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# RESEARCH MEMORANDUM

## FORCED-CONVECTION HEAT-TRANSFER CHARACTERISTICS OF MOLTEN SODIUM HYDROXIDE

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NATIONAL ADVISORY COMMITTEE
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# FORCED-CONVECTION HEAT-TRANSFER CHARACTERISTICS OF MOLTEN SODIUM HYDROXIDE

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## SUMMARY

An investigation of the forced-convection heat-transfer characteristics of sodium hydroxide was made for a range of Reynolds number from 5300 to 30,000, corresponding to velocities from 3.8 to 15.4 feet per second, average fluid temperatures up to 938° F, and heat-flux densities up to 226,000 Btu per hour per square foot for both heating and cooling. Water heat-transfer tests were also made to check the instrumentation. In addition, some heat-transfer tests were made with an aqueous solution of sodium hydroxide.

When the sodium hydroxide heating data are correlated by the familiar Nusselt relation, the data fall slightly above the McAdams correlation line. The sodium hydroxide cooling data are fairly well represented by the McAdams correlation line.

## INTRODUCTION

This report contains the heat-transfer data obtained at the NACA Lewis laboratory for sodium hydroxide flowing in an electrically heated Inconel tube. Heating data were obtained for a range of Reynolds number from 5300 to 29,000, corresponding to velocities from 3.8 to 15.4 feet per second, average surface temperatures up to 967° F, average fluid temperatures up to 918° F, and heat-flux densities up to 226,000 Btu per hour per square foot.

Cooling data were taken concurrently with the heating data, with the sodium hydroxide flowing through the center passage of a single-tube, Inconel, counter-flow, sodium-hydroxide-to-air heat exchanger. Data were obtained for a range of Reynolds number from 6500 to 30,000, corresponding to velocities from 5.9 to 15.4 feet per second, average surface temperatures up to 915° F, average fluid temperatures up to 938° F, and heat-flux densities up to 120,000 Btu per hour per square foot.

## APPARATUS

A photograph and a schematic drawing of the test setup are shown in figure 1. A centrifugal pump was used to circulate the molten sodium hydroxide from the sump tank through the heating test section, cooling test section, heat exchanger, and into the volume tank. From the volume tank, the molten sodium hydroxide returns to the sump tank. The setup is so arranged that upon completion of a run the sodium hydroxide drains back into the sump tank. Each section of the test setup is described in the following paragraphs.

Sump tank. - The sump tank housed the centrifugal pump and served as a storage tank for the 20 pounds of sodium hydroxide circulated through the system. The tank was made of Inconel with an inner diameter of 11 inches and a depth of 5 inches. During operation, an atmosphere of nitrogen was kept in the space above the liquid level.

Circulating pump. - The circulating pump was a centrifugal pump driven by a 1 hp air motor. The rotor, housing, and shaft were made of Inconel. The gasket material used at the split housing was two sheets of 0.004-inch nickel. The pump was totally immersed in the molten hydroxide and supported from the cover plate of the sump tank. The bearings and shaft supports were located in a water-cooled housing above the sump tank and a slinger ring on the pump shaft prevented leakage. The flow rate was controlled by varying the air supply to the motor.

Heating test section. - Preliminary tests showed that an electrically heated test section could be used for the heat-transfer tests because only a negligible amount of heat would be generated in the sodium hydroxide. A schematic drawing of the heating test section is shown in figure 2. The heating test section was fabricated from Inconel tubing having an outside diameter of 3/8 inch, a wall thickness of 1/16 inch, and an effective heat-transfer length of 24 inches. Three stainless steel electric flanges were welded 12 inches apart to the test section and were connected by flexible straps and buss bars to a power source for resistance heating. Electrically, the test section was connected in parallel, the current being divided at the center flange. Since the test section was not electrically insulated from the rest of the system, the outer flanges were grounded, thus maintaining the rest of the system at the same electrical potential. For starting purposes, guard ring heaters were used on each of the electrical flanges to eliminate cold spots on the test section. Mixing tanks provided with baffles were located at each end of the test section. A thermocouple was located at the downstream end of each mixing tank to obtain a mixed temperature of the sodium hydroxide. Outside-tube wall temperatures were measured with 14 chromel-alumel thermocouples spotted at intervals along the test section. Each thermocouple lead was wrapped around the tube for 1/2 turn to prevent conduction losses from the thermocouple junction.

Cooling test section. - The cooling test section consisted of two Inconel tubes forming an annulus with sodium hydroxide in the center tube and counter-flow cooling air in the annulus. A schematic drawing is shown in figure 3. The inner tube had a 3/8-inch outside diameter with a 1/16-inch wall; the outer tube was $1\frac{1}{4}$ inches in diameter with a 1/16-inch wall. A stainless steel bellows in the outer tube was used to take up the differential expansion between the two tubes. The effective heat-transfer length was 24 inches. Sodium hydroxide inlet and outlet temperatures were measured in mixing cans.

Nine buried chromel-alumel thermocouples on the inside tube were used to obtain wall temperatures. As shown in figure 3, a circumferential and a longitudinal groove 0.031-inch deep and 1/32-inch wide were cut at each thermocouple location. The thermocouple junction was placed in the longitudinal groove and each lead was wrapped around the tube 1/2 turn to reduce conduction losses from the junction. A ceramic was used to insulate the thermocouple leads from the tube. Inconel spray weld covered the leads and located them permanently. Alundum tubing inside a 1/8-inch Inconel tube brought the leads to either end of the annulus. The location of each thermocouple junction was measured as accurately as possible and was found to be 0.045 inch from the inside surface.

Service air at 100 pounds per square inch was available for cooling and was controlled by a regulator.

Heat exchanger. - The heat exchanger was used to maintain a constant inlet temperature to the heating test section, since at a high rate of heat input to the heating test section, the cooling test section was inadequate in removing this heat. The heat exchanger was fabricated from two Inconel tubes forming an annulus, with the sodium hydroxide in the inner tube and the counter-flow air in the annulus. The dimensions of the inner tube were 3/4-inch outside diameter with a 1/16-inch wall, and of the outer tube, $1\frac{1}{2}$ inches with a 1/16-inch wall.

Volume measuring tank. - The volume measuring tank was made of Inconel formed into a cylinder $5\frac{3}{4}$-inches inside diameter and 11 inches deep. An air-actuated piston was used to open or close a plunger valve at the bottom of the tank. Electric contact points at measured depths in conjunction with an electric stop clock determined the rate of volume flow through the test sections. During operation, the plunger valve was closed, and as the liquid level rose, the time required to fill the tank between the electric contact points was determined. When the liquid level reached the upper contact point, the plunger valve was opened. Thermocouples located in the tank recorded the fluid temperature. From the volume-flow rate and the density of sodium hydroxide at the measured temperature, the weight-flow rate was calculated.

Electric system. - Electric power from a 208-volt, 60-cycle line was supplied to the heating test section, as shown in figure 1(b), through two saturable reactors and a power transformer. A voltage regulator controlling the direct-current supply to the reactor maintained close voltage regulation at the primary of the power transformer for any setting (heating-test-section input) of the variable transformer control. The capacity of the electric equipment was 25 kilovolt-amperes at a maximum input of 10 volts across the heating test section. The power input was read from a calibrated ammeter, voltmeter, and wattmeter.

Miscellaneous. - Nichrome wires in alundum beads wrapped around each element of the test setup served as preheaters to bring the system up to operating temperature. All temperature measurements were made with calibrated 24-gage chromel-alumel thermocouple wire. Temperature measurements were read on a self-balancing, indicating-type potentiometer, and differential temperatures across both test sections were measured with a potentiometer and an external galvanometer.

Stainless steel tube-to-tube compression fittings connected the various components of the system. All piping between components was 1/2-inch outside diameter with a 1/16-inch wall Inconel tubing.

A cold trap was installed directly before the heating test section to remove impurities from the sodium hydroxide.

## PROCEDURE

Effect of heat generation in an Inconel tube filled with sodium hydroxide. - A preliminary investigation was made to determine the electric resistance of an empty tube and one full of sodium hydroxide. An electrically heated Inconel tube 18 inches long with an outside diameter of 0.319 inch and a wall thickness of 0.055 inch was heated to approximately $1300^{\circ}$ F. The power was then turned off, and the resistance of the center $5\frac{7}{8}$ inches of the tube was recorded at several temperatures as the tube cooled. The resistance measurements were made with a Kelvin bridge. The same procedure was then repeated for a tube filled with sodium hydroxide.

A plot of tube resistance with and without sodium hydroxide against temperature is shown in figure 4. As shown by the plot, the resistance of the tube with sodium hydroxide changed very slightly from that of the empty tube. This test corroborates the findings reported in reference 1, wherein the electric resistivity of sodium hydroxide is given as 0.0116 ohm-ft$^2$/ft at $750^{\circ}$ F. When this value is compared with the electric resistivity of Inconel, which is $3.38 \times 10^{-6}$ ohm-ft$^2$/ft at $750^{\circ}$ F, it can be seen that the resistivity of the sodium hydroxide is many times greater than that of the Inconel. Hence it was concluded that the power supplied to the heating test section would generate heat primarily in the tube wall, and the amount generated in the sodium hydroxide can be assumed negligible.

Volume measuring-tank calibration. - The volume measuring tank was calibrated by disconnecting it from the system and passing a salt water solution through it, which would operate the electric contact points. A predetermined weight flow was passed through the volume measuring tank and the measured weight flow was determined by the apparatus. For the range of weight flow encountered in the investigation, the values as determined by the volume measuring tank checked almost exactly with the predetermined values.

Water heat-transfer tests. - For the purpose of establishing the validity of the sodium hydroxide data in the heating test section, heat-transfer tests were run with water on the same heating test section before and after the sodium hydroxide tests were made. The same instrumentation was used, excluding the method of flow measurement. After sodium hydroxide tests were made, the system was flushed with water for several hours prior to making additional water tests. The water-flow rate was determined by weighing the water in a tank after it issued from the test section.

Sodium hydroxide heat-transfer tests. - The test procedure was as follows: The system was purged with nitrogen prior to starting, and a nitrogen atmosphere was maintained on the liquid free surfaces during operation. The starting heaters were then turned on and the entire system was heated until all temperatures were above the melting point of the sodium hydroxide. The pump was then started which caused the circulation of sodium hydroxide through the system. Next, all the starting heaters except the volume-measuring-tank heater were turned off. The fluid velocity was then set at the desired level by controlling the speed of the air motor driving the pump, and the main power supply to the heating test section was set at a desired level. Air in sufficient quantity to match the drop in sodium hydroxide temperature in the cooling test section with the temperature rise in the heating test section was then passed through the annulus of the cooling test section while the cooling test section wall temperatures were kept close to, or above, the melting point of sodium hydroxide. In some cases, where the heat input to the heating test section could not be matched by the cooling test section, the heat exchanger was brought into use to make up the difference and thus maintain a constant inlet temperature to the heating test section. After equilibrium conditions had been obtained, all fluid temperatures, wall temperatures, and power input readings were recorded for both the heating and cooling test sections, and the fluid-flow rate was determined. This procedure was repeated for a range of flow rate and power input.

## METHOD OF CALCULATION

Water heat-transfer coefficients. - Water heat-transfer coefficients were calculated in the conventional manner, which is identical to the method used for sodium hydroxide explained in the succeeding paragraph.

Heat-transfer coefficients for heating test section. - Average heat-transfer coefficients were obtained for the sodium hydroxide heating test section from the equation

$$h = \frac{WC_p\ (T_2 - T_1)}{S\ (T_s - T_b)}$$

All symbols used herein are defined in the appendix.

The average outside-tube wall temperature $T_W$ was obtained from a plot of local outside-tube wall temperature against distance along the test section by planimetering the area under the curve and dividing by the tube length. The average inside-tube wall temperature $T_s$ was then calculated by subtracting the temperature drop through the tube wall from the average outside-tube wall temperature. The drop through the wall was calculated using the following equation, which assumes uniform heat generation throughout the tube wall:

$$T_W - T_s = \frac{Q}{2\pi Lk_I(R_o^2 - R_i^2)}\left(R_o^2 \ln \frac{R_o}{R_i} - \frac{R_o^2 - R_i^2}{2}\right)$$

Heat-transfer coefficients for cooling test section. - Average heat-transfer coefficients were obtained for the sodium hydroxide in the cooling test section from the equation

$$h = \frac{WC_p\ (T_1 - T_2)}{S\ (T_b - T_s)}$$

The average buried-tube wall temperature $T_W'$ was obtained from a plot of the local buried-tube wall temperature against distance along the test section by planimetering the area under the curve and dividing by the tube length. The average inside-tube wall temperature $T_s$ was then calculated by adding the temperature drop through the tube wall to the average buried-tube wall temperature. The drop through the wall was calculated using the following equation, which assumes pure conduction through the tube wall:

$$T_s - T_W' = \frac{Q \ln (R_m/R_i)}{2\pi Lk_I}$$

Physical properties of sodium hydroxide. - The density $\rho$, viscosity $\mu$, and specific heat $C_p$ are plotted against temperature in figure 5. The viscosity was obtained from reference 1; the density, from reference 2; and the specific heat, from reference 3. The thermal conductivity $k$ was assumed to be 0.6 Btu/(hr)(sq ft)($^{\circ}$F/ft) for the range of temperatures encountered in the investigation as reported in reference 3.

The physical properties in this report are evaluated at the average bulk temperature of the fluid.

## RESULTS AND DISCUSSION

The basic data obtained in this investigation for heating and cooling are listed in tables I and II, respectively.

Water heat-transfer tests. - Water heat-transfer tests were run before and after the sodium hydroxide data were obtained. The same heating test section was used for all the runs. The results are shown in figure 6, where the Nusselt number divided by the Prandtl number raised to the 0.4 power $Nu/Pr^{0.4}$ is plotted against the Reynolds number $Re$. Water data obtained both before and after the sodium hydroxide tests are shown. There are three sets of water data shown: one for water runs before any sodium hydroxide was used, a second for water runs after the first set of sodium hydroxide runs was made, and a third for water runs after the second set of sodium hydroxide runs was made. Fairly good agreement between the water data and the McAdams correlation line (ref. 4) was obtained for all three sets of data, with the water data having a slightly greater slope. Also included for comparison is the correlation line obtained in reference 5. The water data show very good agreement with the correlation line of reference 5.

These data indicate that the instrumentation of the heating test section is fundamentally correct, and furthermore, that the inner-tube wall surface was not affected, so far as heat transfer is concerned, by exposure to the flowing sodium hydroxide in that the water heat-transfer data were not altered.

No water heat-transfer tests were made with the cooling test section because of the relatively small temperature difference between the heated water and the cooling air. This would result in an extremely small temperature drop of the water, and hence make the accuracy of any data obtained very doubtful.

Heat balance. - The heat balance for the water heat-transfer data checked within 5 percent.

The heat balance with sodium hydroxide for the heating test section is shown in figure 7, where the heat transferred to the sodium hydroxide $Q$ as determined from the flow rate, specific heat, and increase in total temperature is plotted against the total electric heat input $Q_P$ minus the external heat loss $Q_L$. A 45° line is drawn to represent the perfect heat-balance condition. The external heat loss was determined by supplying various amounts of power to the test section with no sodium hydroxide flowing. The power input for a given average tube-wall temperature was considered to be the external heat loss for the same average wall temperature with sodium hydroxide flowing through the tube. All the data, with the exception of two points, have a maximum deviation of 10 percent from the 45° line.

No attempt was made to obtain a heat balance on the cooling test section, since the cooling-air temperature and weight flow were not measured.

Tube-wall temperature distribution. - Representative axial temperature distributions of outside-tube wall temperatures are shown in figure 8(a) for the heating test section. The slight irregularity at the center and the drop off at the ends are caused by the comparatively large mass of metal in the electric flanges. Representative axial temperature distributions of the buried-tube wall temperatures are shown in figure 8(b) for the cooling test section.

Some of the thermocouples were inoperative for the runs shown, but a sufficient number remained to give a smooth temperature distribution curve.

Sodium hydroxide heat-transfer data for heating test section. - The sodium hydroxide heat-transfer data are correlated by the familiar Nusselt relation, where the Nusselt number divided by the Prandtl number raised to the 0.4 power $Nu/Pr^{0.4}$ is plotted against the Reynolds number $Re$. A plot of $Nu/Pr^{0.4}$ against $Re$ is shown in figure 9(a) for the heating data. Included for comparison are the McAdams correlation line and the sodium hydroxide correlation line obtained from reference 3. It is seen that the data fall approximately 20 percent above the McAdams correlation line and about 33 percent above the line from reference 3. The sodium hydroxide data were run in two sets, and the plot indicates that there is no apparent change in the heat-transfer coefficient with time. Since a constant value of thermal conductivity was used in the calculations, the correlation may be altered as new physical property data are made available.

Sodium hydroxide heat-transfer data for cooling test section. - A plot of $Nu/Pr^{0.4}$ against $Re$ is shown in figure 9(b) for the cooling data. The McAdams correlation line is included for comparison. The bulk of the data agree fairly well with the McAdams line; however, several scattered points are high.

A comparison of figures 9(a) and 9(b) shows that the heating data are higher than the cooling data but have the same slope.

It should be noted that when the buried thermocouple was positioned in the cooling-test-section wall, the exact location could not be determined. Upon completion of the tests, however, the cooling test section was removed from the test setup, the thermocouple locations were sectioned, and the junction location was measured as accurately as possible.

Heat-transfer coefficients for an aqueous solution of sodium hydroxide. - Average heat-transfer coefficients for a 50 percent by weight aqueous solution of sodium hydroxide are shown in figure 10, where the product of the heat-transfer coefficient and diameter hD is plotted against the product of the mass flow per unit cross-sectional area and the diameter GD. Included for comparison are the water data and the sodium hydroxide data, as well as the lines representing the water and sodium hydroxide data as determined from the McAdams equation. The sodium hydroxide data fall below the water data, and the data for a 50 percent by weight solution of sodium hydroxide and water fall considerably below both the water and sodium hydroxide data. A plot of this type was used because the thermal conductivity of the aqueous solution was not known.

The experimental setup was not designed to test this solution. A considerable amount of scatter is present in the data, and it is felt that the scatter is caused by a constantly varying temperature level of the system.

Remarks on test setup. - Visual inspection of the system in contact with the sodium hydroxide indicated that no serious corrosion took place. The exposed surfaces, however, had a black appearance. The test setup was under flow conditions for approximately 50 hours in the temperature range from 700° to 900° F.

The sodium hydroxide flowed out onto the sump tank cover by creeping up the rotating pump shaft. This leak was remedied by placing a slinger ring on the pump shaft directly underneath the cover plate.

One leak also occurred in the outlet mixing tank of the heating test section, but this was caused by a faulty weld.

A chemical analysis of the sodium hydroxide in the cold trap was made upon completion of the sodium hydroxide tests. This analysis showed the presence of only very slight traces of iron, chromium, and nickel.

## SUMMARY OF RESULTS

Heat-transfer tests for the heating and cooling of sodium hydroxide flowing through an Inconel tube with Reynolds number from 5300 to 30,000, corresponding velocities from 3.8 to 15.4 feet per second, average fluid temperatures up to 938° F, and heat-flux densities up to 226,000 Btu per hour per square foot, gave the following results:

1. The heat-transfer data obtained in the heating tests were correlated according to the familiar Nusselt relation. The heat-transfer data are 20 percent higher than predicted from the McAdams correlation line.

2. The heat-transfer data obtained in the cooling tests were correlated according to the familiar Nusselt relation. The data agree fairly well with the McAdams correlation line.

3. Correlation with the McAdams line may be altered as new physical property data for sodium hydroxide are made available.

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## APPENDIX - SYMBOLS

The following symbols are used in this report:

$C_p$ specific heat, Btu/(lb)($^{\circ}$F)

D inside diameter of heating and cooling test sections, ft

G mass flow per unit cross-sectional area, lb/(hr)(sq ft)

h average heat-transfer coefficient, Btu/(hr)(sq ft)($^{\circ}$F)

k thermal conductivity, Btu/(hr)(sq ft)($^{\circ}$F/ft)

$k_I$ thermal conductivity of Inconel, Btu/(hr)(sq ft)($^{\circ}$F/ft)

L effective heat-transfer length of heating and cooling test sections, ft

Q rate of heat transfer, Btu/hr

$Q_L$ external heat loss, Btu/hr

$Q_P$ rate of electric power input to heating test section, Btu/hr

$R_i$ inner radius of heating and cooling test sections, ft

$R_o$ outer radius of heating test section, ft

$R_m$ radius to buried thermocouple junction in cooling test section, ft

S heat-transfer area of heating and cooling test sections, sq ft

$T_1$ temperature at entrance to heating and cooling test sections, $^{\circ}$F

$T_2$ temperature at exit of heating and cooling test sections, $^{\circ}$F

$T_b$ average bulk temperature $(T_1 + T_2)/2$, $^{\circ}$F

$T_s$ average inside-tube wall temperature of heating and cooling test sections, $^{\circ}$F

$T_w$ average outside-tube wall temperature of heating test section, $^{\circ}$F

$T_w'$ average buried-tube wall temperature of cooling test section, $^{\circ}$F

V velocity, ft/hr

W rate of flow, lb/hr

$\mu$ absolute viscosity, lb/(hr)(ft)

$\rho$ density, lb/cu ft

Nu Nusselt number $hD/k$

Pr Prandtl number $C_p\mu/k$

Re Reynolds number $GD/\mu$

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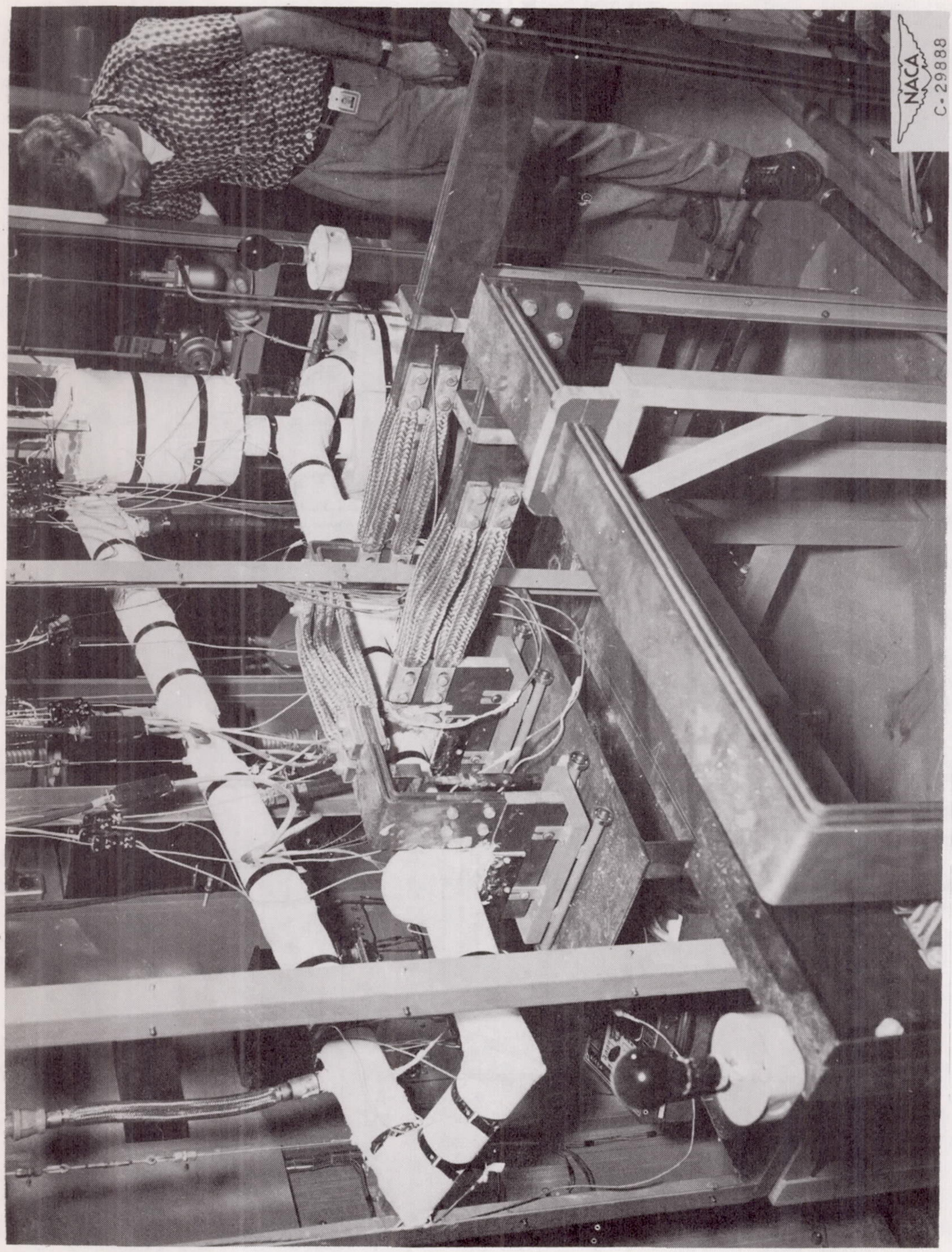
TABLE I. - BASIC EXPERIMENTAL HEATING DATA

| Run | $T_1$, °F | $T_2-T_1$, °F | $T_w$, °F | $T_s$, °F | W, lb/hr | V, ft/hr | $G\times10^{-6}$, lb/(hr)(sq ft) | Q, Btu/hr | $Q/S \times 10^{-3}$, Btu/(hr)(sq ft) | h, Btu/(hr)(sq ft)(°F) | Nu | Pr | Re |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 858 | 15.0 | 914.2 | 889.8 | 2144 | 55,109 | 6.287 | 15,652 | 119.5 | 4917 | 170.4 | 4.104 | 25,845 |
| 2 | 865 | 14.9 | 921.0 | 897.2 | 2119 | 54,519 | 6.214 | 15,294 | 116.7 | 4708 | 163.2 | 4.021 | 25,954 |
| 3 | 881 | 18.9 | 948.0 | 918.2 | 2139 | 55,189 | 6.273 | 19,332 | 147.6 | 5308 | 184.0 | 3.818 | 27,239 |
| 4 | 904 | 29.3 | 1011.6 | 967.4 | 2134 | 55,293 | 6.258 | 29,331 | 223.9 | 4588 | 159.1 | 3.510 | 28,990 |
| 5 | 867 | 22.8 | 940.7 | 910.2 | 1799 | 46,331 | 5.276 | 19,787 | 151.0 | 4750 | 164.7 | 3.956 | 22,304 |
| 6 | 847 | 27.6 | 941.7 | 904.8 | 1777 | 45,640 | 5.211 | 23,939 | 182.7 | 4153 | 144.0 | 4.157 | 21,212 |
| 7 | 766 | 20.8 | 835.9 | 810.0 | 1505 | 38,169 | 4.413 | 16,162 | 123.4 | 3672 | 127.3 | 5.395 | 14,641 |
| 8 | 793 | 31.2 | 900.7 | 863.4 | 1511 | 38,504 | 4.431 | 23,845 | 182.0 | 3322 | 115.2 | 4.839 | 16,057 |
| 9 | 752 | 24.6 | 828.7 | 804.4 | 1182 | 29,923 | 3.466 | 15,129 | 115.5 | 2880 | 99.8 | 5.646 | 11,075 |
| 10 | 779 | 37.4 | 898.0 | 862.2 | 1199 | 30,506 | 3.516 | 22,829 | 174.3 | 2702 | 93.7 | 4.887 | 12,697 |
| 11 | 770 | 32.5 | 866.5 | 840.3 | 992 | 25,201 | 2.910 | 16,546 | 126.3 | 2335 | 80.9 | 5.208 | 9,938 |
| 12 | 740 | 25.6 | 817.1 | 798.9 | 842 | 21,279 | 2.469 | 11,299 | 86.3 | 1871 | 64.9 | 5.897 | 7,609 |
| 13 | 746 | 31.7 | 834.9 | 813.1 | 823 | 20,816 | 2.412 | 13,591 | 103.8 | 2022 | 70.1 | 5.707 | 7,637 |
| 14 | 800 | 43.0 | 911.3 | 892.2 | 567 | 14,488 | 1.664 | 12,228 | 93.3 | 1320 | 45.8 | 4.653 | 6,214 |
| 15 | 795 | 15.9 | 855.9 | 828.3 | 2149 | 54,720 | 6.302 | 17,341 | 132.4 | 5222 | 181.0 | 4.931 | 22,484 |
| 16 | 842 | 27.7 | 946.1 | 900.3 | 2187 | 56,131 | 6.413 | 29,684 | 226.6 | 5098 | 176.7 | 4.214 | 25,853 |
| 17 | 806 | 14.8 | 854.6 | 833.6 | 1766 | 45,038 | 5.179 | 13,170 | 100.5 | 4977 | 172.5 | 4.770 | 18,965 |
| 18 | 810 | 26.4 | 903.2 | 867.4 | 1733 | 44,258 | 5.082 | 22,912 | 174.9 | 3957 | 137.2 | 4.632 | 19,047 |
| 19 | 786 | 16.7 | 839.3 | 818.4 | 1534 | 39,009 | 4.499 | 13,068 | 99.8 | 4148 | 143.8 | 5.084 | 15,647 |
| 20 | 837 | 31.8 | 941.0 | 903.4 | 1562 | 40,069 | 4.581 | 24,384 | 186.1 | 3686 | 127.8 | 4.246 | 18,358 |
| 21 | 785 | 20.3 | 847.2 | 826.5 | 1254 | 31,892 | 3.677 | 12,983 | 99.1 | 3161 | 109.6 | 5.066 | 12,834 |
| 22 | 848 | 38.2 | 962.2 | 925.4 | 1292 | 33,215 | 3.789 | 23,996 | 183.2 | 3142 | 108.9 | 4.084 | 15,636 |
| 23 | 793 | 23.8 | 859.4 | 839.0 | 1062 | 27,049 | 3.114 | 12,812 | 97.8 | 2868 | 99.4 | 4.900 | 11,169 |
| 24 | 721 | 15.0 | 765.8 | 752.5 | 1030 | 25,936 | 3.021 | 8,222 | 62.8 | 2637 | 91.4 | 6.599 | 8,444 |
| 25 | 700 | 15.1 | 744.1 | 732.6 | 853 | 21,406 | 2.501 | 6,943 | 53.0 | 2120 | 73.5 | 7.279 | 6,422 |
| 26 | 761 | 28.6 | 843.1 | 822.3 | 879 | 22,291 | 2.578 | 12,994 | 99.2 | 2110 | 73.2 | 5.426 | 8,511 |
| 27 | 769 | 20.3 | 824.5 | 812.7 | 700 | 17,766 | 2.053 | 7,326 | 55.9 | 1669 | 57.9 | 5.352 | 6,856 |
| 28 | 768 | 26.3 | 836.8 | 825.1 | 541 | 13,740 | 1.588 | 7,329 | 55.9 | 1274 | 44.2 | 5.310 | 5,335 |

TABLE II. - BASIC EXPERIMENTAL COOLING DATA

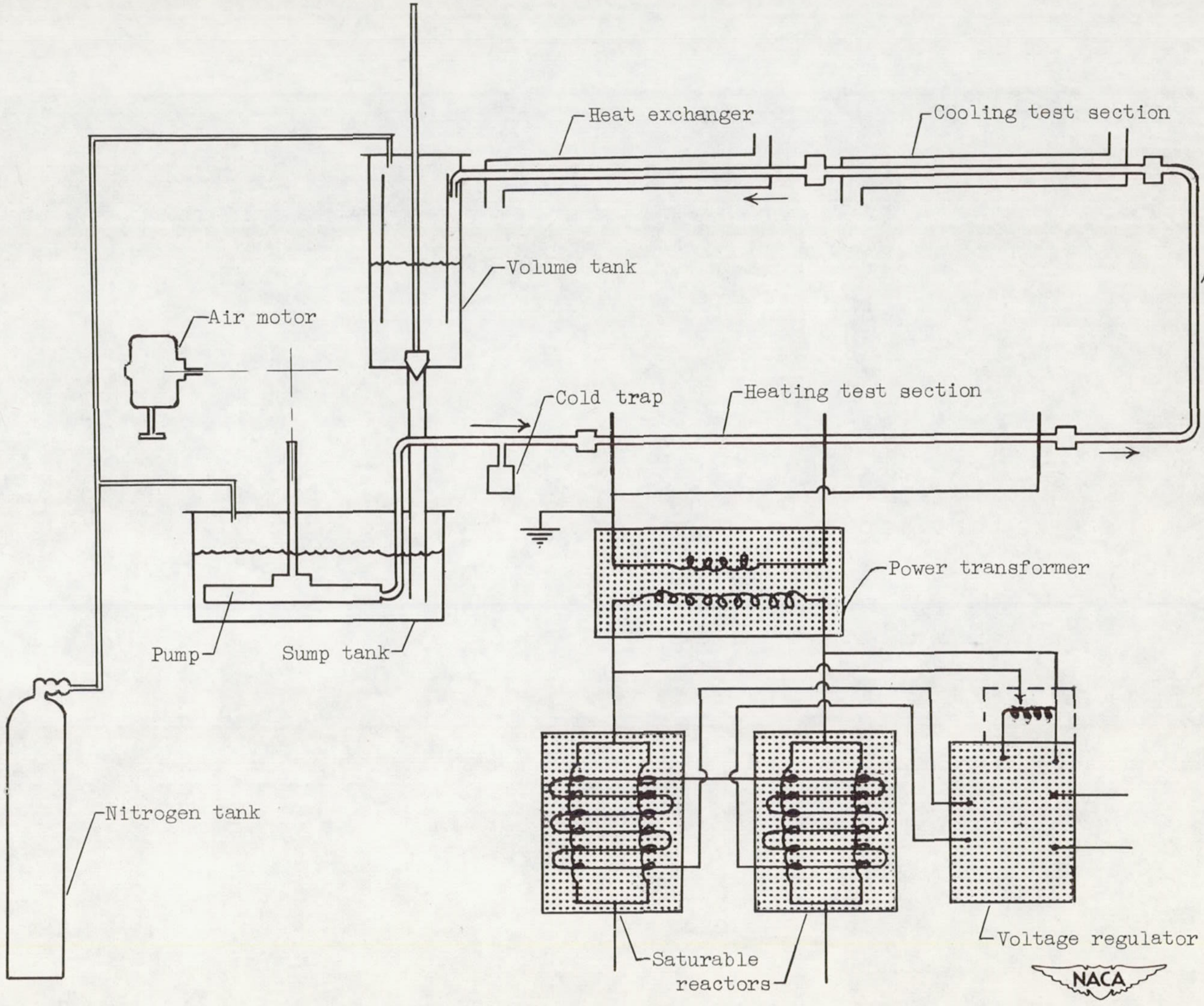
| Run | $T_1$, $^{\circ}F$ | $T_1-T_2$, $^{\circ}F$ | $T_w'$, $^{\circ}F$ | $T_s$, $^{\circ}F$ | W, $\frac{lb}{hr}$ | V, $\frac{ft}{hr}$ | $G \times 10^{-6}$, $\frac{lb}{(hr)(sq\ ft)}$ | Q, $\frac{Btu}{hr}$ | $Q/S \times 10^{-3}$, $\frac{Btu}{(hr)(sq\ ft)}$ | h $\frac{Btu}{(hr)(sq\ ft)(^{\circ}F)}$ | Nu | Pr | Re |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 881 | 7.2 | 852.1 | 868.0 | 2144 | 55,211 | 6.287 | 7,451 | 56.88 | 6044 | 209.5 | 3.958 | 26,581 |
| 2 | 889 | 7.6 | 860.0 | 876.4 | 2119 | 54,629 | 6.214 | 7,730 | 59.01 | 6728 | 233.2 | 3.872 | 26,705 |
| 3[a] | | | | | | | | | | | | | |
| 4 | 944 | 12.6 | 889.2 | 915.4 | 2134 | 55,460 | 6.258 | 12,441 | 94.97 | 4255 | 147.5 | 3.316 | 30,272 |
| 5 | 892 | 13.8 | 830.4 | 856.0 | 1799 | 46,379 | 5.276 | 11,917 | 90.97 | 3127 | 108.4 | 3.880 | 22,625 |
| 6 | 880 | 14.9 | 819.2 | 846.9 | 1777 | 45,724 | 5.211 | 12,823 | 97.88 | 3806 | 131.9 | 4.020 | 21,766 |
| 7 | 790 | 14.7 | 727.0 | 752.4 | 1505 | 38,205 | 4.413 | 11,376 | 86.84 | 2877 | 99.7 | 5.288 | 14,878 |
| 8 | 834 | 12.8 | 782.8 | 803.9 | 1511 | 38,615 | 4.431 | 9,657 | 73.72 | 3114 | 108.0 | 4.577 | 16,758 |
| 9 | 778 | 14.2 | 723.5 | 743.0 | 1182 | 29,951 | 3.466 | 8,696 | 66.38 | 2376 | 82.4 | 5.509 | 11,301 |
| 10 | 825 | 13.6 | 784.4 | 802.3 | 1199 | 30,599 | 3.516 | 8,192 | 62.53 | 3935 | 136.4 | 4.697 | 13,037 |
| 11 | 807 | 15.9 | 754.3 | 772.0 | 992 | 25,247 | 2.910 | 8,027 | 61.28 | 2274 | 78.8 | 5.003 | 10,258 |
| 12 | 770 | 13.1 | 723.8 | 736.6 | 842 | 21,312 | 2.469 | 5,743 | 43.84 | 1639 | 56.8 | 5.667 | 7,865 |
| 13 | 782 | 10.4 | 751.5 | 761.3 | 823 | 20,862 | 2.412 | 4,415 | 33.70 | 2172 | 75.3 | 5.385 | 8,015 |
| 14[a] | | | | | | | | | | | | | |
| 15 | 820 | 9.3 | 782.3 | 804.3 | 2149 | 54,820 | 6.302 | 10,059 | 76.79 | 6924 | 240.0 | 4.739 | 23,201 |
| 16 | 882 | 14.9 | 814.2 | 848.3 | 2187 | 56,293 | 6.413 | 15,759 | 120.30 | 4569 | 158.4 | 3.998 | 26,895 |
| 17 | 825 | 11.5 | 779.2 | 801.5 | 1766 | 45,077 | 5.179 | 10,195 | 77.82 | 4407 | 152.8 | 4.685 | 19,236 |
| 18 | 846 | 17.8 | 766.0 | 799.7 | 1733 | 44,354 | 5.082 | 15,303 | 116.82 | 3124 | 108.3 | 4.440 | 19,685 |
| 19 | 807 | 11.0 | 766.7 | 786.0 | 1534 | 39,050 | 4.499 | 8,766 | 66.92 | 4314 | 149.6 | 5.065 | 15,995 |
| 20 | 880 | 16.3 | 815.9 | 842.6 | 1562 | 40,185 | 4.581 | 12,338 | 94.18 | 3221 | 111.7 | 4.030 | 19,094 |
| 21 | 810 | 15.1 | 754.5 | 775.8 | 1254 | 31,928 | 3.677 | 9,612 | 73.37 | 2755 | 95.5 | 4.941 | 13,098 |
| 22 | 895 | 20.0 | 823.2 | 849.9 | 1292 | 33,308 | 3.789 | 12,403 | 94.68 | 2700 | 93.6 | 3.880 | 16,249 |
| 23 | 817 | 22.1 | 739.8 | 766.2 | 1062 | 27,053 | 3.114 | 11,888 | 90.75 | 2282 | 79.1 | 4.888 | 11,188 |
| 24 | 740 | 12.1 | 693.1 | 708.1 | 1030 | 25,956 | 3.021 | 6,607 | 50.44 | 1944 | 67.4 | 6.414 | 8,654 |
| 25 | 720 | 8.2 | 691.4 | 699.9 | 853 | 21,434 | 2.501 | 3,752 | 28.64 | 1790 | 62.0 | 6.994 | 6,652 |
| 26[a] | | | | | | | | | | | | | |
| 27[a] | | | | | | | | | | | | | |
| 28[a] | | | | | | | | | | | | | |

[a]No cooling data were taken during runs 3, 14, 26, 27, and 28.




(a) Over-all view.

Figure 1. - Test setup.




(b) Schematic drawing.

Figure 1. - Concluded. Test setup.

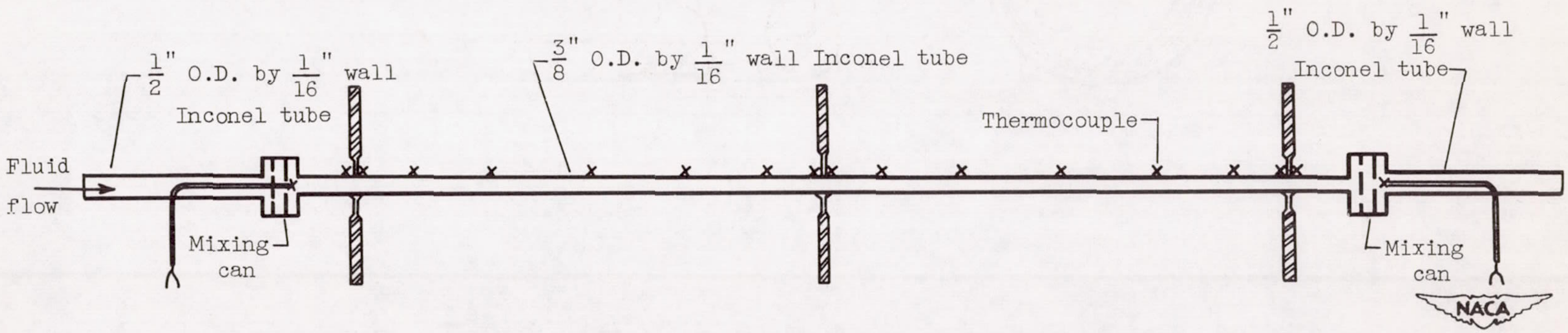



Figure 2. - Schematic drawing of heating test section.

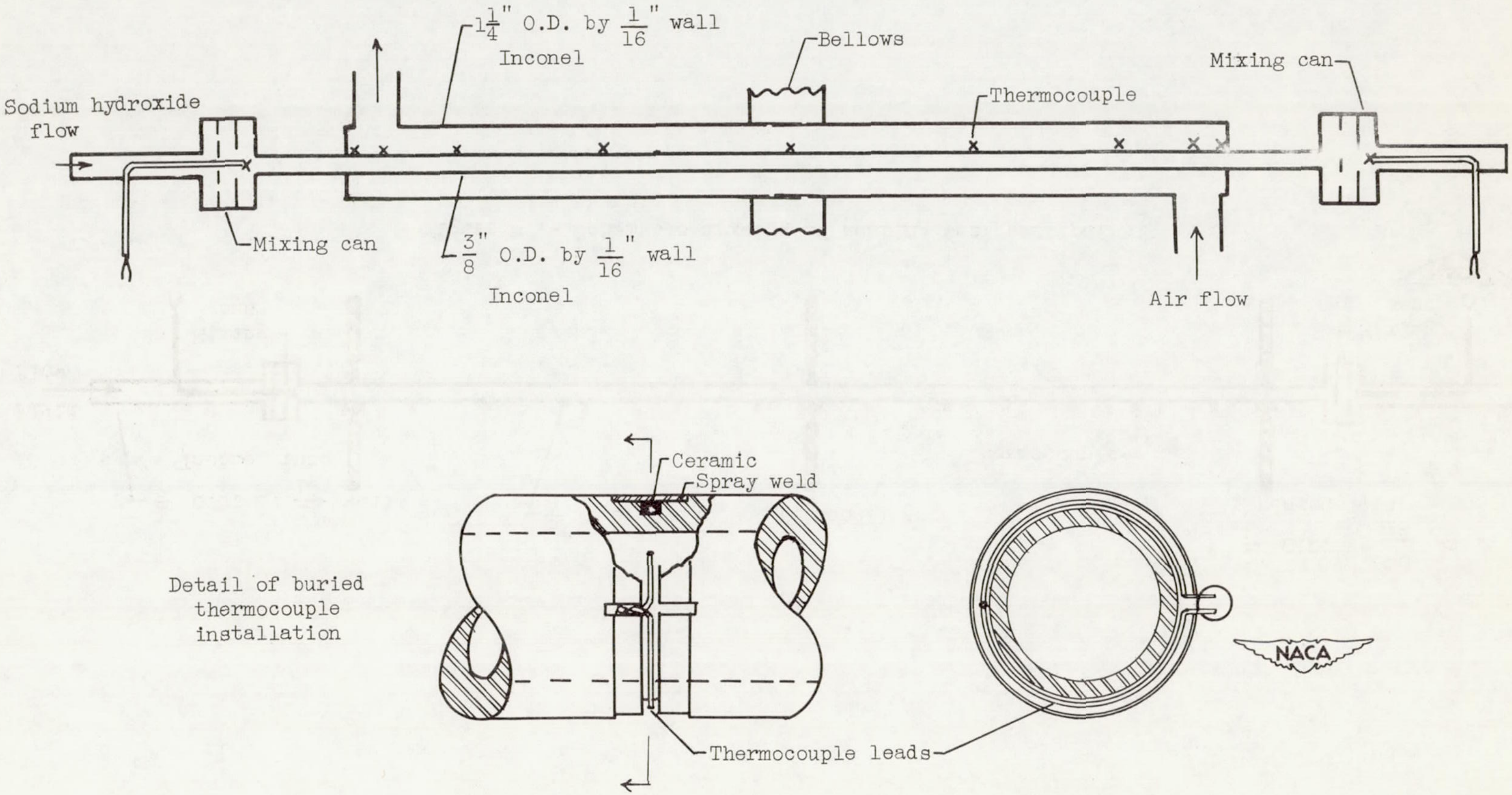



Figure 3. - Schematic drawing of cooling test section.

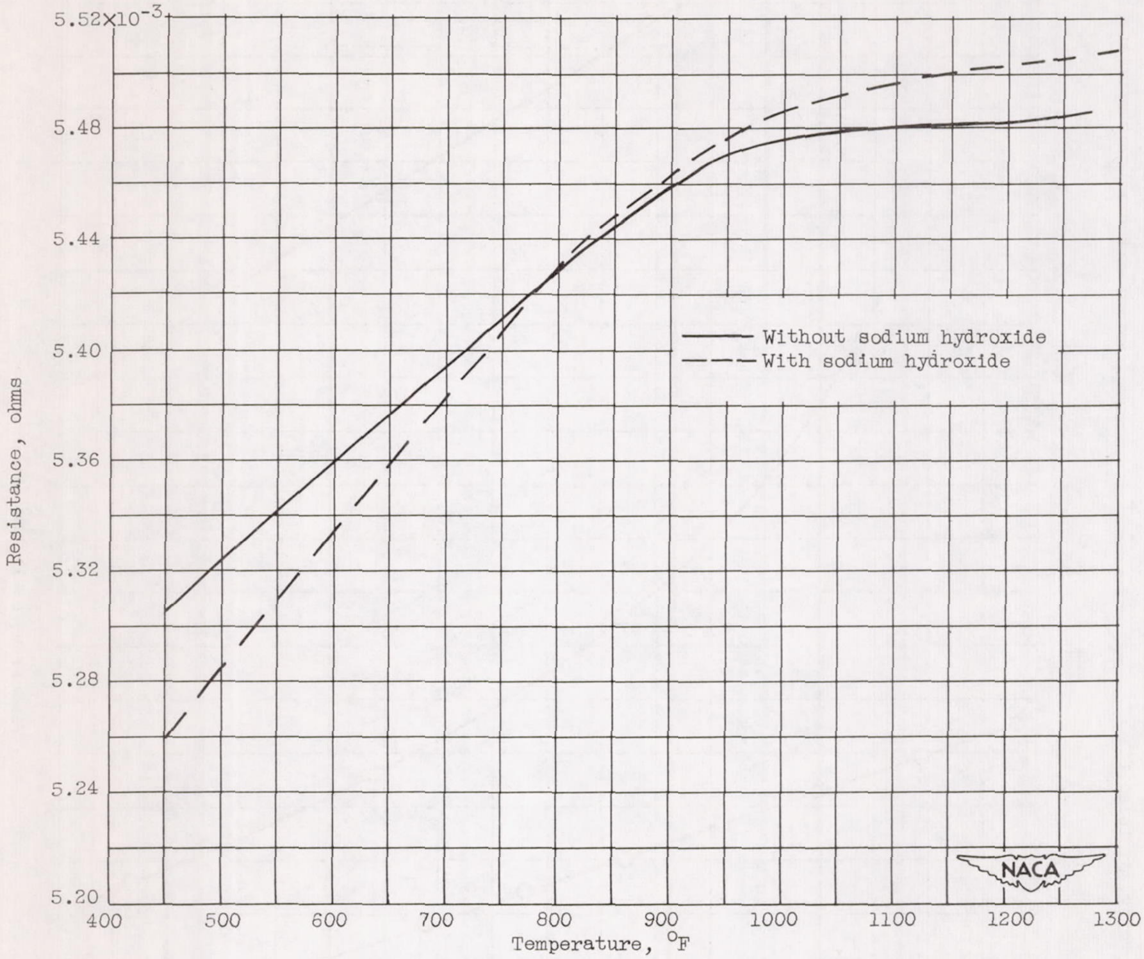



Figure 4. - Measured resistance of Inconel tube with and without sodium hydroxide.

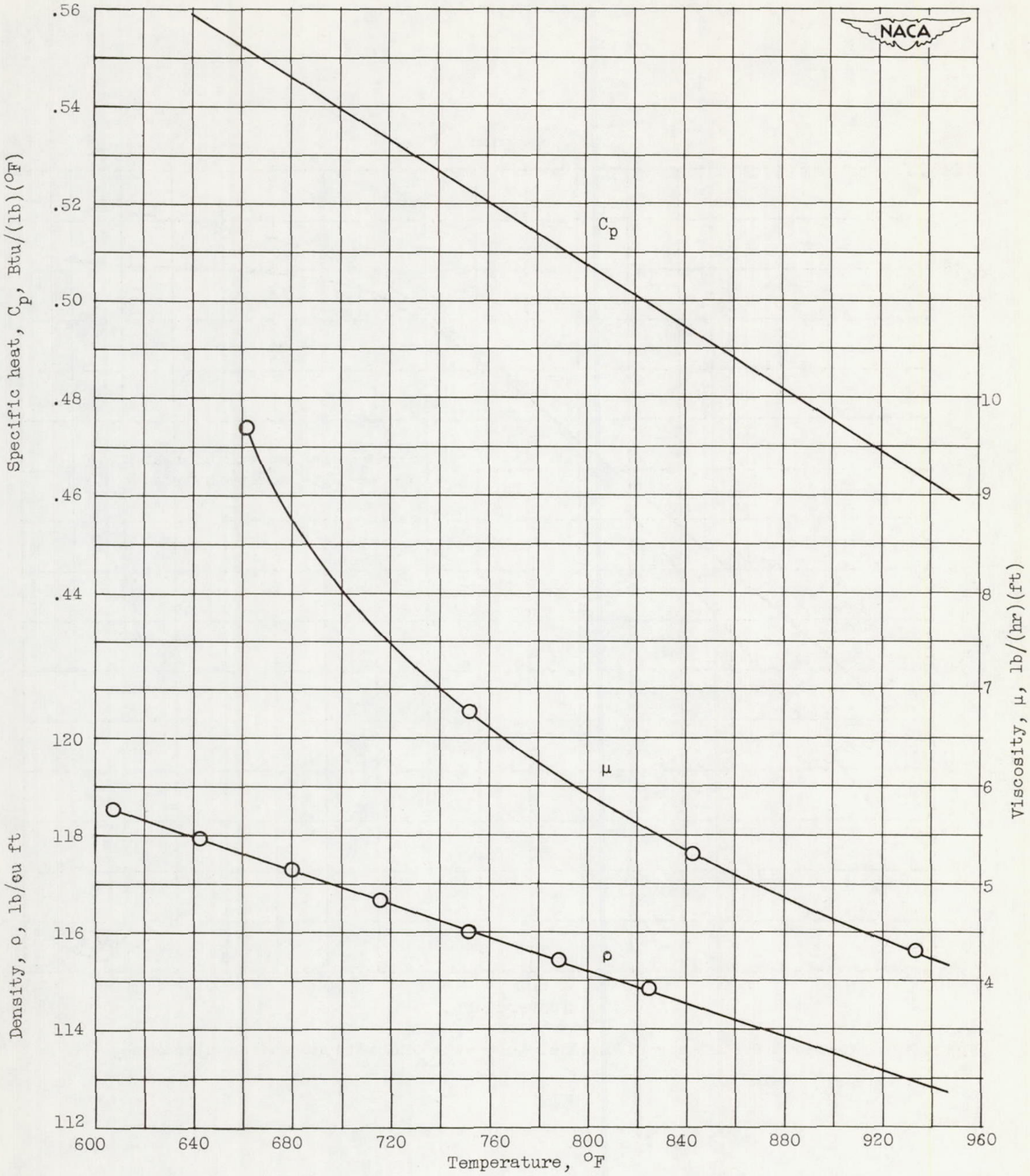



Figure 5. - Variation of specific heat, viscosity, and density of sodium hydroxide with temperature.

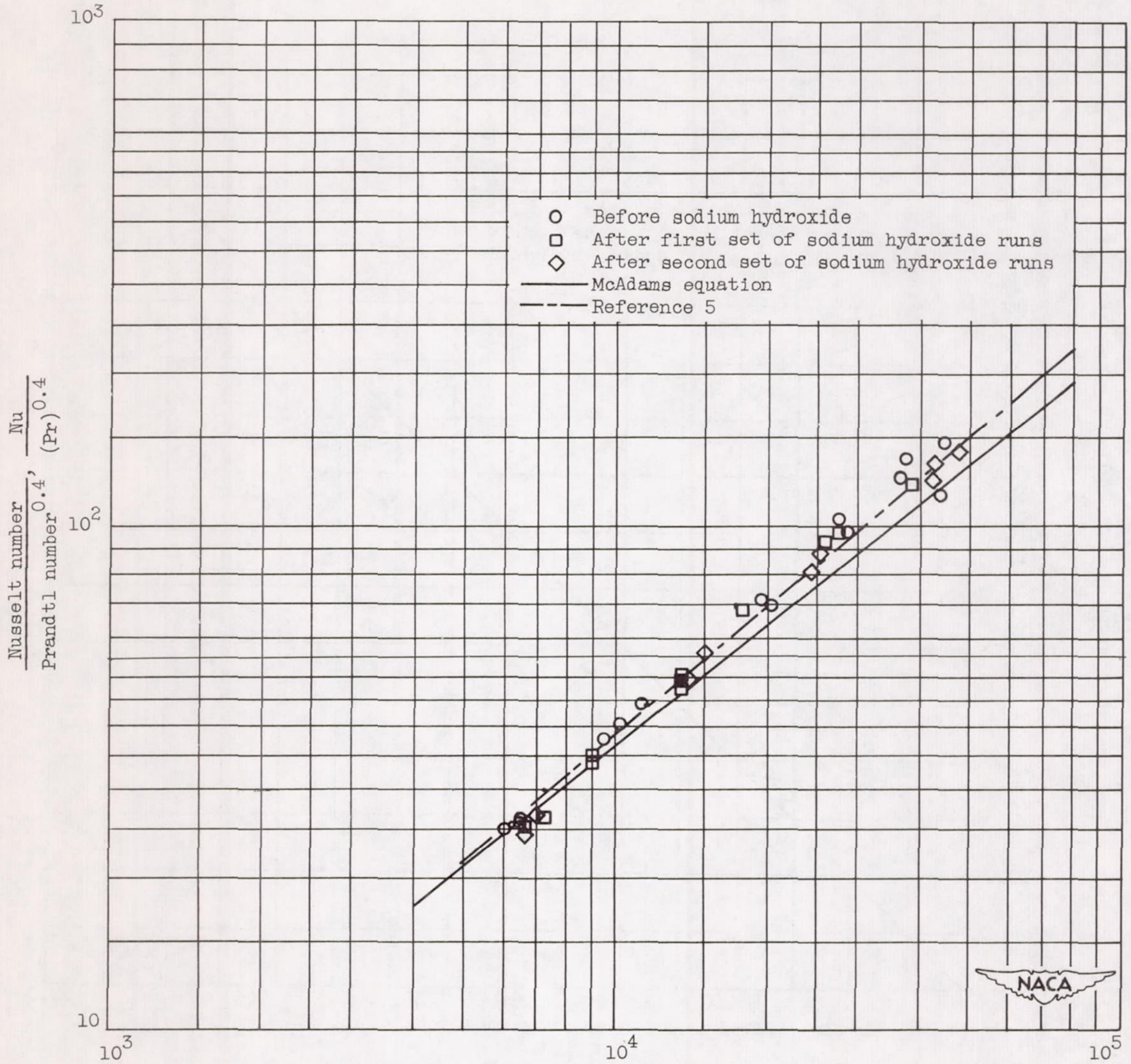



Figure 6. - Water heat-transfer data.

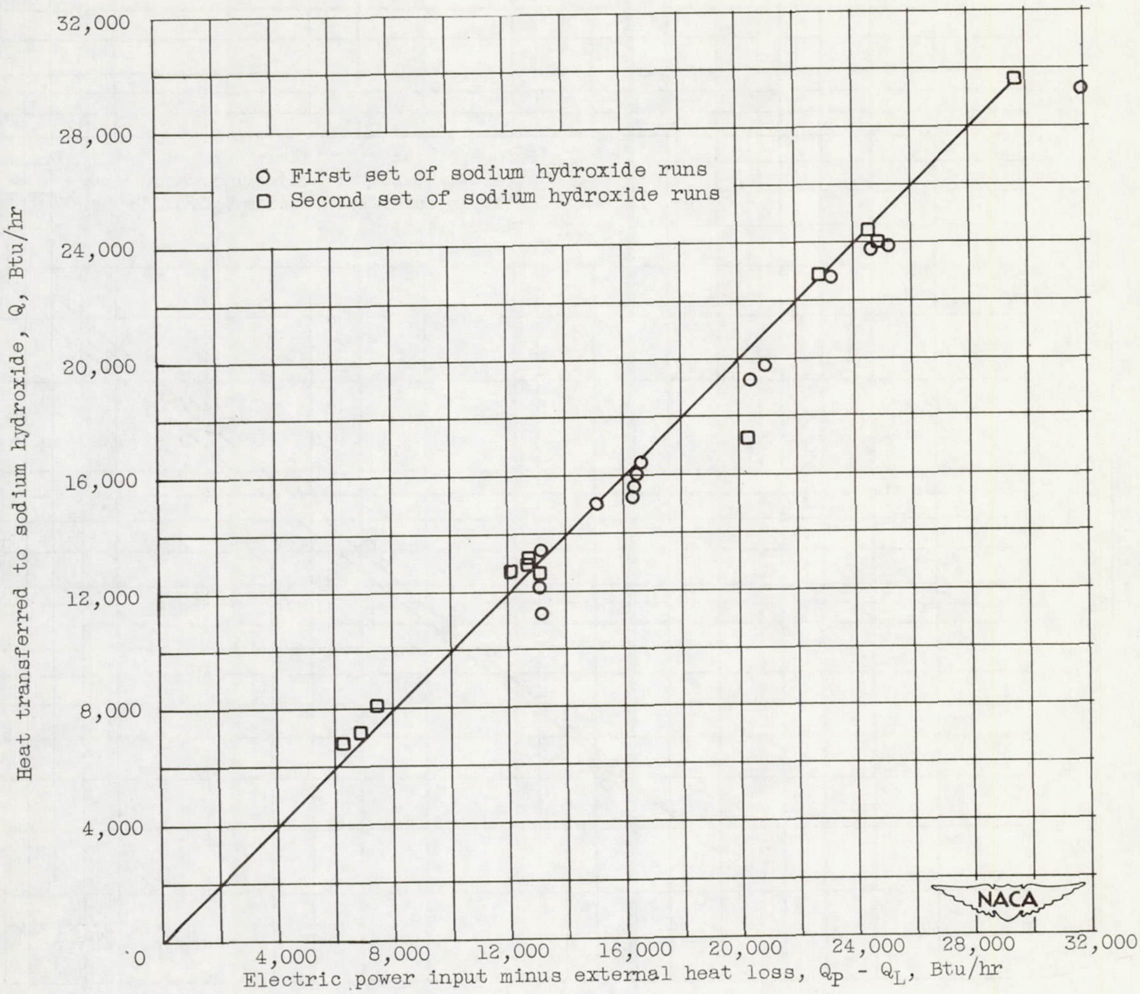
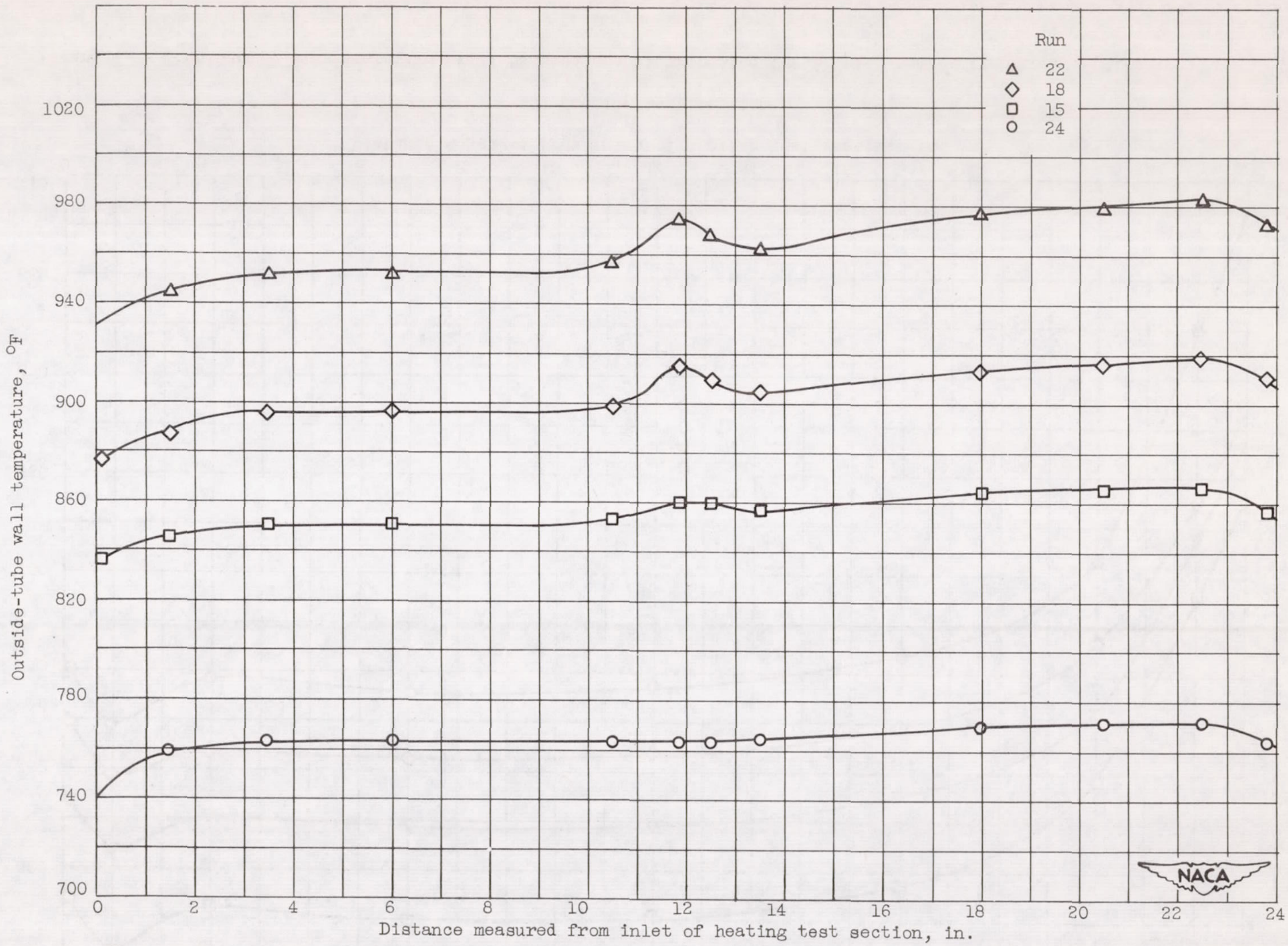
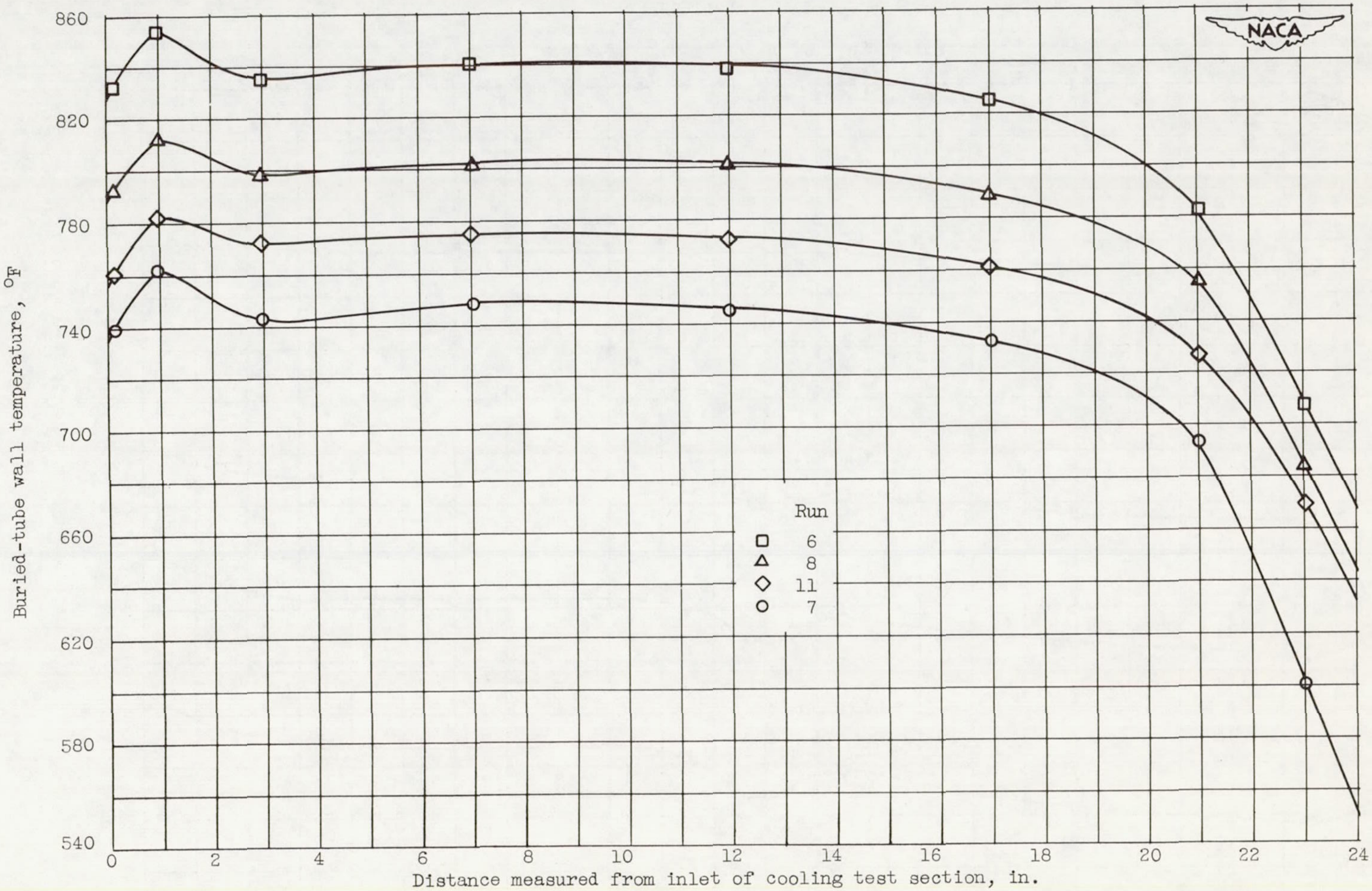



Figure 7. - Heat balance for sodium hydroxide.



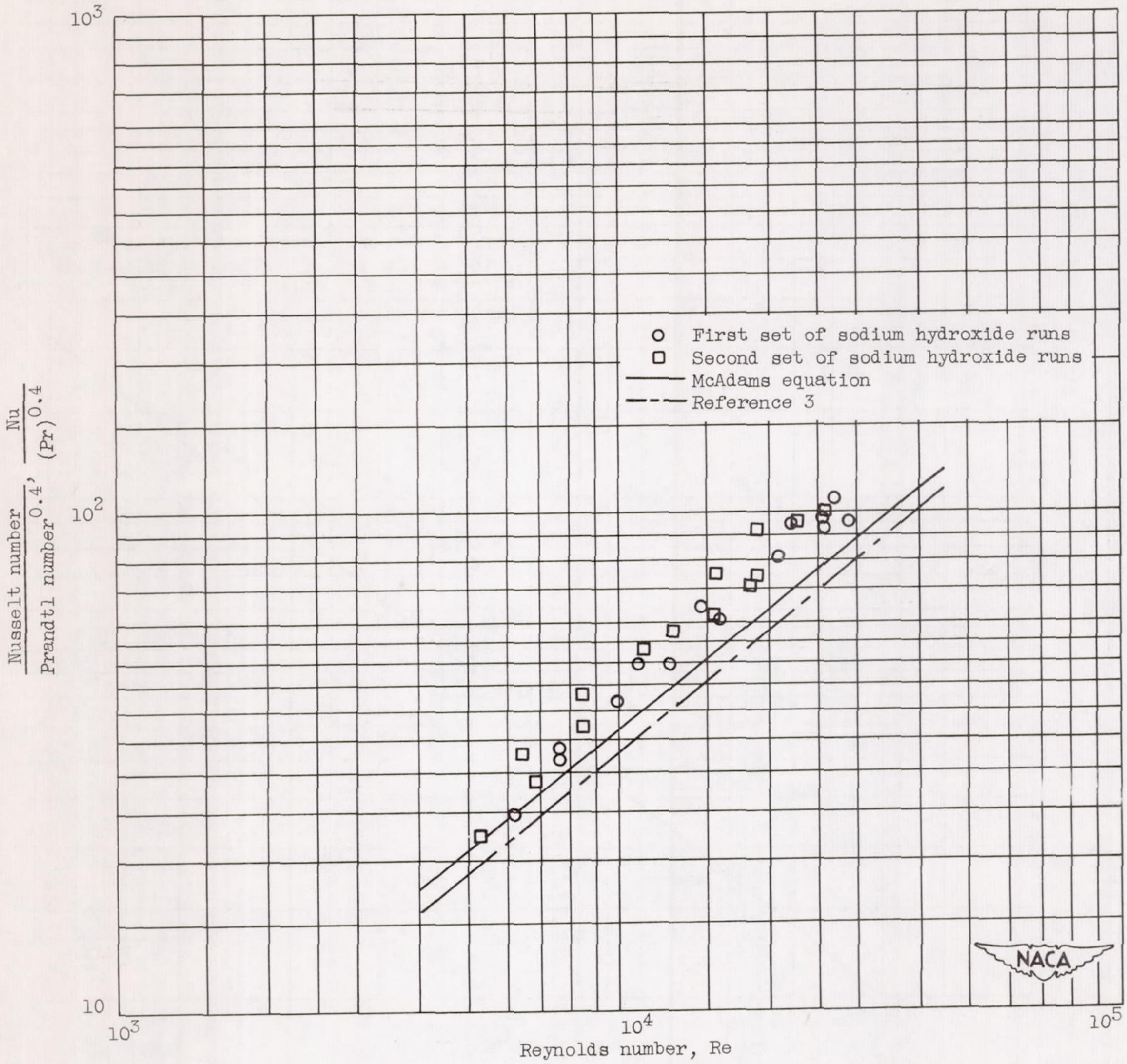

(a) Heating test section.

Figure 8. - Representative axial temperature distribution for heating and cooling test sections.



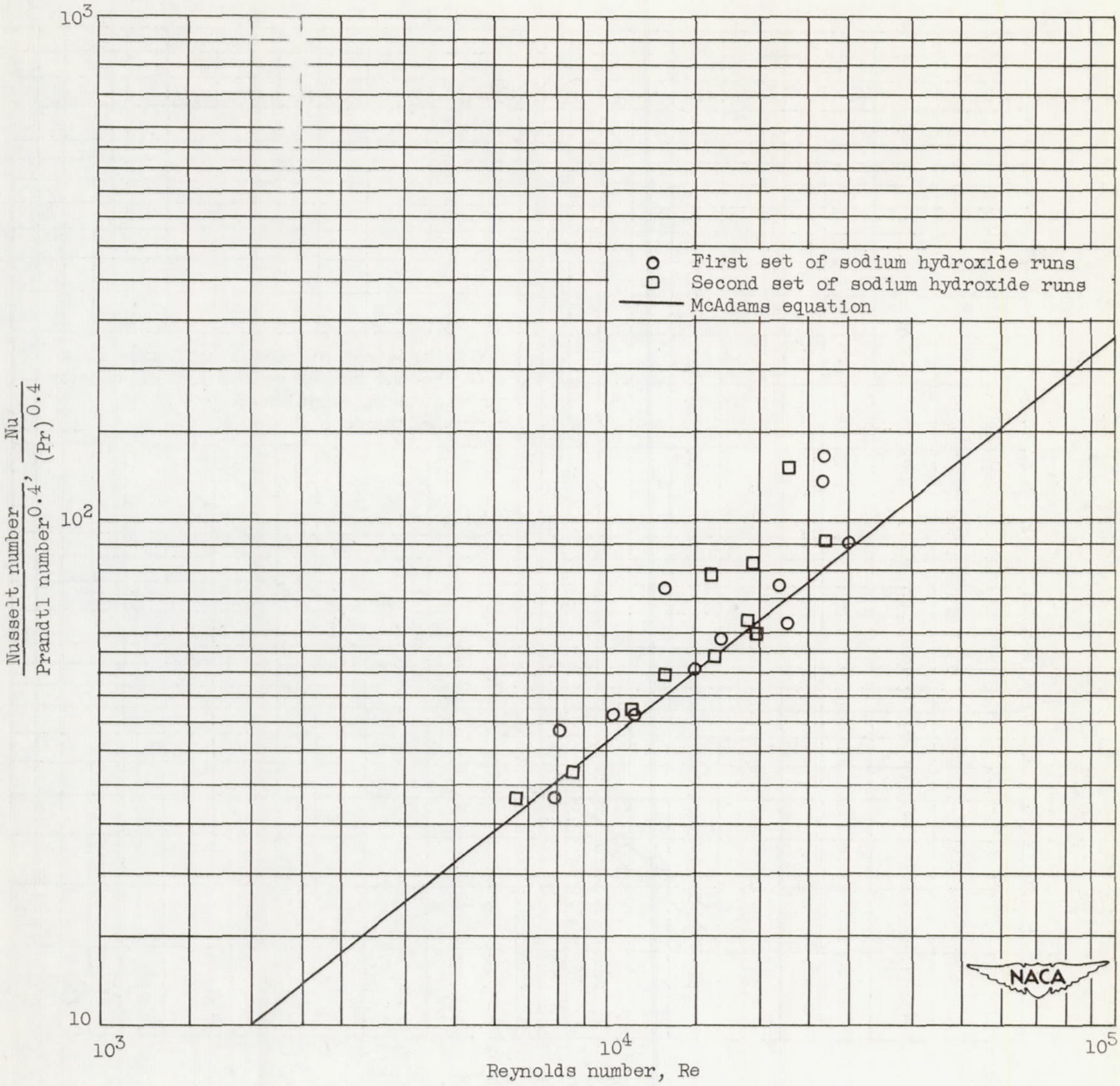

(b) Cooling test section.

Figure 8. - Concluded. Representative axial temperature distribution for heating and cooling test sections.




(a) Heating data.

Figure 9. - Sodium hydroxide heating and cooling data.




(b) Cooling data.

Figure 9. - Concluded. Sodium hydroxide heating and cooling data.

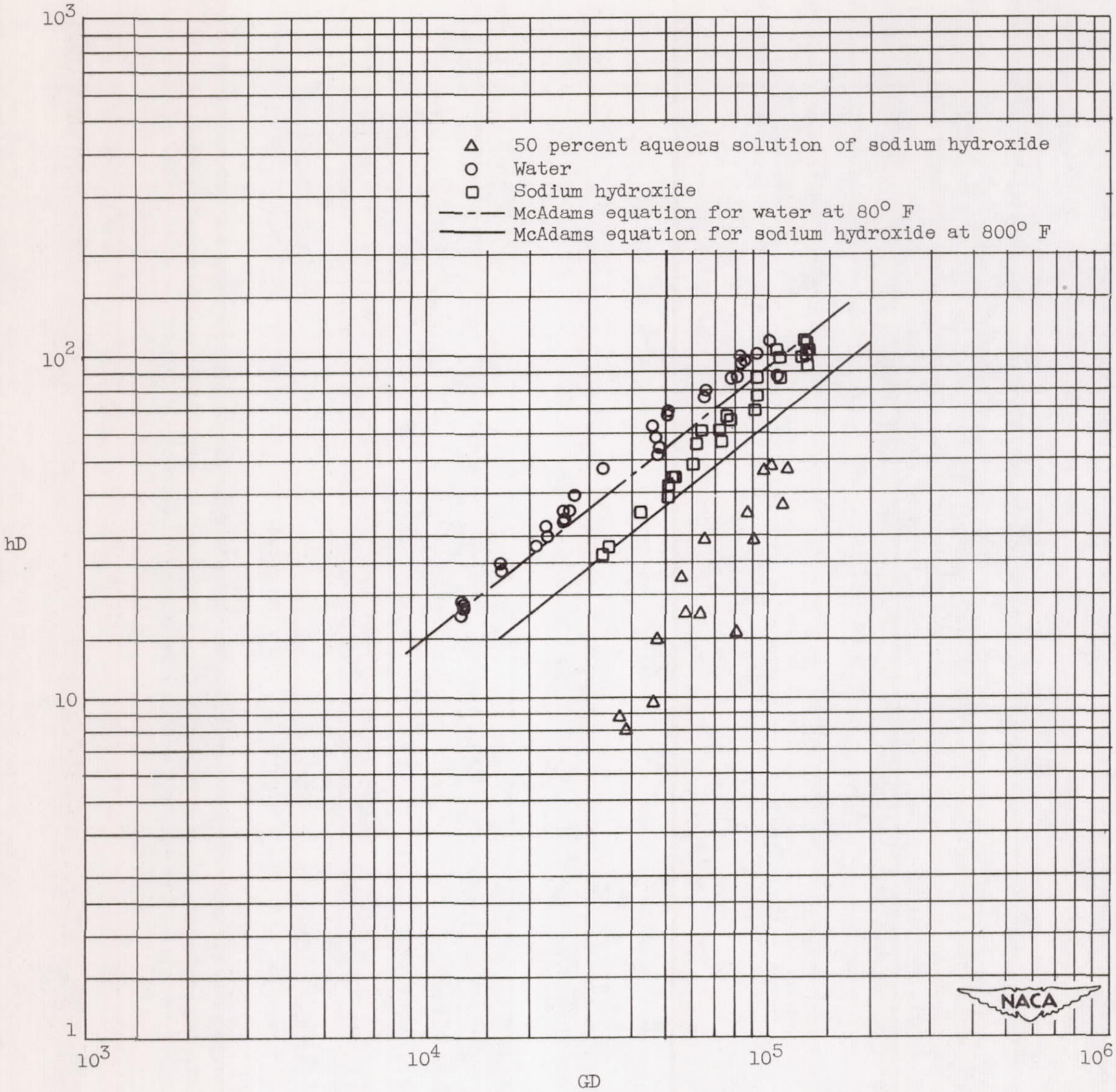



Figure 10. - Comparison of heat-transfer coefficients for water, sodium hydroxide, and an aqueous solution of sodium hydroxide.