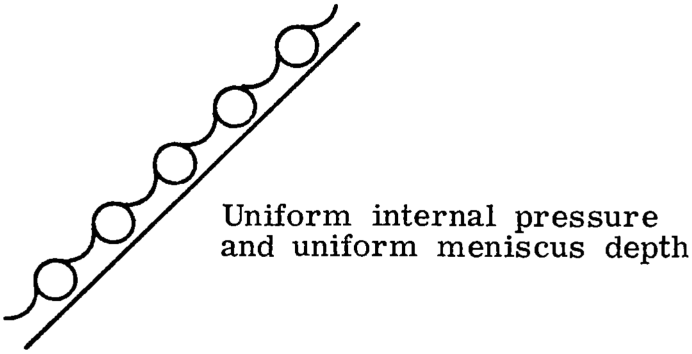
The studies described herein are essentially preliminary or developmental in nature, with a rather simple apparatus and a corresponding technique; however, the feasibility and basic simplicity of the method are considered to have been adequately established by the studies.

TEST SPECIMEN AND TEST METHOD

Test specimen.- Figure 1 depicts a mounted test specimen. The figure shows a stainless-steel plate (the substrate) in which two shallow reservoirs were cut and onto which the wick, consisting of 100-mesh (40 per centimeter) stainless-steel screen shaped as shown, was diffusion bonded. The distance between the nearest edges of the two reservoirs is the nominal wick test length. Into the bottom of each reservoir is inserted a short length of stainless-steel tubing, sealed in place with an epoxy cement.

Four such mounted test specimens were made up: two different distances between reservoirs, namely 2.54 and 5.08 cm; and two different wick constructions, namely one thickness and two thicknesses of 100-mesh (40 per centimeter) stainless-steel screen.

Test arrangement and theory.- Figure 2 shows the test setup that was used. The wick, which constitutes the only significant flow resistance in the siphon circuit, is inclined at 45°. Lengths of rubber tubing extend from the short reservoir tubes down into test tubes containing water. The test tube on the left is filled to the brim so that the water, as it siphons over into the tube, simply spills over, thereby maintaining a constant level. The test tube on the right is filled to a marked level and carefully maintained at that level by adding water, dropwise, to replace that which siphons over through the wick. The effective water levels in the two test tubes are at equal distances from the respective ends of the wick test length. Thus, the two ends of the wick are maintained at the same hydrostatic pressure, so that the rate of flow along the wick is determined only by the equilibrium between the downward-directed gravity force on the liquid and the oppositely directed wick resistance. Furthermore, the internal pressure all along the wick is uniform and known, since it must equal the pressure applied to the two ends (sketch (b)).



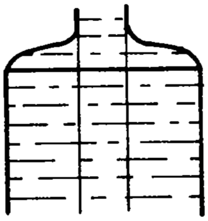
Sketch (b)

Test procedure.- Essentially the tests consist of measuring, for several heights h of the wick above the test tubes, the times required for 1 ml of water to siphon over. In general about four or five different wick internal pressures (or different heights h of the wick above the water level in the test tubes) were used, starting with the least suction (the smallest height). Water was added to the right-hand test tube until its level was slightly above the mark, and a stopwatch was started when the bottom of the meniscus fell to the mark. Water was added, dropwise, to keep the meniscus at the mark. The time required to add a total of 1 ml of water was noted and, without stopping the watch, a second milliliter of water was started, and so on. Usually, 3 or 4 ml were added altogether in this way, mainly in order to check the reproducibility of the time measurements.

After the measurements for the least suction were completed, the siphon was raised about 2 to 3 cm and another set of measurements was made. Further sets of measurements were made with successively greater suction heads until either (a) the suction was enough to draw air through the wick into the reservoir and tube and thereby break the siphon, or (b) the flow rate became very low, often also irreproducible.

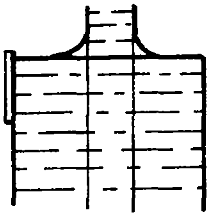
Notes on the technique.- Following are several notes concerning the technique. They may not all apply when more sophisticated setups are used.

(1) As the water siphons over into the lower test tube, a convex meniscus forms at the top (sketch (c)), which - when it is high enough - suddenly overflows with a sudden small, but appreciable, reduction in meniscus height. The internal pressure at the lower end of the wick drops correspondingly, so that



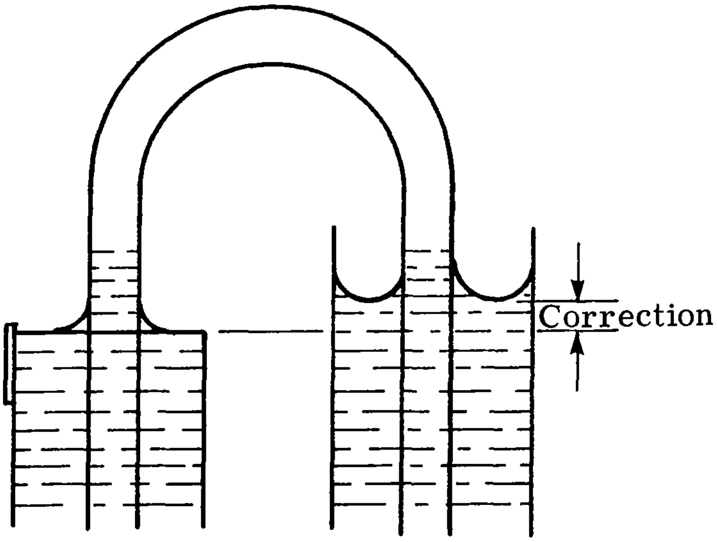
Sketch (c)

the pressure is no longer quite the same at both ends of the wick. The problem was eliminated by attaching a tiny strip of blotting paper to the outer edge of the test tube. The strip, about 1 mm wide and 1 cm long, is attached so that it protrudes about 1 mm above the edge (sketch (d)). Then as the water is siphoned into the test tube, the level is maintained constant by a small stream of water that extends across the test-tube rim to the blotting paper, which siphons it away and lets it run down the outside of the test tube.



Sketch (d)

(2) In the upper test tube, a concave meniscus raises the water level about 2 to 3 mm above the zero-pressure level. This height correction is determined by connecting a piece of the tubing as a siphon between the two test tubes, and at equilibrium (no flow) measuring the difference in height between the water levels in the two test tubes (sketch (e)).



Sketch (e)

(3) The tiny menisci in the screens over the reservoirs cannot withstand quite as much suction as the menisci in the bonded wick. Furthermore, they are especially vulnerable during a height adjustment, since a slight upward jerk of the test specimen can draw air through the screen and spoil the siphoning action. In order to minimize these problems, a small pad of paper, made of about 24 thicknesses of facial tissue, was placed over each reservoir. Since the pads extend beyond the edges of the reservoirs and have relatively small resistivity,

the effective test lengths of the wicks are thereby reduced to less than the distance between the nearest edges of the two reservoirs. It is this reduced length that is shown as the effective wick length in figure 2. This item is discussed further in a later section of this report.

(4) Evaporation from the wick during a test introduces a small inaccuracy. A separate test with a horizontal nonsiphoning 5.08-cm wick showed an evaporation rate of about 0.4 ml/hr. Presumably, during a siphoning test, half of this evaporation would occur upstream of the wick midpoint and half would occur downstream of the wick midpoint. At the midpoint, where the average flow exists, the corresponding reduction in flow rate for the wicks should then be 0.2 ml/hr. Thus, for example, in a test of a 5.08-cm, one-layer wick in which 1 ml of water is added dropwise to the upper test tube in about 6 minutes, the average flow along the wick over this period is actually less than 1 ml by the amount $0.2 \times 6/60 = 0.02$ ml. For a true average flow of 1 ml, then, the time should be increased by 2 percent. The corrections would be less for the 2.54-cm wicks (less evaporation area) and for the two-layer wicks (less time).

(5) Another effect of evaporation is that it reduces the temperature of the wick below that of the ambient air and of the "feed water" in the upper test tube. Surface tension (which determines the depth of the menisci) is not greatly increased by such a temperature reduction, but viscosity is significantly increased - about 12 percent for a 5° C temperature reduction. After the present small test series was completed, a thermocouple was attached to the bottoms of the substrates of both longer test specimens, and temperature measurements were made while some of the siphoning tests were repeated. It was found that, for the then existing laboratory conditions, wick temperatures were indeed nearly 5° C below that of the room and of the feed water. The difference corresponds to a viscosity increase of about 10 to 11 percent and a corresponding resistance increase of the same amount. During some of the earlier tests, the air humidity was very low and the temperature difference may well have been greater. It is apparent, then, that wick temperature readings are essential if consistent sets of resistivity determinations are to be obtained.

(6) In making the setup, the siphon must be filled with water without leaving air bubbles in the reservoirs or tubes. In the present work, the filling was accomplished by putting the specimen upside down into a dish of water and applying suction to the ends of the rubber tubes.

TEST RESULTS

The test results are shown in figure 3, where the time for 1 ml of water to siphon over is plotted against the suction head (the internal wick pressure). Each point represents the average of three to five measurements, the scatter of which seldom exceed ±2 percent from the average. The same results, converted to resistivity, are plotted in figure 4. Resistivity is here defined as

$$\text{Resistivity} = \frac{\Delta p_r w}{\ell \mu V}$$

where

w	wick width, cm
ℓ	wick length (between pads), cm
μ	liquid viscosity, poises, (1 poise = 1 dyn-sec/cm^2)
V	volume flow rate, cm^3/sec
Δp_r	resistance pressure drop, dyn/cm^2

In the present method Δp_r is the increment in gravity head between the upper and lower ends of the wick test length, $\rho g \ell \sin 45^\circ$, where

ρ	liquid density, g/cm^3
g	acceleration of gravity, 980 cm/sec^2

In these cgs units, resistivity has the dimension centimeter^{-3}. Estimated corrections for evaporation and for temperature have been included in the computation of the resistivities plotted in figure 4.

Each of the four sets of wick test data plotted in figure 3 shows considerable internal consistency, since the points lie on smooth curves - which are nearly straight lines, except for the very last points on two of the curves (the curves for the one-layer, 2.5-cm wick and the two-layer, 5-cm wick). No measurements at higher suction were attempted for these two curves, since these two points were clearly close to the ends of the useful ranges of operation of the wicks; in fact, operating at even these two points would not be considered safe. For each of the other two wicks, the siphon broke (that is, air was pulled through the wick) at the last point while the fourth milliliter was being added. These two points, then, must be considered as slightly beyond the useful ranges of operation of the two wicks.

The bottom curve of figure 3 was obtained after the other tests were completed, in an effort to verify the assumed low resistance of the paper pads. A sheet of the facial tissue was folded to provide the same number of thicknesses as the pads, and it was then cut to a shape like that of the screen wick shown in figure 1. It was then superimposed on the 5.08-cm, one-layer wick and tested in the same manner as the wicks. In effect, the test determined the resistivity of the combination of the one-layer wick and the paper pad in parallel. The results are similar to those for the screen wicks; also, again the siphon broke after two time measurements at the last point (highest suction). The curve is not low enough to justify the assumption that the pads had negligible resistivity; rather, it indicates that the pads had about the same resistivity as the two-layer wicks. When the pad was used with the one-layer wick, the resistivity of the combination was about 0.25 to 0.30 times that of the one-layer wick, which is in roughly satisfactory agreement with the assumption; when it was used with the two-layer wick, the resistivity of the combination was about 0.5 times that of the two-layer wick alone, which is much less satisfactory.

Both the curves for the 5.08-cm wicks lie well below the corresponding curves for the 2.54-cm wicks. In both cases, the differences seem rather more than can be explained by temperature and humidity differences (high humidity would reduce evaporative cooling of the wick). Possibly the differences reflect slight differences in the diffusion-bonding conditions for the short and the long wicks. However, since these tests were only developmental, no effort was made to exercise the usual extreme care in purifying the liquid, cleaning the wick, and avoiding contamination that characterizes careful heat-pipe research. Accordingly, thorough analysis and discussion of the present data are hardly justified.

EFFECT OF REYNOLDS NUMBER

For flow rates near those of the present tests, Reynolds-number effects should be negligible. A simple pair of tests was made to verify this fact:

(1) A test similar to those previously described and illustrated in figure 2. Only one suction head (4.60 cm of water) was used.

(2) A similar test with the same suction head but with the slope of the wick reduced from 45° to 20°42' in order to halve the pressure gradient

$$\left(\sin 20^{\circ}42' = \frac{1}{2} \sin 45^{\circ}\right).$$

In the second case, with the pressure gradient halved, the flow rate should be halved, or the time for 1 ml of water to siphon over should be doubled. The mean measured times were, respectively, 6.4 minutes and 12.4 minutes. The second reading is approximately twice the first, and correcting for evaporation would make the agreement even better. Such excellent agreement is perhaps fortuitous, but in any case the comparison is sufficient not only to indicate that scale effect on resistivity is negligible in this small range, but also to demonstrate a degree of internal consistency in the test results.

As exemplified by this agreement, Darcy's law of constant resistivity, originally used in studies of ground-water seepage, has been generally found applicable to low-speed flows along wicks, for which the local Reynolds numbers in the flow passages are very low. The local Reynolds numbers involved in the present studies, and also in many practical heat-pipe applications, are, in fact, very low. If the one-layer wick is assumed to contain 40 parallel tubes per centimeter of width, each 1/80 cm in diameter, the Reynolds numbers of the flow through the tubes in these 45° slope tests are of the order of 0.4. The Reynolds numbers must be much larger before there is significant deviation from Darcy's law of constant resistivity; accordingly, low-Reynolds-number studies like those described herein would provide results that are applicable to many heat pipes designed for low or medium rates of transfer.

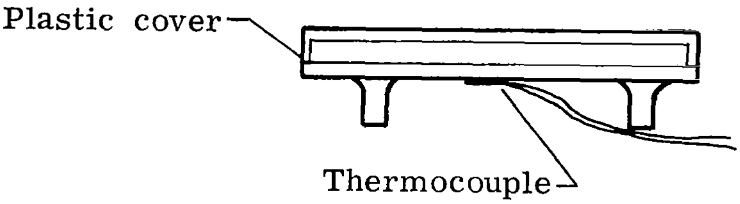
This constant-resistivity range, however, may well be exceeded in heat-pipe evaporators with high rates of heat transfer, in which the liquid is nearly completely evaporated within a few millimeters from the foot of the artery pedestal. Such high heating rates are quite possible and have been demonstrated for wicks of the present type with heat supplied by an acetylene flame. Local flow Reynolds numbers for these high heating rates may be of the order of 100, for which resistivities measured at Reynolds numbers of 0.4 would hardly be applicable.

Such high heating rates, however, do not actually seem to represent cases of practical interest. Heating rates of about one-tenth as much (65 to 70 W/cm^2) are more representative of practical "extreme" cases; and cooling for such cases by means of one-layer wicks has been demonstrated. Correspondingly, with one-tenth as much flow rate, the Reynolds number would be reduced and the resistivity is much more likely to be close to that measured in tests such as those herein described.

SUGGESTIONS FOR DESIGN MODIFICATIONS

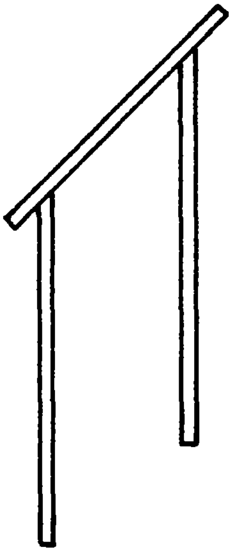
Some modifications of the design or technique have already been indirectly suggested in the preceding text. The most important of these are means of preventing evaporation from the wick and a means of measuring the wick temperature. For preventing evaporation, it is not necessary to enclose the entire setup; a small clear plastic cover over the top, as indicated in the sketch, ought to suffice. The wall of the plastic cover must not be in contact with the edge of the wick. (See ref. 1.)

A thermocouple, spot-welded to the wick substrate (sketch (f)) is a simple approach to measuring the wick temperature.



Sketch (f)

Figure 2 shows rather sharp bends in the rubber tubing just below the wick support. The strong tendency of these bends to straighten out made every test setup somewhat precarious. Long stainless-steel tubes inserted into the reservoirs at an angle of 45° (sketch (g)) would obviate this problem and make the apparatus easier to use.



Sketch (g)

It might be best to replace each paper pad with a single thickness of a soft thin paper, and consider the wick length as the total distance between the closest edges of the reservoirs. If this distance is at least 5 cm, the small uncertainty in defining the effective wick length should not be significant.

CONCLUDING REMARKS

A relatively simple method has been described for determining the resistivity of thin heat-pipe wicks as a function of the internal pressure. The method provides resistivities for low-speed flows through the wick; however, the results are probably satisfactorily applicable over the entire operating ranges of most heat pipes. Resistivities were measured for one- and two-layer, 100-mesh (40 per centimeter) stainless-steel wicks bonded to stainless-steel substrates. Suggested improvements in the apparatus are mainly for the purposes of simplifying its adjustment and avoiding problems caused by evaporation.

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Hampton, VA 23665
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1. Phillips, E. C.: Low-Temperature Heat Pipe Research Program. NASA CR-66792, 1969.

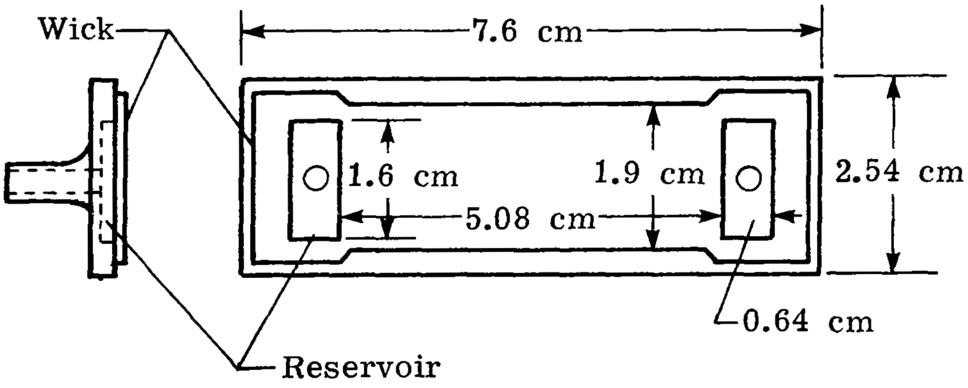

Figure 1.- Wick sample mounted on the support.

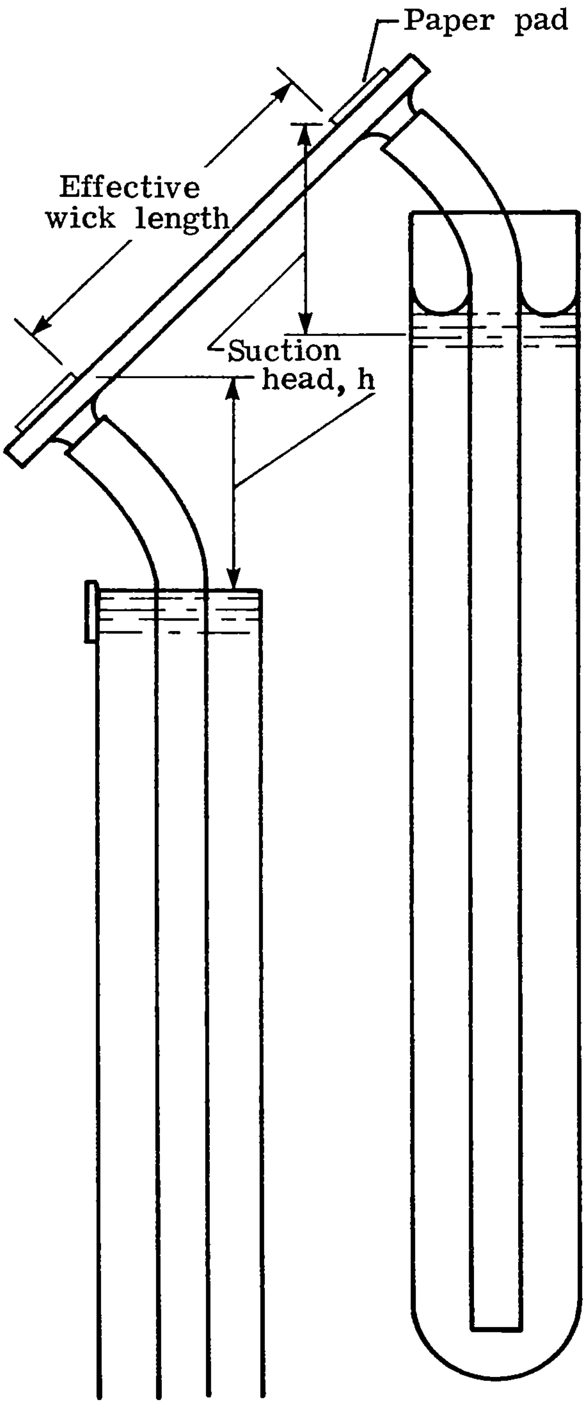

Figure 2.- Test arrangement.

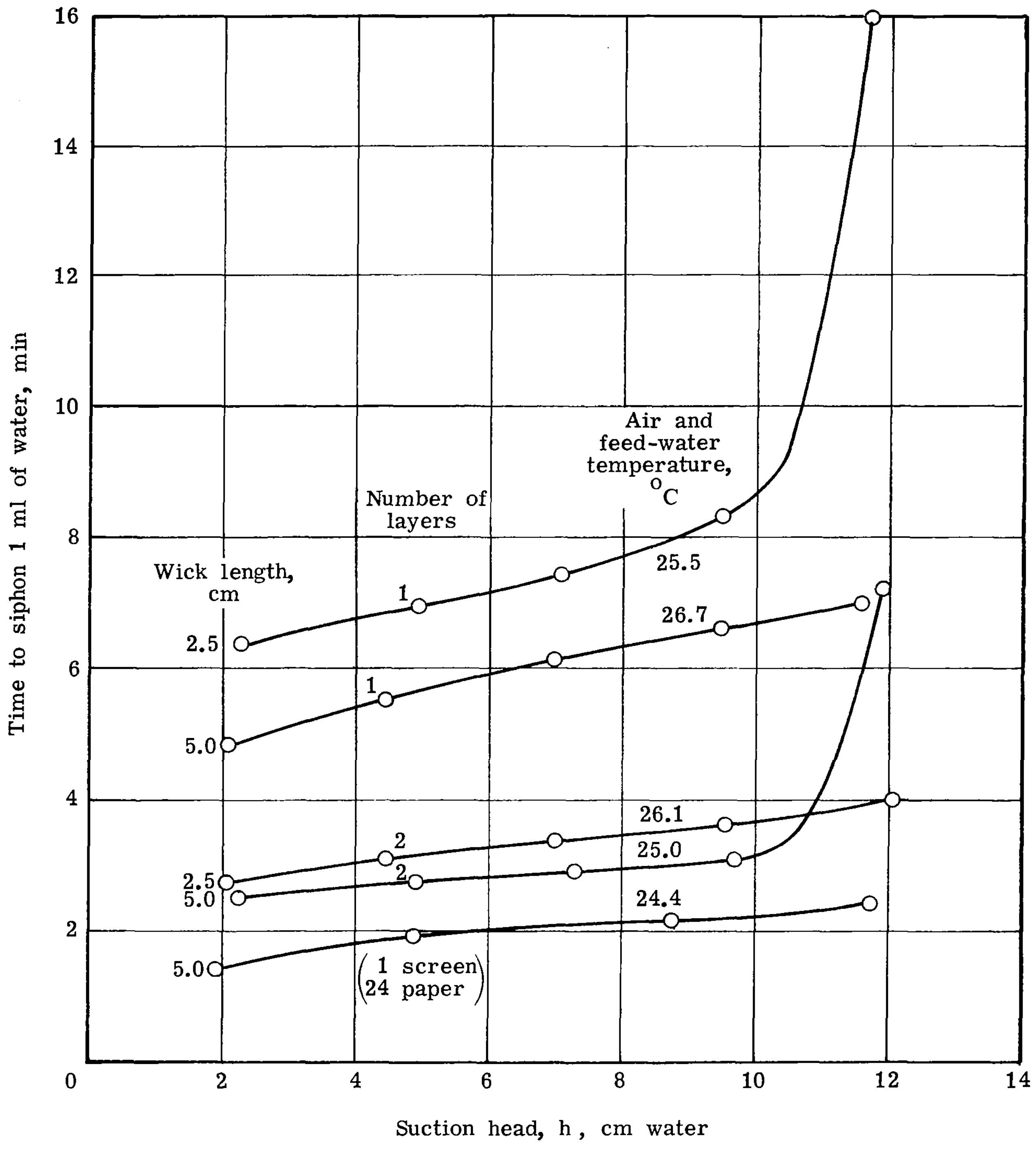

Figure 3.- Experimental data: time for siphoning 1 ml of water plotted against suction head.

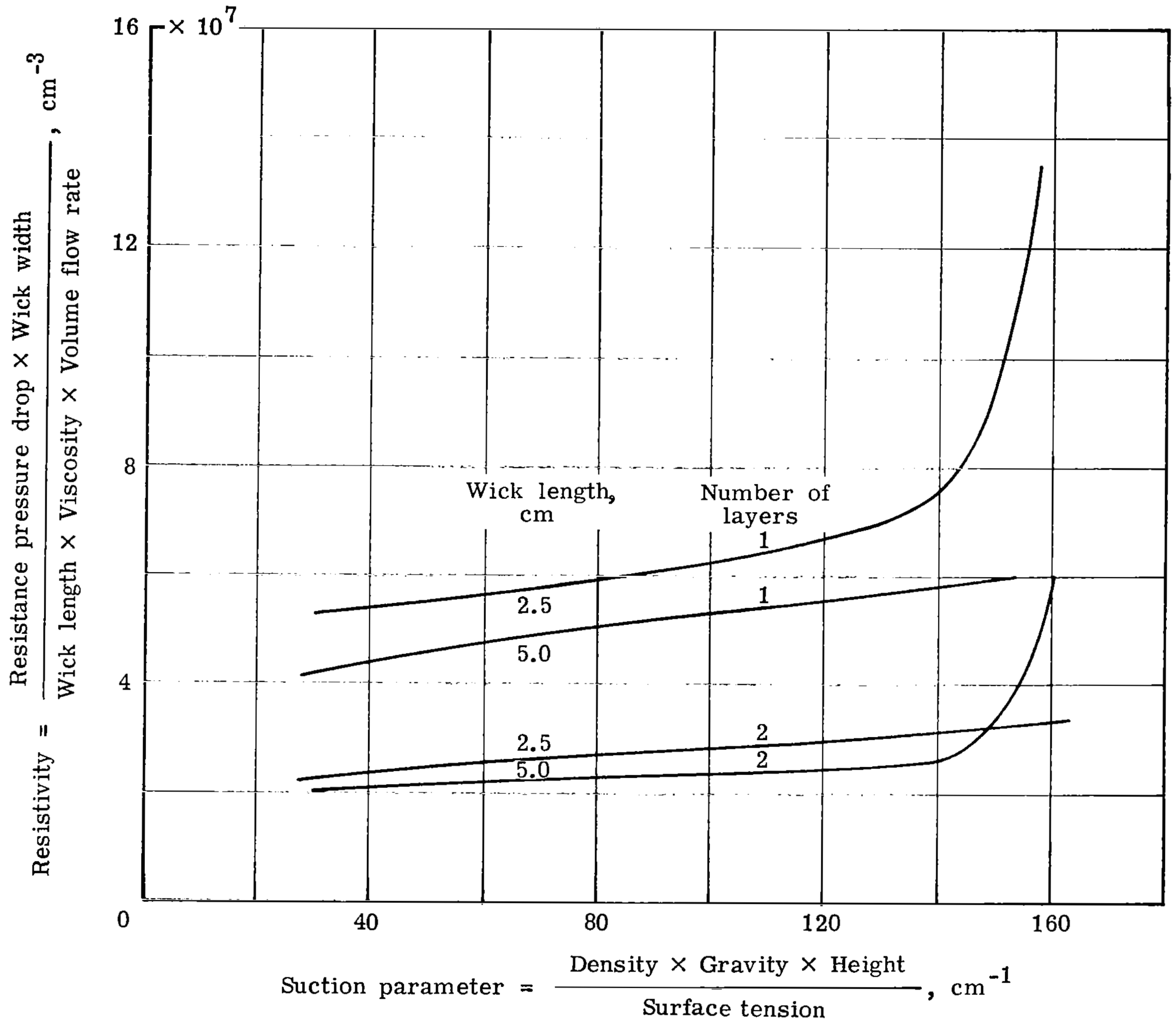

Figure 4.- Resistivity against suction parameter.

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16. Abstract

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