HEAT TRANSFER FROM AN OSCILLATING SPHERE

by

LYLE GORDON RHEA

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Approved by:

Ralph G. Nevins

Major Professor

TABLE OF CONTENTS

NOMENCLATURE iii

INTRODUCTION 1

EXPERIMENTAL EQUIPMENT 1

EXPERIMENTAL TECHNIQUE 6

RESULTS 9

ACKNOWLEDGMENT 19

LITERATURE CITED 20

NOMENCLATURE

A	Surface area of sphere (ft^2)
a	Amplitude of oscillation (ft)
c_p	Specific heat (Btu/lb_m-F)
D	Diameter of sphere (ft)
f	Frequency of oscillation (cyc/hr)
$\bar{h}$	Mean unit surface conductance (Btu/hr-ft^2-F)
$\bar{h}_c$	Mean unit surface convective conductance (Btu/hr-ft^2-F)
$\bar{h}_r$	Mean unit surface radiative conductance (Btu/hr-ft^2-F)
k	Thermal conductivity (Btu/hr-ft-F)
m	Mass of the sphere (lb_m)
T	Absolute temperature (R)
T_m	Mean temperature (R)
T_f	Film temperature $(T_m + T_\infty)/2$ (R)
T_o	Temperature when $\theta = 0$ (R)
T_{θ_c}	Temperature when $\theta = \theta_c$ (R)
T	Temperature of ambient fluid (R)
V	Volume of sphere (ft^3)
ϵ	Average emissivity of surface
θ	Time (hr)
μ	Dynamic viscosity (lb_m/ft-hr)
ρ	Density (lb_m/ft^3)
σ	Stephan-Boltzman constant (0.1714×10^{-8} Btu/hr-ft^2-R^4)
ω	Angular velocity (1/hr)
Bi	Biot number (hV/kA)
Nu	Nusselt number ($h_c D/k_f$)
Re	Reynolds number ($\rho D a \omega/\mu$)

INTRODUCTION

In recent years, much work has been done with regard to the heat transfer from spheres. The investigations thus far have been concerned with natural convection, combined natural and forced convection from stationary spheres, and convection from a rotating sphere. This report presents the results of an experimental study of the heat transfer from an oscillating sphere to a quasi infinite medium as a function of frequency and amplitude.

EXPERIMENTAL EQUIPMENT

Plate I is a photograph of the equipment used in the experiments. The one inch diameter sphere was made of copper and was within 0.005 inches of being spherical. The size and material were selected so that the internal thermal resistance was negligible compared to the thermal resistance at the surface of the sphere. Kreith (A) states that when the internal resistance is less than ten percent of the external resistance, the error in assuming the temperature throughout the sphere to be constant is less than five percent. That is, $Bi < 0.1$.

The mechanism used to obtain sinusoidal oscillations of the sphere in a vertical direction was a Scotch yoke. The drive system consisted of a 1/15 horsepower variable speed a-c motor with a speed reducing pulley. A variable length crank arm connected the pulley shaft to the Scotch yoke. The frequency of oscillation was varied by using an autotransformer. The low torque characteristic of the motor at low input voltage made it necessary to balance the system in order to obtain true sinusoidal oscillations. At frequencies less than three cps, the frequency varied during a test as much

EXPLANATION OF PLATE I

Fig. 1. Arrangement of test equipment.

PLATE I

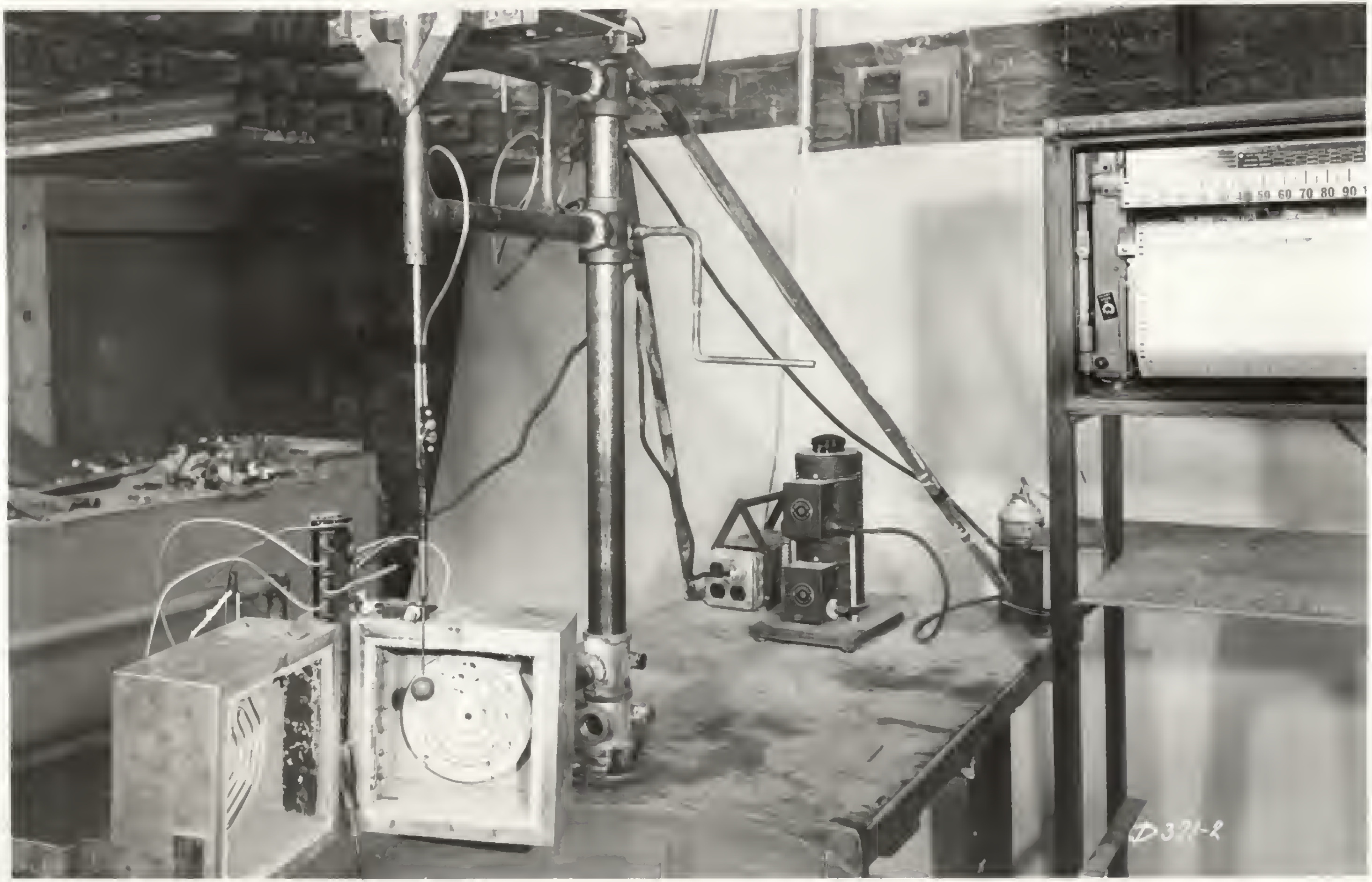

Fig. 1

EXPLANATION OF PLATE II

Fig. 2. Relative positions of the heater and sphere during the test period.

PLATE II

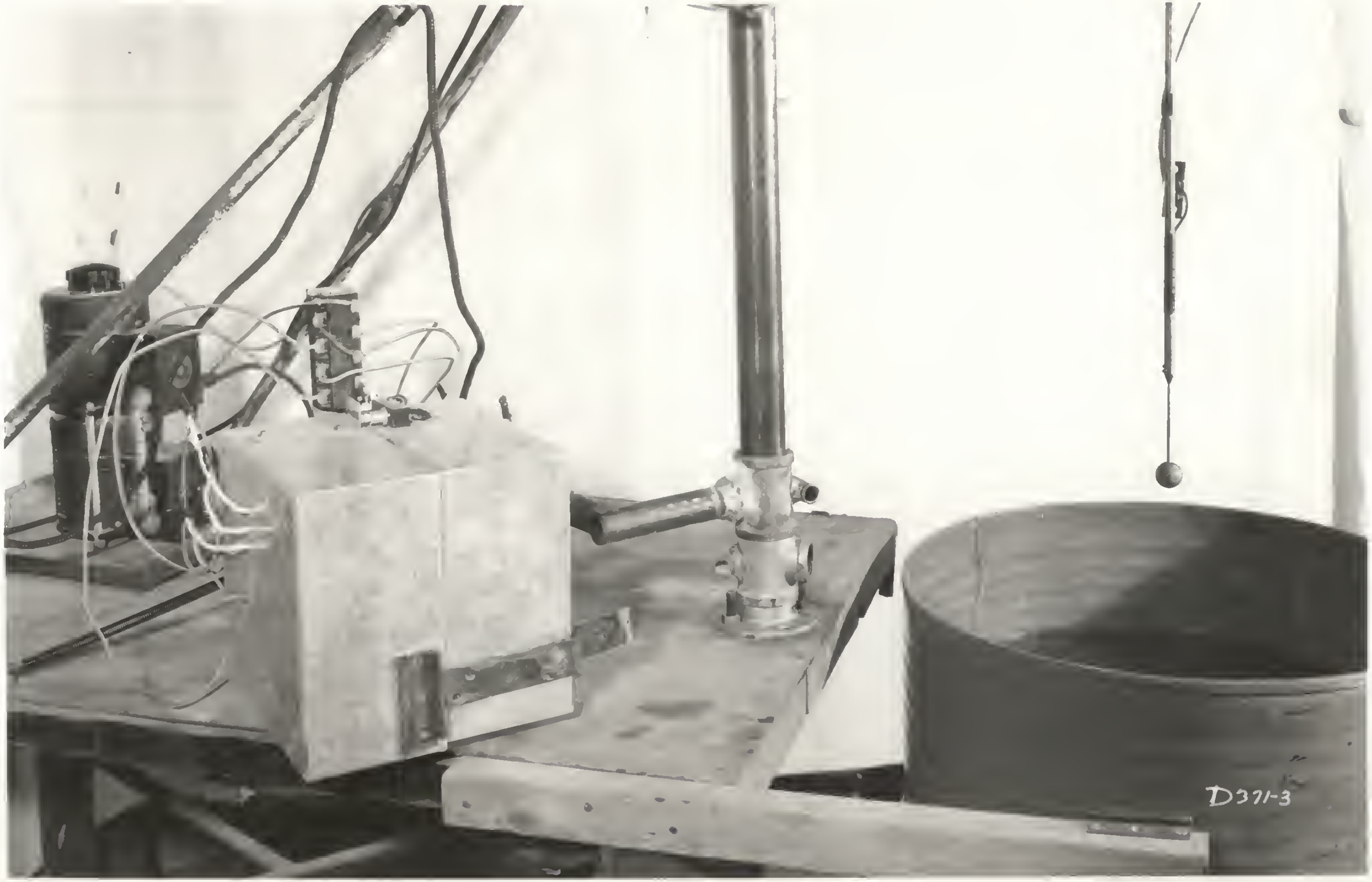

Fig. 2

as four percent from a mean value. Above three cps, a stroboscope showed that the frequency remained constant over the entire time of the test run.

The sphere was connected to the Scotch yoke by means of a six inch length of 1/8 inch diameter Megopak thermocouple wire and a 3/8 inch diameter thin walled steel tube. The Megopak was soldered to the sphere with 1200 F silver solder so that the iron-constantine thermocouple junction was located at the center of the sphere. The sphere and drive system could be lowered from the position shown in plate I for immersion in a water filled barrel to a depth of approximately six inches.

The sphere was heated by two resistance heaters located on opposite sides of a nine inch cube shaped oven. The oven was made in halves and spring loaded so that it would open quickly from around the sphere and swing away a distance of approximately three feet (see plate II).

A Honeywell recorder was used to obtain the temperature-time records for the sphere cooling in air. When the cooling medium was water, a Sanborn d-c amplifier and recorder was used in order to obtain a chart speed of 100 mm per second. A disadvantage of this instrument was that its accuracy is not guaranteed for input voltages less than 5 mv.

EXPERIMENTAL TECHNIQUE

Each test was begun by heating the sphere to a temperature well above that desired for the upper limit of the cooling range. During heating, the sphere was brought to the desired frequency of oscillation. Then the oven was triggered and a temperature-time history for the sphere was recorded.

For the tests in air, the oven was closed immediately in order to prevent radiation from the oven to the sphere and heating of the air. This was done while the sphere temperature was still well above the temperature corresponding to time zero for the test. Thus, the cooling process was not affected by the oven during the test period. For the tests in water, the heating to a higher temperature eliminated the effects of dunking.

The cooling of a sphere with negligible internal resistance is analogous to the discharge of a capacitor in an R-C electrical circuit (A). A first law analysis on the sphere yields the equation

$$(1) \qquad -\, mc_p dT = \bar{h}A(T - T_\infty)d\theta$$

The solution for this differential equation gives the temperature of the sphere as a function of time. It is

$$(2) \qquad \frac{T - T_\infty}{T_o - T_\infty} = e^{-\frac{\bar{h}A}{mc_p}\theta}$$

The term $\frac{mc_p}{\bar{h}A}$ is called the time constant and will be designated by θ_c in this report. When

$$(3) \qquad \theta = \theta_c = \frac{mc_p}{\bar{h}A}$$

equation (2) reduces to

$$(4) \qquad T_{\theta_c} - T_\infty = 1/e(\, T_o - T_\infty \,)$$

The temperature range for each test was determined from equation (4) by choosing an initial temperature T_o and calculating the final temperature T_{θ_c}. Because the room temperature T changed from day to day, initial temperatures of 610 F, 590 F, and 580 F were selected for the tests in air in order to obtain a temperature range less than that of the recorder. An initial temperature of 796 F was selected for the tests in water to include the four regimes of cooling on the temperature-time record. The time constant for each test run was calculated from the temperature-time record by dividing the measured distance between T_o and T_{θ_c} by the chart speed of the recorder. With the time constant known, the unit surface conductance was calculated from equation (3).

Since the specific heat of copper varies with temperature (B), a value corresponding to the mean temperature of the sphere over the test range was used in equation (3). The mean temperature was determined from the equation

$$(5) \qquad T_m - T_\infty = \frac{\int_0^\theta (T_o - T_\infty) e^{-\frac{\bar{h}A}{mc_p}} d\theta}{\theta}$$

When equation (5) is integrated from 0 to θ_c, it reduces to

$$(6) \qquad T_m - T_\infty = (1 - 1/e)(T_o - T_\infty)$$

It was noted that the value of $\bar{h}$ obtained by using a value of c_p corresponding to an average temperature calculated by the equation

$$(7) \qquad T_{avg.} = \frac{T_o + T_\infty}{2}$$

was less than three percent lower than the $\bar{h}$ obtained using c_p corresponding to T_m.

The heat loss to the Megopak by conduction was determined to be less than one percent by calculation of both sides of equation (1) in the form

$$(8) \qquad mc_p(T_o - T_{\theta_c}) = \bar{h}A(T_m - T_\infty)\theta_c$$

The heat transfer by radiation was found to be a major part of the total heat transfer for the tests in air; however, it was negligible when the cooling medium was water. The unit surface conductance was separated into two parts by the equation

$$(9) \qquad \bar{h} = \bar{h}_r + \bar{h}_c$$

The unit radiative conductance was calculated from the equation

$$(10) \qquad \bar{h}_r = \frac{\epsilon\sigma\,(T_m^4 - T_\infty^4)}{(T_m - T_\infty)}$$

and substituted into equation (9) to determine $\bar{h}_c$ for each test run. Equation (10) is of the form given by Yuge (D). The emissivity of the copper was taken as 0.87 from Kreith (A).

RESULTS

Several tests were made in air at zero frequency. The values of $\bar{h}_c$ obtained agreed with the correlation equation published by Nordlie and Kreith (C) within their prescribed limits. This check served to establish the reliability of the test equipment and calculation procedure.

In plate III, the cooling curve for the sphere oscillating at 8 cps and one inch amplitude is compared to that for the sphere at zero frequency. Also shown is a plot of equation (2) using the $\bar{h}$ obtained from test. These curves are typical of those for the series of tests on the sphere cooling in air. The series covered a range of frequencies from 0 to 10 cps at amplitudes of 1, 3/4, and 1/2 inch. A plot of $\bar{h}$ versus f is shown in plate IV. The mathematical relation for $\bar{h}$ as a function of f in cps for each amplitude was determined by the calculus of finite differences. The relations

$$(11) \qquad \begin{aligned} \bar{h} &= 3.66 + 0.175\,f + 0.015\,f^2 && (a = 1 \text{ inch}) \\ \bar{h} &= 3.66 + 0.0655\,f + 0.0145\,f^2 && (a = 3/4 \text{ inch}) \\ \bar{h} &= 3.66 + 0.045\,f + 0.005\,f^2 && (a = 1/2 \text{ inch}) \end{aligned}$$

describe the data to within $\pm$ 5 percent. A plot of Nusselt number versus Reynolds number for the data obtained is shown in plate V. The fluid properties were evaluated at the film temperature.

Although no equation is given, the curve shown correlates the data to within $\pm$ 15 percent.

Four tests were made at an amplitude of 1/2 inch using water at 60 F as the cooling medium. The cooling curves for these tests are shown in plate VI. In each test, the sphere was cooled from 796 F to approximately 80 F. Four regimes of cooling are covered by these curves (B). The regimes are indicated approximately for the curve with a frequency of 9.2 cps. During film boiling, the plot shows that equation (2) is correct to within 5 percent and that the unit surface conductance is not a function of frequency. However, it was noted that the transition from film boiling to nucleate boiling occured at a higher temperature for a higher frequency of oscillation. A visual observation indicated that the sphere moved out of the film.

EXPLANATION OF PLATE III

Fig. 3. Typical cooling curves for a one inch diameter copper sphere cooling in air. The curves are a plot of equation (2) using the $\bar{h}$ determined from test.

⊗ - Points from actual cooling curve for $f = 0$.

⊙ - Points from actual cooling curve for $f = 8$ cps and $a = 1$ inch.

PLATE III

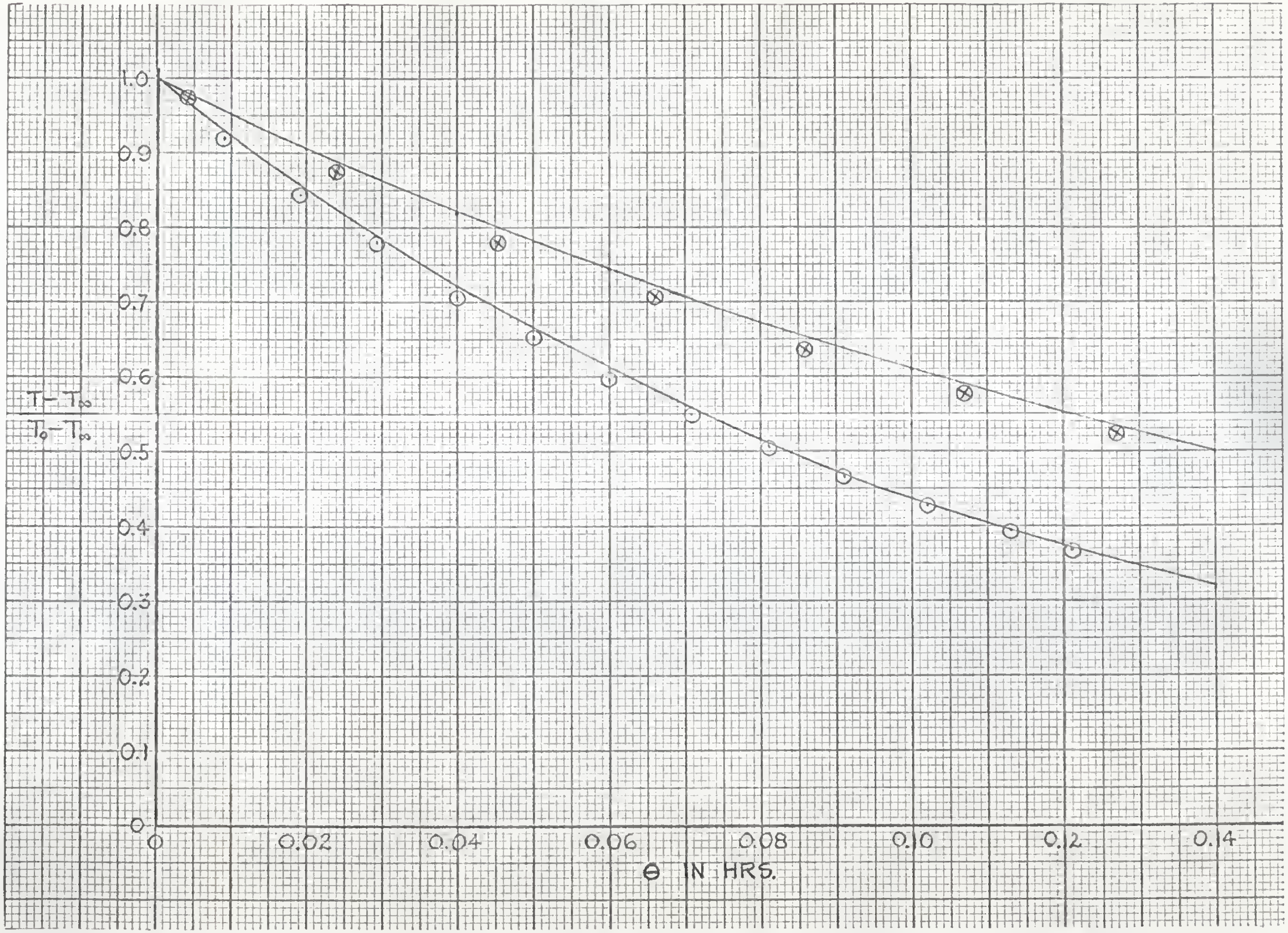

Fig. 3

EXPLANATION OF PLATE IV

Fig. 4. Plot of unit surface conductance versus frequency for a one inch diameter copper sphere cooling in air.

$\boxdot$ $\bar{h} = 3.66 + 0.175\,f + 0.015\,f^2$ (a = 1 inch)

$\odot$ $\bar{h} = 3.66 + 0.0655\,f + 0.0145\,f^2$ (a = 3/4 inch)

$\triangle$ $\bar{h} = 3.66 + 0.045\,f + 0.005\,f^2$ (a = 1/2 inch)

PLATE IV

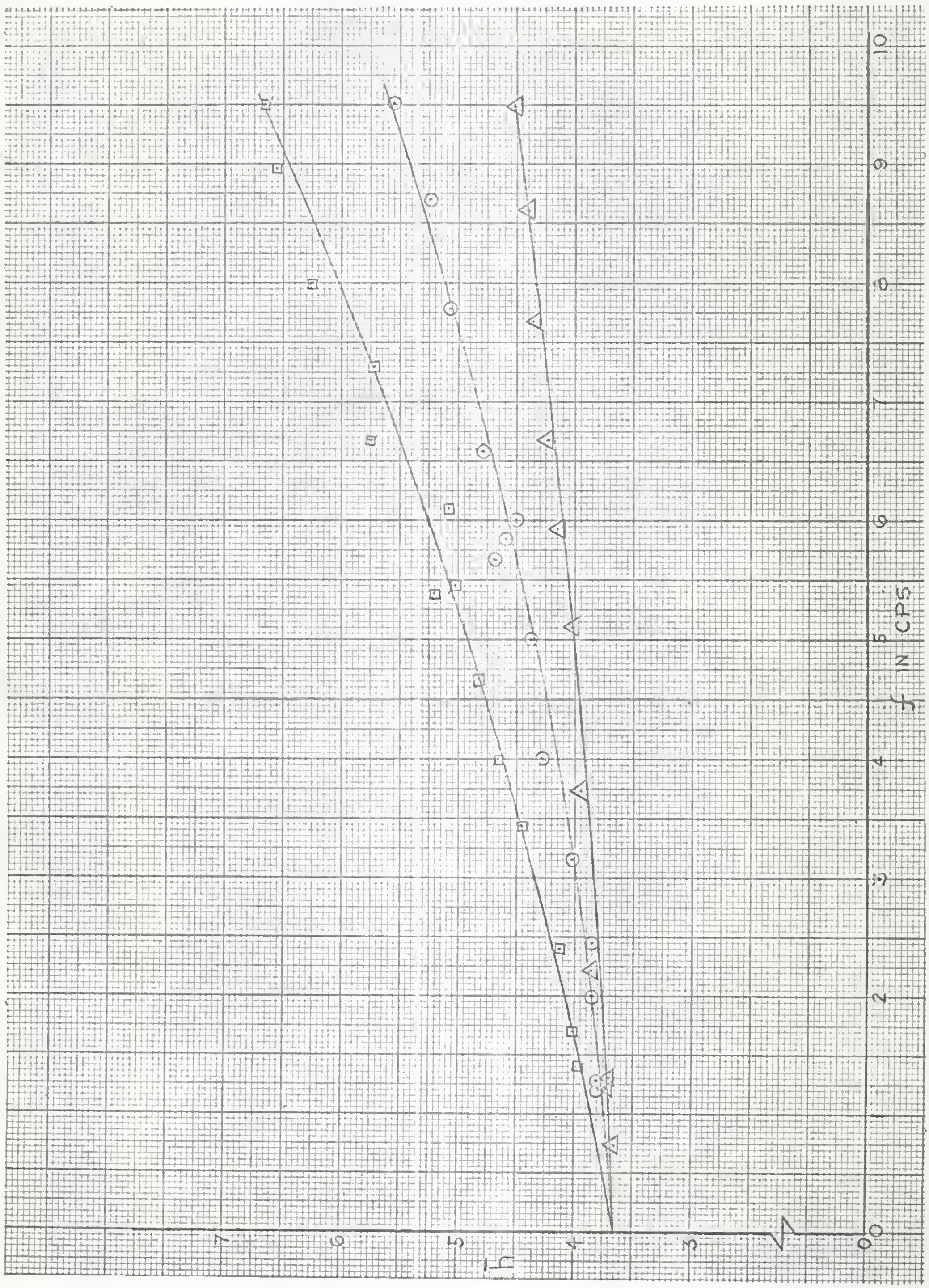

Fig. 4

EXPLANATION OF PLATE V

Fig. 5. Plot of Nusselt number versus Reynolds number for a one inch diameter copper sphere cooling in air.

PLATE V

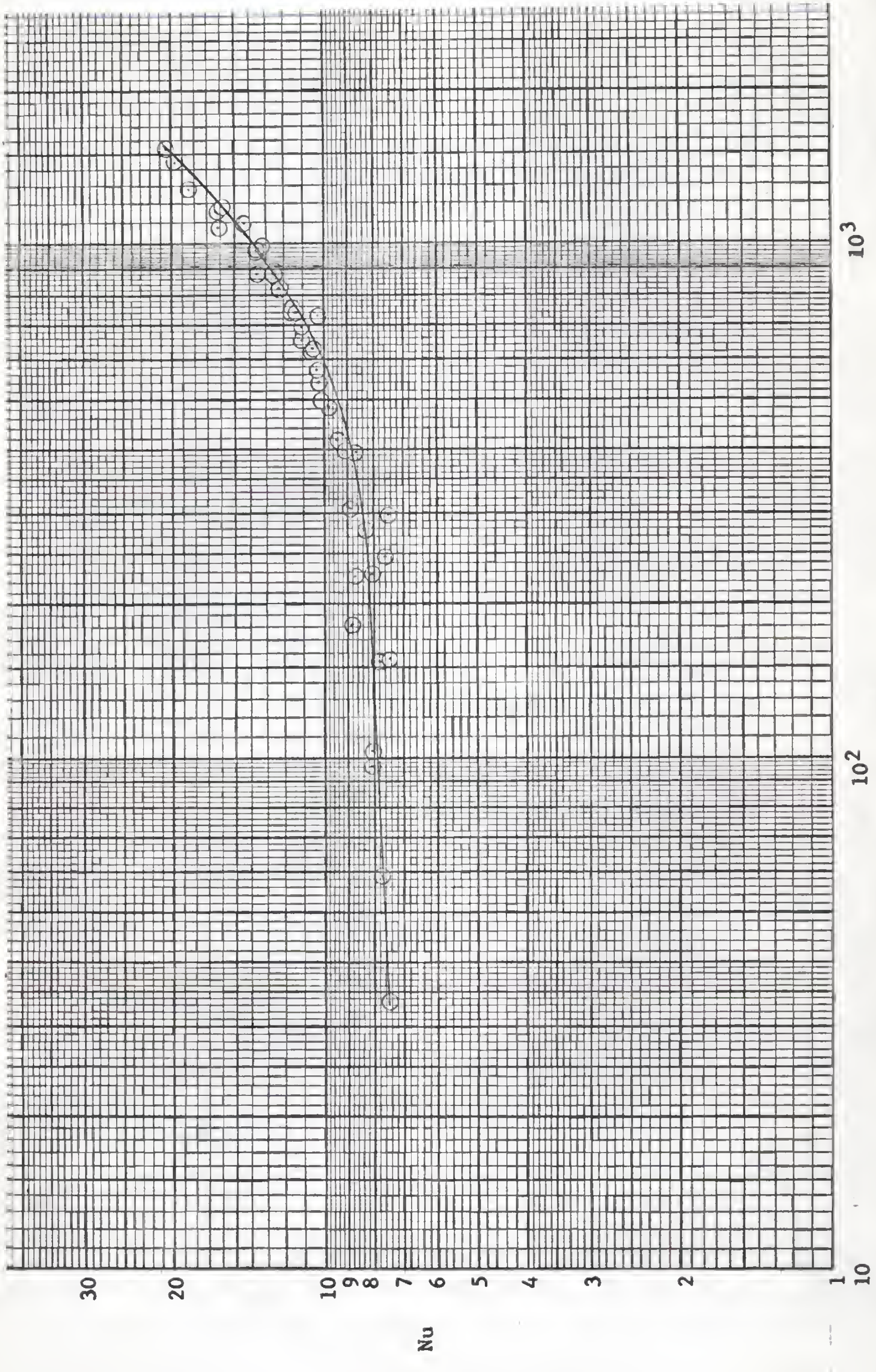

Fig. 5

EXPLANATION OF PLATE VI

Fig. 6. Cooling curves for a one inch diameter copper sphere cooling in water. Amplitude is 1/2 inch for all curves.

○ $f = 0$	A - Film boiling
△ $f = 2.5$ cps	B - Partial film boiling
⊡ $f = 6.33$ cps	C - Nucleate boiling
⊗ $f = 9.2$ cps	D - No boiling

PLATE VI

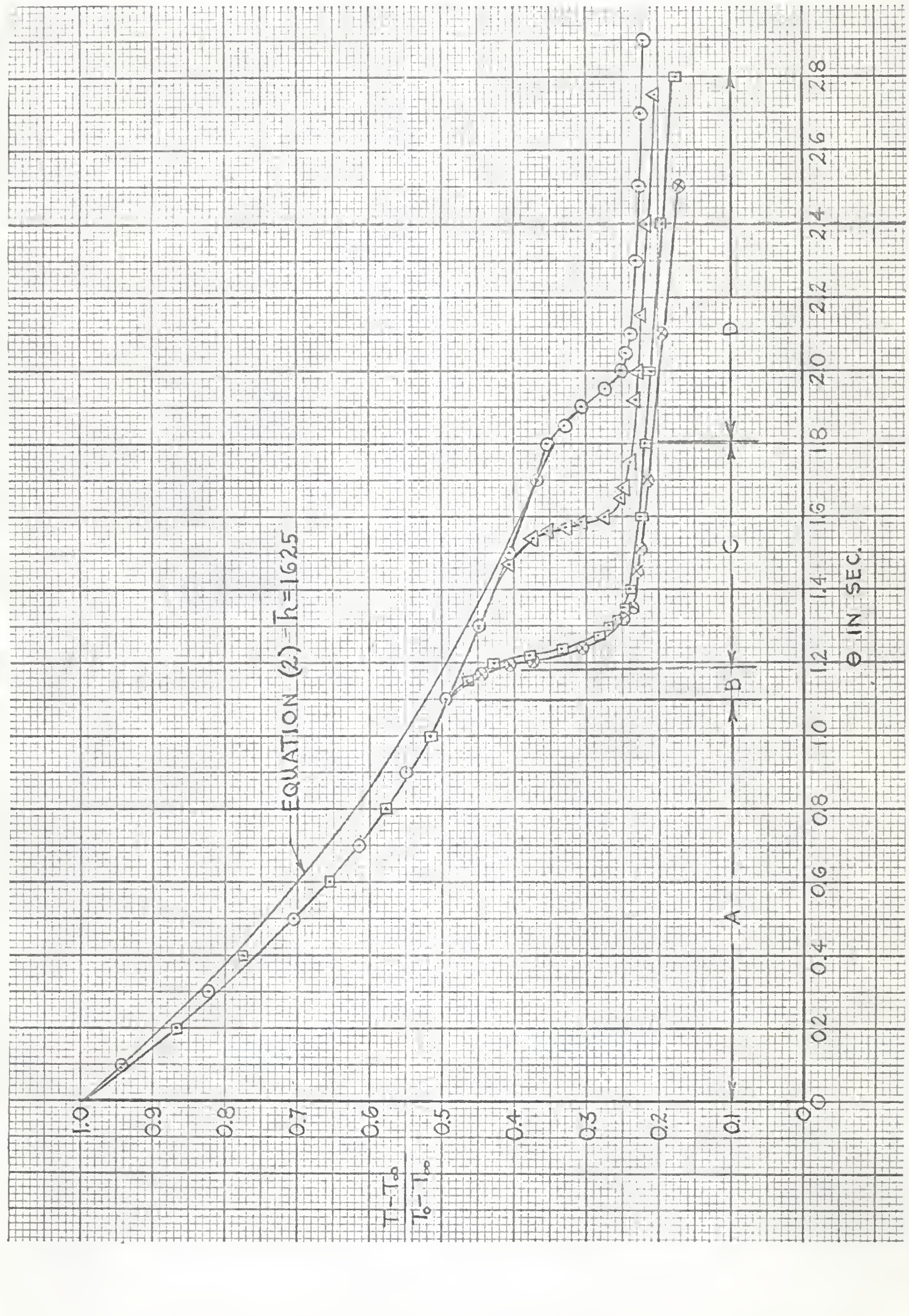

Fig. 6

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The heat transfer from a one inch diameter copper sphere oscillating in a quasi infinite medium, both air and water, has been studied. Unit surface conductances were experimentally determined for frequencies from 0 to 10 cps at amplitudes of 1, 3/4 and 1/2 inch. The oscillating conditions correspond to a Reynolds number range from 33 to 1.6×10^3. The results of the tests in air are shown graphically by a plot of Nusselt number versus Reynolds number. The curve shown correlates the results to within $\pm$ 15 percent. Four tests were run in water using an amplitude of 1/2 inch and frequencies of 0, 2.5, 6.33, and 9.2 cps. The cooling curves show that the unit surface conductance is not a function of frequency during film boiling and that the transition from film boiling to nucleate boiling occurs at a higher temperature for a higher frequency of oscillation.