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A DEVICE FOR RAPID DETERMINATION OF THERMOPHYSICAL PROPERTIES OF PHASE-CHANGE WIND-TUNNEL MODELS

Theodore R. Creel, Jr.

Langley Research Center
Hampton, Va. 23665

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16. Abstract

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Several tests were performed on model materials with heat-transfer rates varying from 11.34 to 177 kW/m^2. Duration of heating was either 3 or 30 sec (each data run consisted of 30 data points or frames) depending on magnitude of heat-transfer rate. Combined thermophysical properties of the model materials ranged from 0.65 to 1.5 $kJ/m^2\text{-}K\text{-}sec^{1/2}$. The experimental data agreed reasonably well with combined thermophysical properties obtained from the standard steady-state method. The apparatus produced consistent and accurate data over the range of materials tested.

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SUMMARY

An experimental method for direct measurement of the thermophysical properties of wind-tunnel heat-transfer models has been developed. The technique consists of placing the model under a bank of high-intensity, radiant heaters so that the fast-opening water-cooled shutters, which isolate the heater bank from the model, allow a step-input heat rate to be applied. Measurements of the heat-transfer rate coupled with a surface-temperature time history of the same material are sufficient to determine the material thermophysical properties. An infrared thermometer is used to measure model surface temperature and a slug calorimeter provides heat-transfer rate information. The output from the infrared thermometer and calorimeter is then fed into an analog-to-digital converter which provides digitized data to a computer. This computer then calculates combined thermophysical properties and a teleprinter prints out all the data. Thus, results are available within 7 minutes of test initiation as opposed to the weeks or months required using prior techniques.

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from the standard steady-state method. The apparatus produced consistent and accurate data over the range of materials tested.

INTRODUCTION

In 1960 a method of measuring qualitative aerodynamic heat-transfer rates over an entire model surface was reported in reference 1. This method utilized a temperature-sensitive coating, which changed color within a known temperature range, to indicate model surface temperature. Improvements to the technique which made possible quantitative measurements of heat-transfer rates were reported in reference 2. This phase-change paint technique utilized a temperature-sensitive coating which changed phase from an opaque solid to a clear liquid at a precisely known temperature to indicate the temperature at the surface of a solid model. If the model wall is assumed to be a semi-infinite slab, heat-transfer coefficients can be determined from the following equations:

$$h = \sqrt{\rho c k}\,\frac{\beta}{\sqrt{t}} \tag{1a}$$

and

$$\frac{T_s - T_i}{T_{aw} - T_i} = 1 - e^{\beta^2}\,\mathrm{erfc}(\beta) \tag{1b}$$

where erfc is the complementary error function; T_s is the known model surface temperature at the time t at which the phase change occurs; T_i is the initial model temperature at time $t = 0$; T_{aw} is the local fluid adiabatic-wall temperature; and ρ, c, and k are, respectively, the density, specific heat, and thermal conductivity of the model material. The parameters T_{aw}, T_s, T_i, and t are wind-tunnel test dependent; the thermophysical properties parameter $\sqrt{\rho c k}$, however, must be determined apart from the wind-tunnel test.

The work reported in references 3 and 4 has resulted in methods to improve the accuracy of determining the wind-tunnel dependent parameters. However, reference 3 emphasized the need for accurate knowledge of the thermophysical properties parameter. An examination of equations (1a) and (1b) indicates the direct (1:1) relationship between the accuracy of the known thermophysical properties parameter and the accuracy of the indicated heat-transfer coefficient.

The method which to date has been used to measure model material thermophysical properties is the steady-state measurement of material bulk average values of ρ, c, and k measured independently on sample blocks of the model material. These laboratory analyses are both time-consuming and expensive. In addition, bulk average thermal properties may not be appropriate for reduction of phase-change data.

Figure 1 is a photomicrograph (from the unpublished data of L. L. Trimmer and R. K. Matthews, Arnold Engineering Development Center) of a Stycast plastic sample cut from an actual wind-tunnel model. This material is a mixture of epoxy and alumina, two materials which vary substantially in thermal properties. Figure 1 illustrates the variation of properties that could occur with material depth in a wind-tunnel model. At the surface, the quantity $\sqrt{\rho ck}$ would approach that of the alumina since this material has migrated toward the sample surface. With increasing depth, $\sqrt{\rho ck}$ would approach that of the epoxy. Steady-state values of $\sqrt{\rho ck}$ would provide only an average value for the model, not the surface $\sqrt{\rho ck}$. Also, if the material used in casting was not mixed sufficiently, there could be variations of $\sqrt{\rho ck}$ over the surface of the model resulting in erroneous heat-transfer coefficients.

Although the sample blocks used for steady-state property measurements were cast from the same material batch as the wind-tunnel model and underwent the identical cure cycle, thermophysical properties might vary from model to sample. Thermal conductivity and specific heat of some model materials also vary with temperature; thus $\sqrt{\rho ck}$ would vary as a function of depth within a model as heat

penetrated the model material. Therefore, a nondestructive method whereby the thermophysical properties could be obtained directly from the model was needed. Reference 5 reported the development of a nondestructive thermophysical properties measurement (TPM) apparatus which used an "inverse" phase-change paint technique and a radiant heat source. Data gathering and reduction when using the nondestructive TPM apparatus was automated (ref. 6) by adapting an infrared thermometer, analog-to-digital converter, a digital computer, and a teleprinter to the system.

The TPM apparatus was used to measure the quantity $\sqrt{\rho ck}$ for three materials. This report presents a description of the apparatus, a discussion of the measurement techniques, and the results of measuring $\sqrt{\rho ck}$ for three model materials.

SYMBOLS

c	specific heat, J/g-K
erfc	complementary error function
h	aerodynamic heat-transfer coefficient
k	thermal conductivity, W/m-K
$\dot{q}$	heat-transfer rate, W/m^2
T_{aw}	adiabatic-wall temperature, K
T_i	initial temperature of model, K
T_s	surface temperature of model, K
t	$= t_1 - t_0$ where t_0 is initial time

t_1 time during test, sec

t_2 total test time, sec

x test-plane coordinate normal to specimen rows, m (see fig. 2)

y test-plane coordinate along specimen rows, m (see fig. 2)

β parameter in equation (1)

ρ density, g/m^3

APPARATUS AND TEST PROCEDURES

Basic Apparatus

The experimental apparatus was designed based on the need to measure the thermophysical properties $\sqrt{\rho ck}$ as defined in the following equation:

$$\sqrt{\rho ck} = \frac{\dot{q}}{T_s - T_i} \frac{2}{\sqrt{\pi}} \sqrt{t} \tag{2}$$

Derivation of equation (2) (ref. 7) was based on the conduction of heat into a semi-infinite slab which was assumed to have a uniform initial temperature and a constant impressed $\dot{q}$. The quantities that are needed for the solution of equation (2) are initial temperature, sample surface temperature, test time at a particular surface temperature, and heat-transfer rate. All of these quantities can be measured using the thermophysical properties measurement (TPM) apparatus.

Figure 2 is a schematic of the basic TPM apparatus. This figure shows the arrangement of heat source, isolating shutters, reference calorimeter, and the test samples as reported in reference 5. The TPM apparatus has an aluminum housing which supports four high-intensity, modular, radiant heat sources. Each heat source consists of six tungsten filament lamps installed in a water-cooled reflector housing. The tungsten filament lamps are forced air cooled. The radiant heating rate can be varied from 11.35 to 1138 kW/m^2 by varying the lamp voltage. Supporting the lamp housing is a 0.0254-m-thick base plate with 10 symmetrically spaced holes which hold the calorimeters (used to measure heat-transfer rate) and samples. The present sample holder can accommodate five 0.0381-m-diameter by 0.0172-m-thick samples and an equal number of calorimeters. Water-cooled shutters isolate the sample holder from the radiant heat source so that a step input in heat-transfer rate may be applied to the calorimeter and sample simultaneously. The shutters are held closed by two locking handles which are keyed together so that the shutters will open simultaneously.

Associated Equipment

The basic apparatus may be used with a phase-change paint to indicate sample surface temperature at some time t and thereby determine $\sqrt{\rho ck}$. However, inclusion of the following equipment (see fig. 3) provides improved accuracy and greatly reduced data-reduction time.

Infrared thermometer.- An infrared thermometer (fig. 3(a)) is used to measure surface temperature and has a temperature range of 286 K to 536 K. The infrared thermometer has a field of view of 0.7° which measures the temperature over a 0.01016-m-diameter target spot at a distance of 0.508 m.

Two-channel analog-to-digital converter.- A two-channel analog-to-digital converter (fig. 3(b)) receives the output voltage from both the infrared thermometer and the reference calorimeter

and converts these voltages into digital form so that a digital computer can use the data.

Digital computer.- The digital computer (fig. 3(b)) used in the TPM apparatus is a small general purpose computer with 4096 words of core memory. This computer stores the digitized temperature, heating-rate data, and time. The software for the computer reduces this digitized temperature, heating-rate data, and time to the product $\sqrt{\rho ck}$ through the solution of equation (2).

Teletype.- After computations have been completed, the average heat-transfer rate, model surface temperature, time, and $\sqrt{\rho ck}$ are listed by the teletype (fig. 3(b)).

Radiation absorption filter.- Because the radiant heat source will be at a temperature of 3303 K, it will emit a large amount of radiation over the passband of the infrared thermometer. (See ref. 8.) The envelopes of the lamps are made of high-temperature quartz (consisting almost entirely of silica) which absorbs most of the radiation at wavelengths within the infrared-thermometer passband. This absorbed radiation, however, raises the quartz-envelope temperature considerably higher than the lowest temperature to be measured by the infrared thermometer. Therefore, the quartz envelope radiates at wavelengths extending over the passband of the infrared thermometer and such radiation can represent a significant noise source. This noise source is eliminated by using a radiation absorption filter (fig. 3(c)) in which water is forced between two parallel glass plates. The water layer absorbs all wavelengths within the passband of the infrared thermometer (ref. 8); thus, the infrared thermometer will indicate the correct model surface temperature.

Models

The sample had a 0.0381 m diameter and was 0.0127 m thick. Each sample and calorimeter used in the TPM apparatus was coated with a high-temperature, high-absorptivity black paint (ref. 5) so that the samples absorbed as much heat energy as the calorimeter.

In this description only small samples have been discussed, but, as previously stated, the TPM apparatus is a nondestructive method of obtaining $\sqrt{\rho ck}$ for actual wind-tunnel models. These wind-tunnel models require a modified holder plate to support the wind-tunnel model and one reference calorimeter. Positioning will be difficult because of the curved wind-tunnel model surfaces; therefore, the experience gained in the present tests can be quite useful when designing a sample holder plate to support a wind-tunnel model.

Operational Procedure

Data were collected by carefully following the procedures outlined in references 5 and 6. These procedures are briefly outlined in this section. Refer to figure 3 for equipment identification.

(1) The sample and calorimeter are painted with black, high-temperature, high-absorptivity paint which is allowed to cure according to manufacturer's specifications.

(2) The sample and calorimeter are placed in the sample holder plate and are adjusted so that test surfaces are parallel with and in the same plane as sample holder surface.

(3) The infrared thermometer is sighted onto the sample, focused, and fixed into position.

(4) A surface-contacting thermometer is used to record initial sample temperature.

(5) Water-cooled shutters are closed and locked.

(6) Initial data are typed into the digital computer using the teletype. Input constants are initial sample temperature, a calorimeter constant, a thermocouple millivolt conversion constant, and a time constant.

(7) The power source is turned on and lamp voltage adjusted so that the desired heat-transfer rate is obtained. Time is allowed for the radiant heat source to reach a constant temperature.

(8) The test is now ready to begin. The water-cooled shutters are released. Calorimeter temperature, sample surface temperature,

and time are stored in the computer. Heat-transfer rate and thermophysical properties are computed and printed out by the teletype.

Error Sources

Since $\sqrt{\rho ck}$ data could be affected by any of the following error sources, care is taken in collecting the data and in preparing the samples to minimize these errors.

As previously mentioned, the sample and calorimeter were coated with a high-temperature, high absorptivity black paint to insure that the sample absorbed as much heat energy as the calorimeter. The surface of the water-cooled shutters and the inside of the TPM apparatus were also coated with a flat black paint (low reflectance) so that the infrared thermometer read a normal, low temperature prior to test initiation.

The semi-infinite slab theory requires that the sample initial temperature must be uniform throughout and that the test duration be restricted to a time length less than the time required for the back-side temperature to change.

At low values of the quantity $T_s - T_i$ an inaccuracy in the measurement of either T_s or T_i has the potential of introducing large errors in $\sqrt{\rho ck}$. As the value of $T_s - T_i$ increases, this error potential is reduced. Therefore, in order to reduce this error, the sample was cooled to as low an initial temperature as practicably possible.

Time zero is indicated by the closing of a switch activated by the water-cooled shutters. Operation of the switch coincides with the movement of the shutter lip over the center of the sample. Because the shutters open completely in 0.05 sec, there is a minimum error in $\sqrt{\rho ck}$ caused by errors in initial time.

Another possible error source comes from air bubbles trapped within the radiation absorption filter. Since these air bubbles could extend from top to bottom of the water channel and allow uneven illumination, a different heat-transfer rate could be regis-

tered by the calorimeter than what was actually heating the sample surface.

Reference 6 incorporated in the data-reduction program an equation, based on the calorimeter calibration, which computed the heat-transfer rate utilizing the calorimeter temperature at the 5th and 30th time frame. The resulting average $\dot{q}$ value agreed well with data in this study.

RESULTS AND DISCUSSION

During initial tests of the TPM apparatus three model materials were fabricated into 0.0381-m-diameter by 0.0127-m-thick samples and tested over a $\dot{q}$ range of 11.35 to 177 kW/m^2. Test times varied from 3 sec for high heating rates to 30 sec for low heating rates. The total time increment from test initiation to final data printout required 7 minutes for each test. Figure 4 presents the results of testing a sample of Stycast plastic in which the alumina has been finely ground, a heterogeneous material, in the TPM apparatus. Except for approximately the first five data points, $\sqrt{\rho ck}$ increased slightly with test time from a mean value of 1.45 to 1.513 $kJ/m^2\text{-}K\text{-}sec^{1/2}$. Heat-transfer rate did not have a definite effect on $\sqrt{\rho ck}$. There is no pattern to the slope or magnitude of $\sqrt{\rho ck}$ for these tests during the first five data points, no matter whether the run was 3 or 30 sec (each run consists of 30 data points).

This scatter in $\sqrt{\rho ck}$ values for the first five data points is attributed to the accuracy with which the thermometer measures the temperatures at the low initial temperature levels. At these temperatures, small errors in measured surface temperature T_s result in large errors in the quantity $T_s - T_i$ and therefore large variations in the computed value of $\sqrt{\rho ck}$ (see eq. (2)).

The results of testing a material called "Grumman G" in the TPM apparatus are presented in figure 5. The $\sqrt{\rho ck}$ of this low conductivity plastic was initially 1.1858 $kJ/m^2\text{-}K\text{-}sec^{1/2}$ and decreased to approximately 1.143 $kJ/m^2\text{-}K\text{-}sec^{1/2}$. These data again

show that the first five data points may be erratic. Thus, this area of the data readout is ignored. Also, these data, as all other data, do not indicate a systematic variation of thermophysical properties with heat-transfer rate.

Figure 6 shows the $\sqrt{\rho ck}$ of a red rubber sample determined both by steady-state measurement of ρ, c, and k independently and by use of the TPM apparatus. The steady-state method of measuring ρ, c, and k has been the accepted standard technique for determining $\sqrt{\rho ck}$. The $\sqrt{\rho ck}$ values determined by the two methods are in good agreement. Such a data comparison is expected for the sample since this material is extremely homogeneous and has $\sqrt{\rho ck}$ which are temperature independent. Also presented in figure 6, is an "effective $\sqrt{\rho ck}$" which are determined by mathematically correcting the measured steady-state values of ρ, c, and k to an "effective" value of $\sqrt{\rho ck}$. This "effective" value accounts for the transient temperature response of a wind-tunnel model (ref. 9) and also for changes in thermal properties with depth resulting from material inhomogeneities. "Effective $\sqrt{\rho ck}$" values agree well with the steady-state measured values as expected for a material with temperature independent properties.

The TPM apparatus measurements of $\sqrt{\rho ck}$ for the material "Grumman G" of reference 5 are compared with steady-state measurements in figure 7. The TPM apparatus data were obtained on a sample cut from a hemispherical model which was made of this material. Since this material is also a homogeneous material, $\sqrt{\rho ck}$ should be constant from sample to sample, with thickness or depth having no effect. A slight temperature dependence is noted however.

Any one of these three methods (steady state, TPM apparatus, or "effective") could be used to determine material $\sqrt{\rho ck}$ values; however, the most rapid and convenient method uses the TPM apparatus with the infrared thermometer to determine surface temperature.

CONCLUDING REMARKS

An experimental apparatus for the direct measurement of the thermophysical properties of wind-tunnel models has been developed. Model materials which exhibit thermophysical properties over a range appropriate for wind-tunnel heat-transfer models were tested in the thermophysical properties measurement apparatus. The experimental data agreed reasonably well with combined thermophysical properties obtained from the standard steady-state method. The results of these tests in the thermophysical properties measurement apparatus were available for use within 7 min of test initiation as opposed to the weeks or months which were required in using prior techniques. The thermophysical properties measurement apparatus has been shown to be the most rapid device available for obtaining thermophysical properties of phase-change heat-transfer model materials.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
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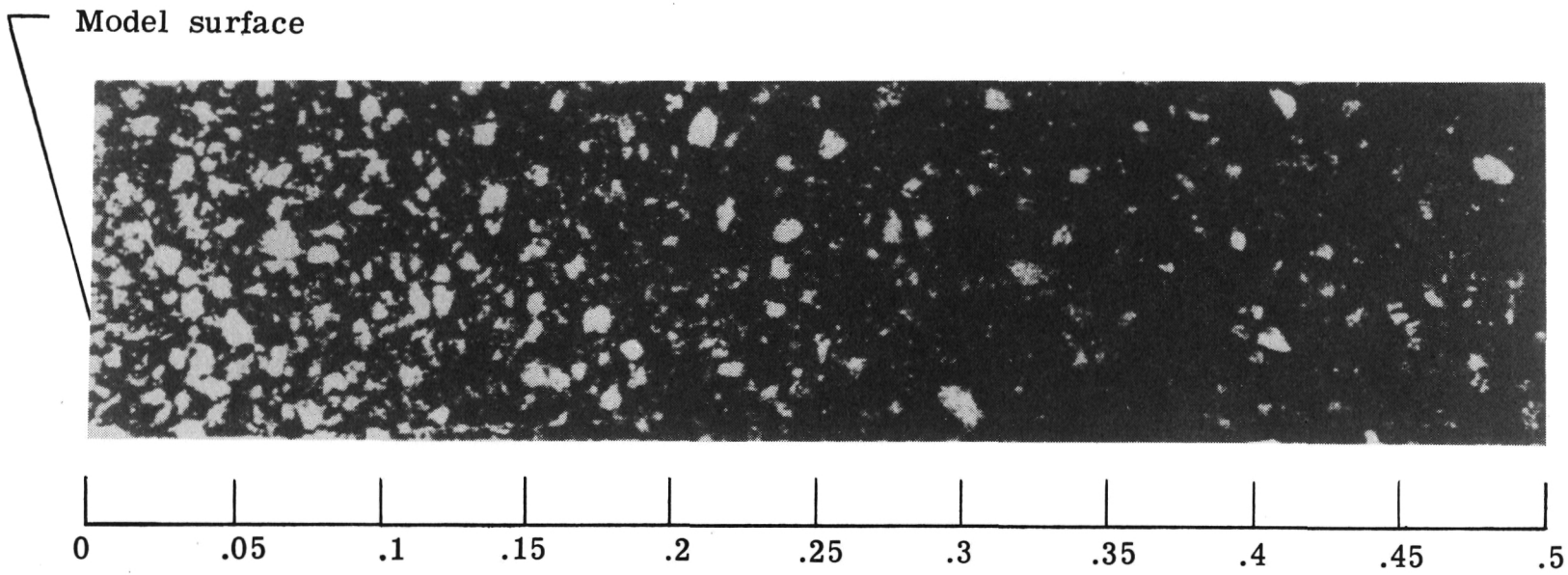


Figure 1.- Photomicrograph of Stycast plastic sample cut from wind-tunnel model.

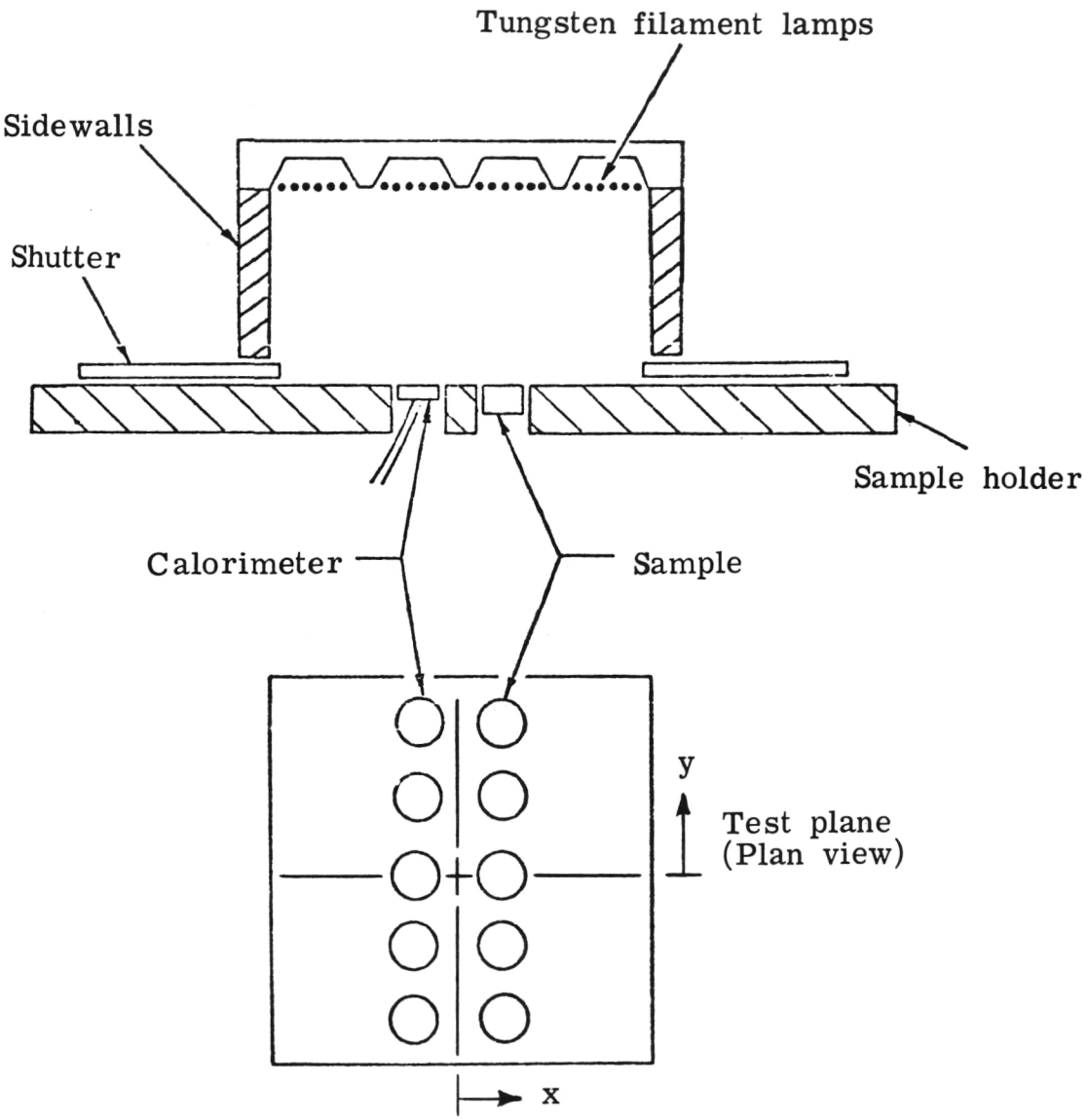
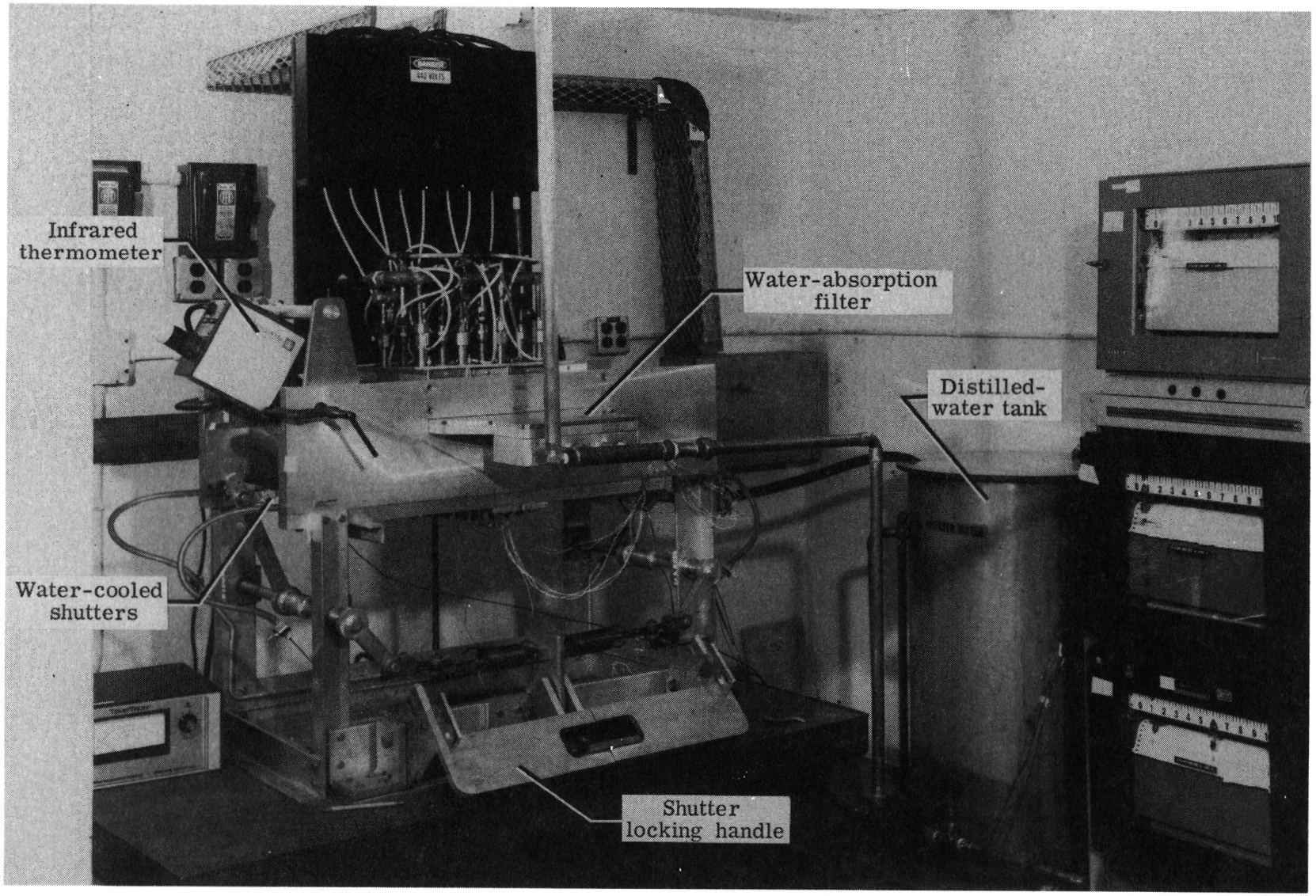


Figure 2.- Basic thermophysical properties measurement apparatus.



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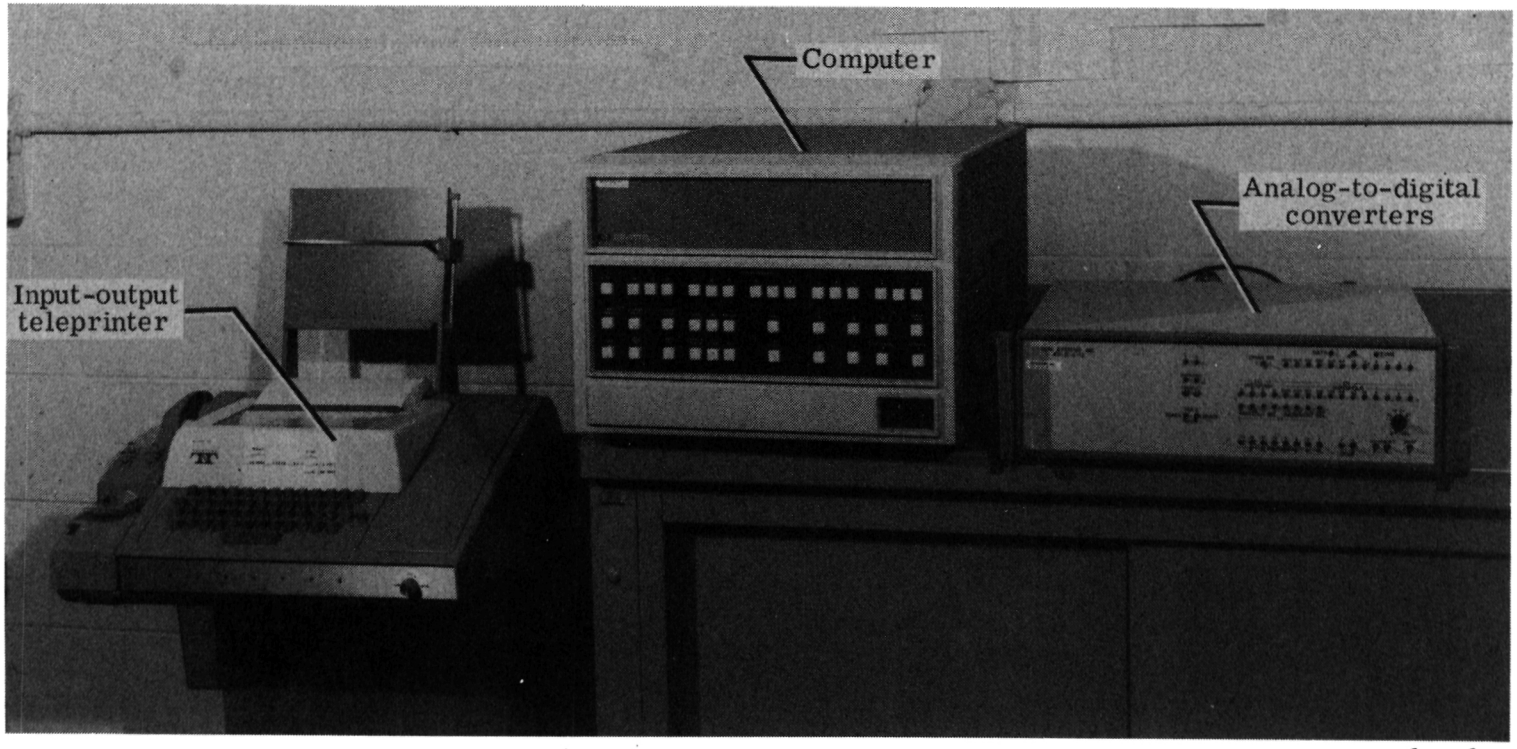
(a) Basic apparatus, infrared thermometer, and distilled-water tank.

Figure 3.- Automated thermophysical properties measurement apparatus.



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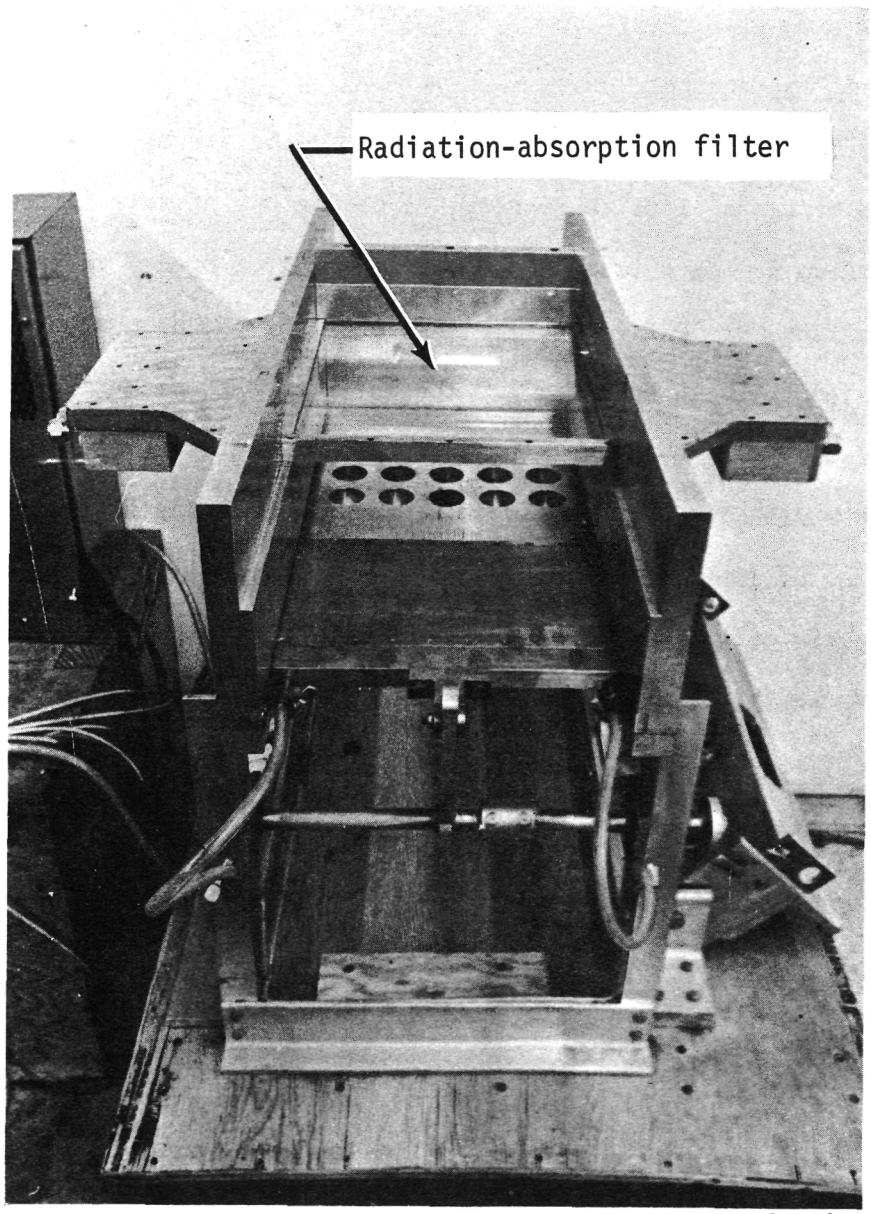
(b) Data reduction system.

Figure 3.- Continued.



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(c) Radiation-absorption filter.

Figure 3.- Concluded.

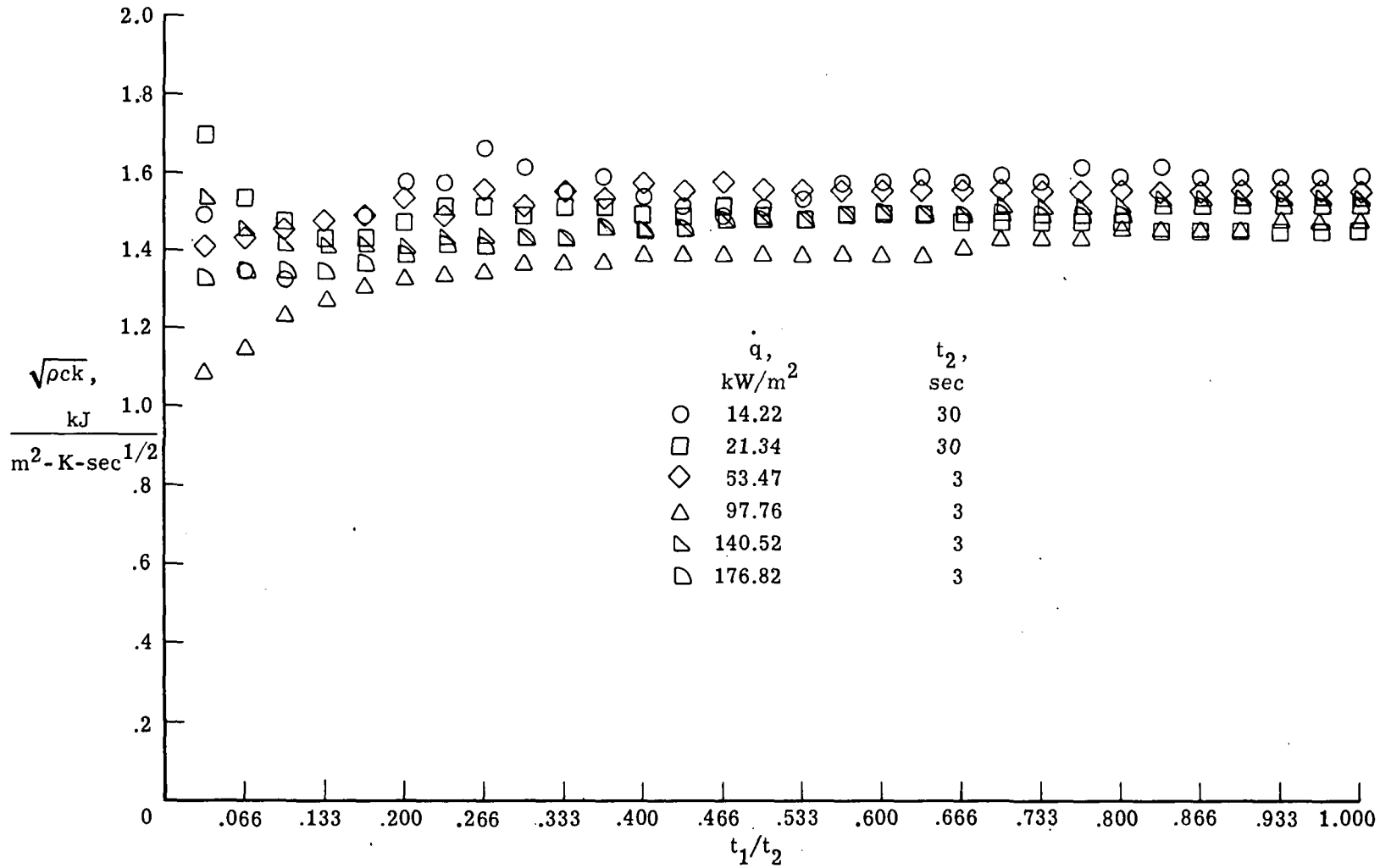

Figure 4.- Effects of heat-transfer rate $\dot{q}$ on the thermophysical properties ($\sqrt{\rho ck}$) of Stycast plastic with finely ground alumina.

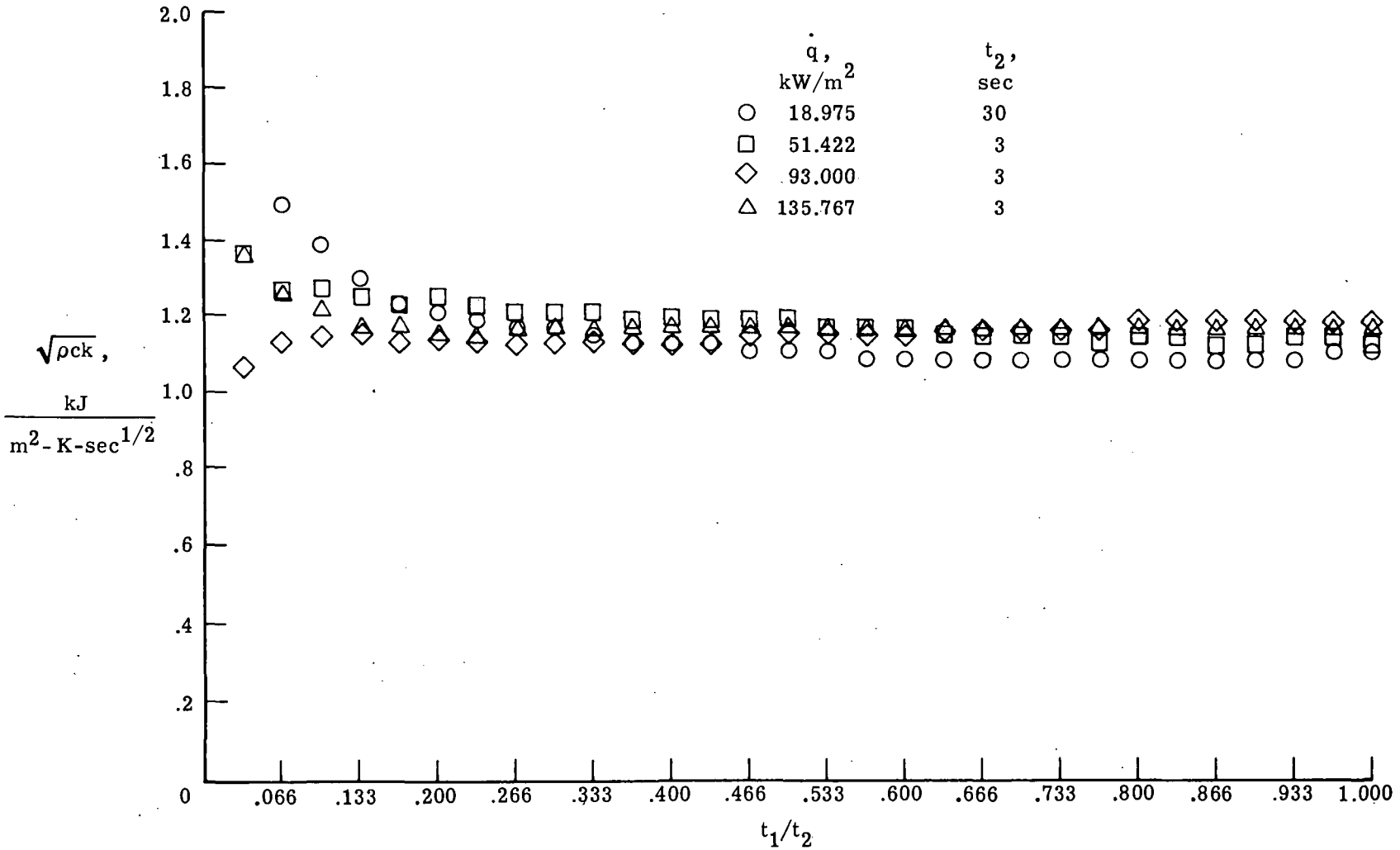

Figure 5.- Effects of heat transfer rate $\dot{q}$ on the thermophysical properties ($\sqrt{\rho ck}$) of "Grumman G".

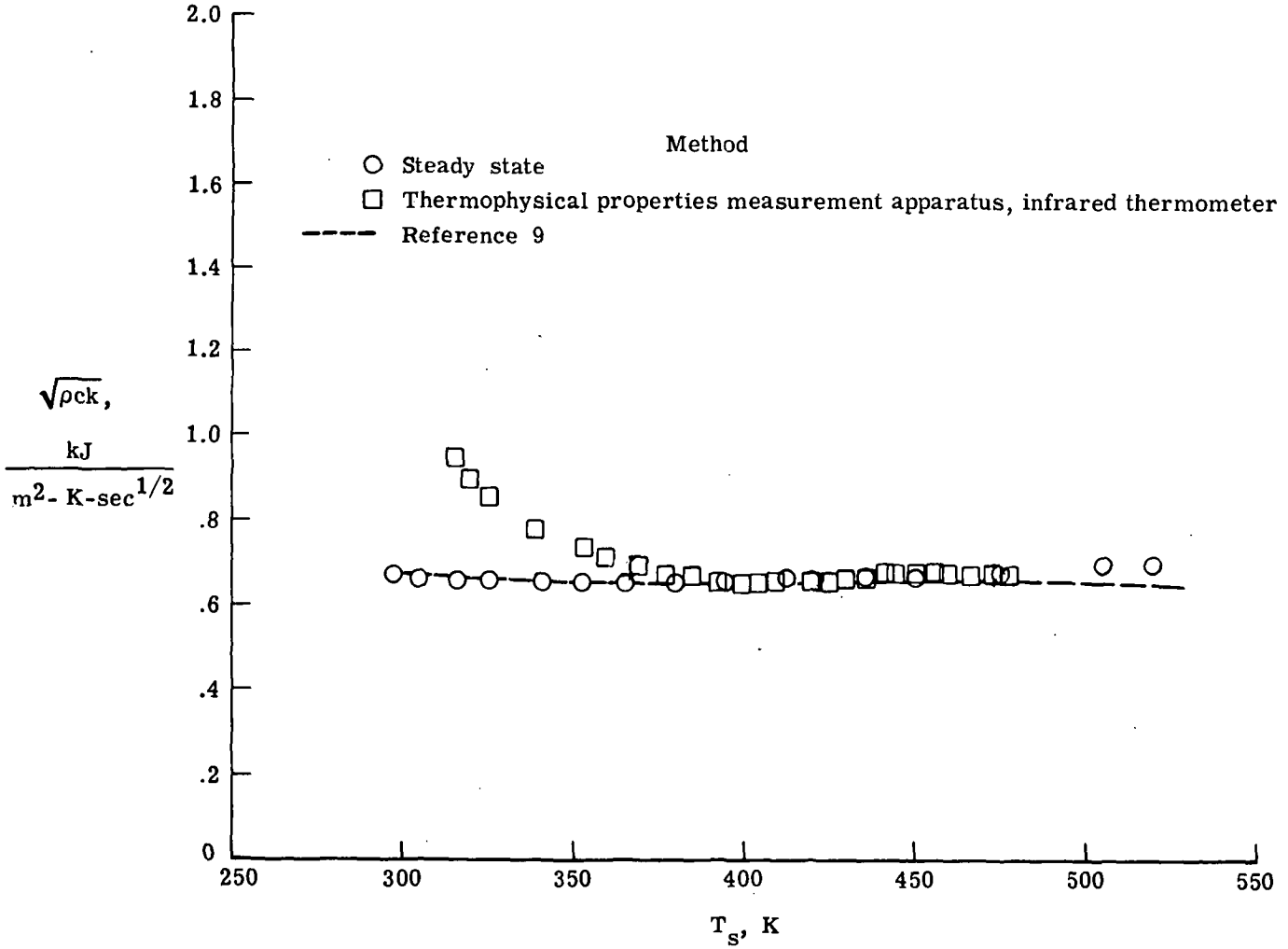

Figure 6.- A comparison of experimental thermophysical properties ($\sqrt{\rho ck}$) of red rubber with an "effective" value of $\sqrt{\rho ck}$.

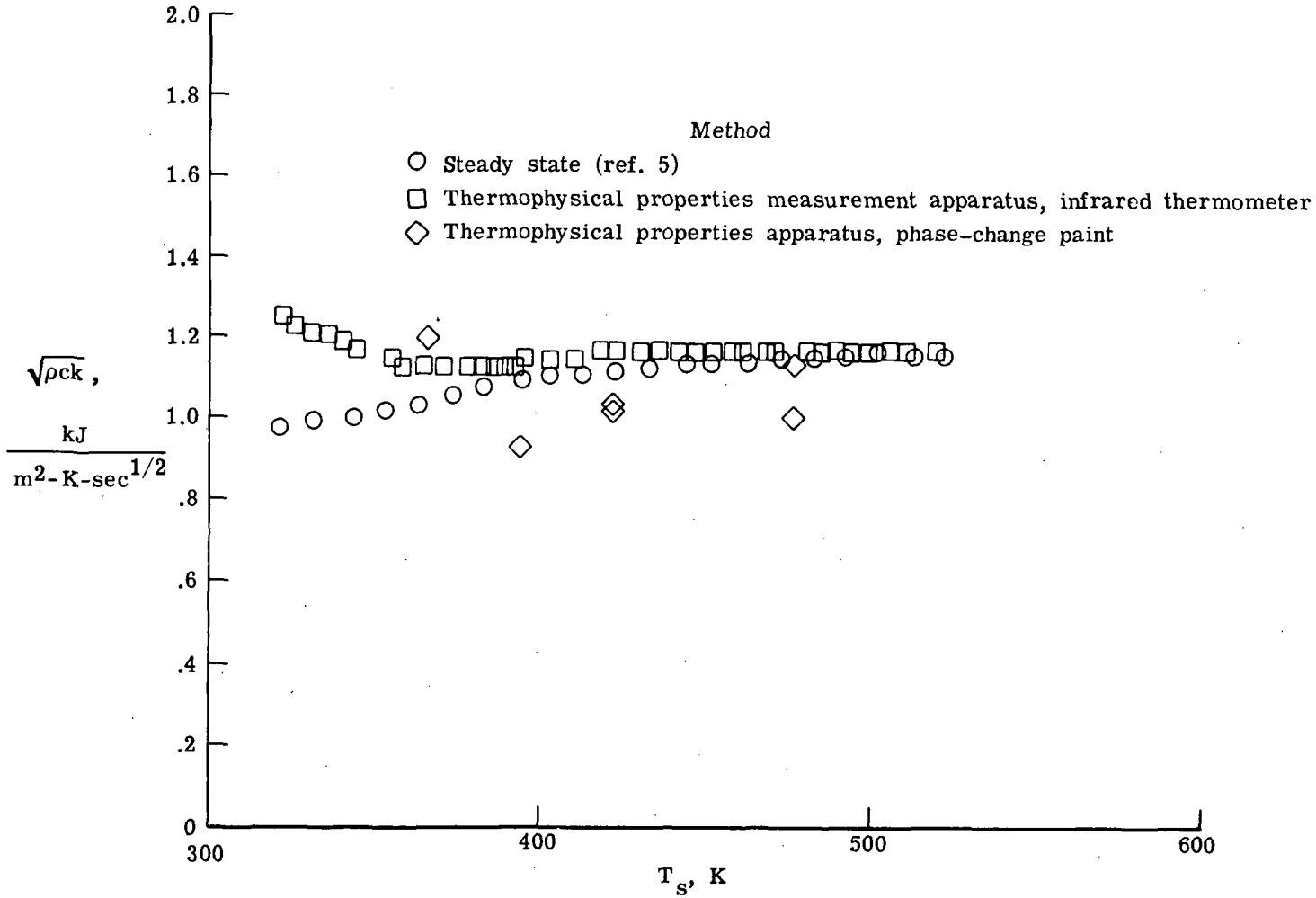

Figure 7.- A comparison of the thermophysical properties parameters $\sqrt{\rho ck}$ obtained by three methods (low conductivity plastic).

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