COMPARISON OF HEAT EXTRACTION PROPERTIES OF QUENCHING MEDIA BY MAGNETIC QUENCH TEST

A THESIS

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in
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in
Chemical Engineering

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by

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CHAPTER I

SUMMARY

The purpose of this investigation was to compare heat extraction properties of quenching oils, water, and air, and to determine the effect of additives and agitation on the heat extraction properties of liquid quenching media.

A magnetic quenchometer was designed and constructed. The time required to cool a 7/8-inch diameter nickel sphere from 1350° F to its Curie point, 670° F, at which point it was attracted by a magnet, was used as a measure of the properties under consideration. The effect of agitation was studied by bubbling a stream of air through the quenching bath, and the effect of additives was determined by comparing the cooling rate of an oil which contained additives with two oils which contained none.

The time required to cool the sphere from 1350° F to 670° F varied from 311 seconds in air at 75° F to 0.69 seconds in a saturated ice water-sodium chloride solution at 22° F. Agitation decreased the cooling rate in a naphthenic oil by 1.19 per cent. It decreased the cooling rate in water by 27.2 per cent. A comparison of cooling times for the three oils without agitation revealed that Super Quench 70 oil, a proprietary quenching oil containing additives, cooled the sphere 26.8 per cent faster than a naphthenic oil and 46.5 per cent faster than a paraffinic oil.

The average deviation found for individual tests varied from 0.02 per cent with air to 7.17 per cent with 100 second naphthenic oil. For all tests the average deviation was found to be 3.13 per cent.

CHAPTER II

INTRODUCTION

One of the most important requirements in the heat treatment of steel is that of extracting heat from the metal in such a manner that desired mechanical properties are obtained. This process of heat removal is commonly referred to as quenching.

The rate at which a steel cools determines the microstructure and mechanical properties of the finished product, and the rate of cooling is dependent on the heat transfer characteristics of the quenching medium used. For example, the continuous-cooling-transformation diagram in Figure 1 shows two cooling rates and the resulting microstructures and properties for a eutectoid (0.8% C) steel. Curve A, the faster of the two, results in the formation of hard and brittle martensite, while curve B results in the formation of relatively soft and ductile pearlite. Intermediate cooling rates produce structures with properties varying between the two extremes considered. Generally, it is desirable in the first step of a heat-treating process to quench at such a rate that a uniform martensite structure is obtained. It is desirable, therefore, to have a means for comparing the heat extraction properties of quenching media.

This study is concerned with a comparison of heat extraction properties of quenching oils, water, saturated sodium chloride solution, and air, and with the equipment for making

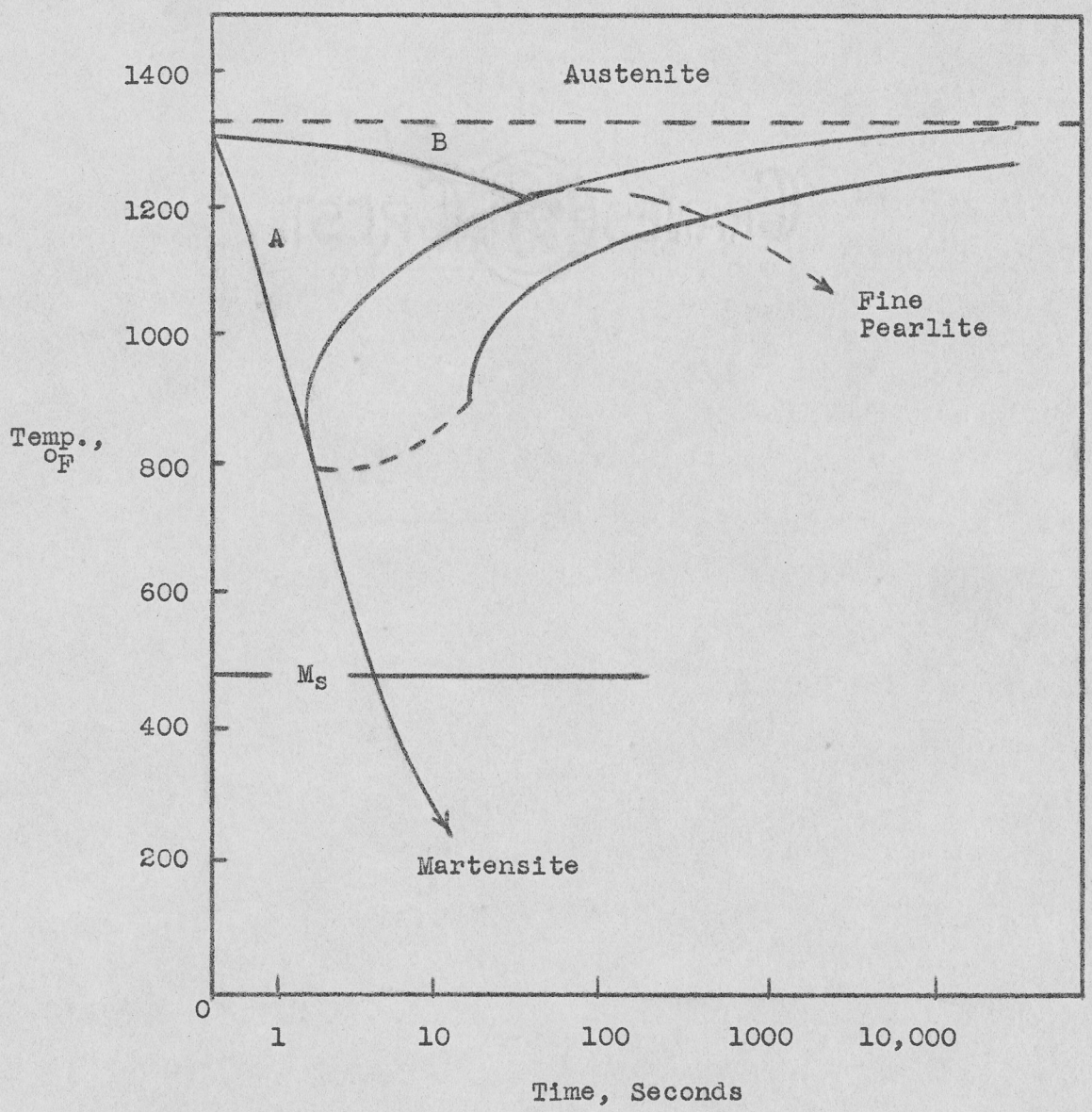

Figure 1. Continuous-Cooling-Transformation Diagram for 0.8% carbon steel. Microconstituents indicated are those obtained after (B) normalizing, (A) water quench.

the comparison.

Factors that affect the rate of cooling in liquid media include temperature, thermal conductivity, viscosity, specific heat, volatility, and degree of agitation of the quenching bath.[1] Liquids transfer heat from the cooling body by conduction and convection. Therefore, viscosity is an important factor. For a medium such as water, whose viscosity does not change appreciably with temperature, a colder bath gives a more rapid quench. A viscous medium such as oil has a much slower cooling rate than water. Quenching baths with greater specific heats and thermal conductivities are able to transfer heat from the cooling body faster than those with lower values of these physical properties.

During the cooling of steel in a liquid medium from the austenitizing temperature, three overlapping stages of quenching occur, as shown in Figure 2. The first stage is marked by the presence of a vapor film around the red-hot metal. This low-conductivity film causes slow cooling in the temperature range in which rapid cooling is necessary to avoid pearlite formation. For effective quenching this first stage should be eliminated as nearly as possible by such means as agitation of the quenching medium or addition of suitable surface-active chemicals. Sodium chloride and sodium hydroxide are useful additives for water quenching. During the second stage of cooling, both vapor and liquid are in contact with the hot metal, and vapor bubbles

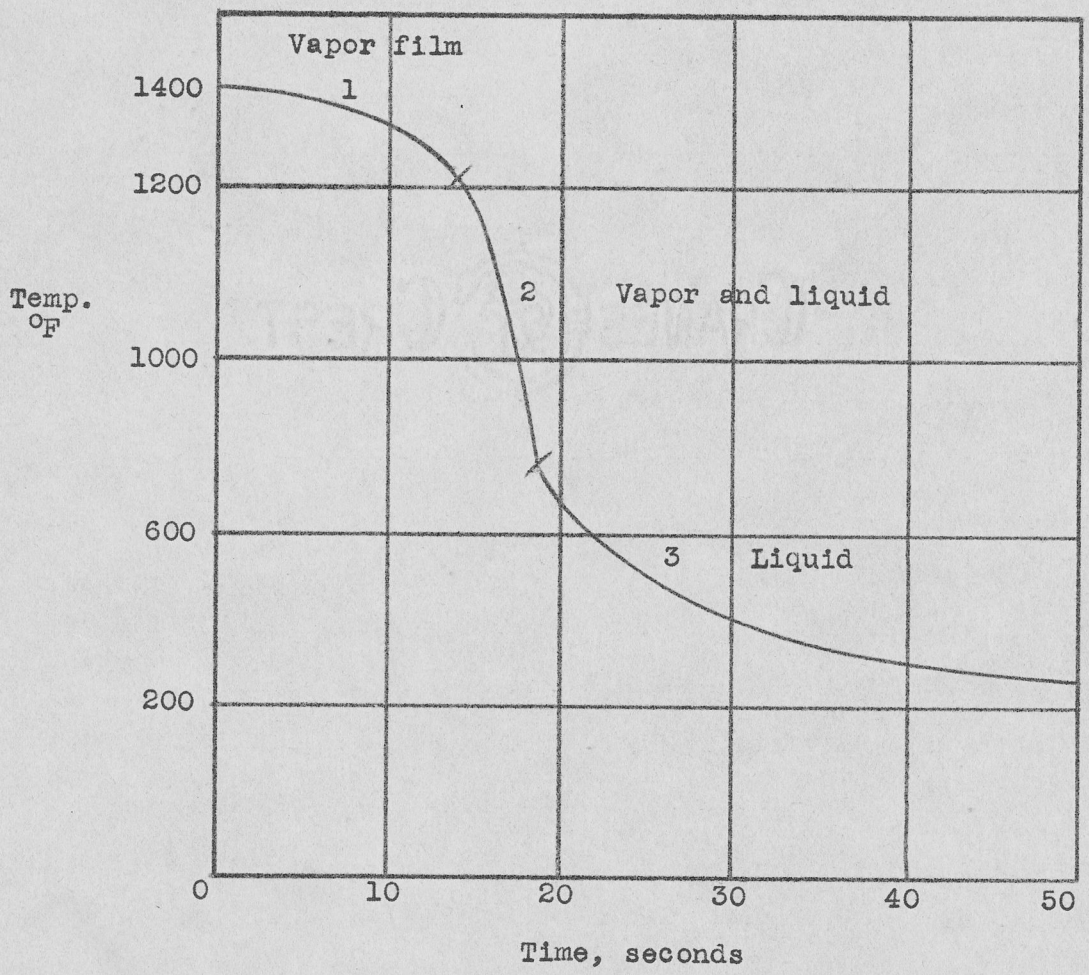

Figure 2. Schematic Illustration of the Three Stages of Cooling During Quenching in a Liquid

effectively transfer heat from the metal surface to the body of the quenching medium. Third stage cooling begins when the surface of the metal cools below the liquid boiling point. In this stage the liquid is in complete contact with the metal, and heat is transferred by the relatively slow processes of conduction and convection.[2]

A rapid rate of cooling, however, is not the only object in practical quenching. Proper quenching results in a uniform hardness pattern, small dimensional changes, elimination of quenching cracks and undesirable transformation structures, and long service from the quenching medium.[3] Large temperature gradients between the surface and center of the metal, as a consequence of using a drastic quenching medium, tend to cause cracking and distortion. Thus, it is often necessary to choose a milder quenching medium such as oil. This also normally requires the use of an alloy steel whose continuous-cooling-transformation curve would be shifted to the right relative to the plain-carbon C-C-T diagram shown in Figure 1.

Several methods of comparing the heat extraction properties of quenching media have been reported in the literature. One such method is the magnetic quench test,[4] which was used in the present study. In this test a nickel specimen is heated to 1600° F, at which temperature it is non-magnetic, and dropped into a quenching medium within a magnetic field. The time required for the specimen to cool from 1600° F to its Curie point

(670° F), at which instant it becomes ferromagnetic and is attracted to the magnet, serves as a measure of the heat extraction power of the quenchant.

In this study three quenching oils, air, water, ice water and ice water-sodium chloride solution were compared. The effects of additives and quenchant agitation were also investigated. It was decided to use quenchants at 75° F with the obvious exception of cases in which ice was used. The furnace for heating the nickel sphere was to have been at 1600° F, the common austenitizing temperature for steels. Subsequent tests revealed, however, that the actual furnace temperature was 1350° F.

CHAPTER III

MATERIALS AND EQUIPMENT

A magnetic-quench apparatus was designed with provisions for a) heating the nickel sphere to a constant temperature on each run, b) transferring the hot sphere to the quenching medium, and c) measuring the time required to cool from 1350° F to the Curie point.

A drawing of the equipment is shown in Figure 3, and a photograph is shown in Figure 4. With reference to Figure 3, the furnace, A, was made of two half-shell electric heaters insulated with fire brick and enclosed in a steel jacket. The 7/8-inch nickel sphere was suspended in the furnace by a 5-7/8-inch stainless steel rod 1/8-inch in diameter. A stainless steel beaker, B, containing 2260 milliliters of quenchant, was placed directly beneath the furnace.

A solenoid relay connected to the finger clamp was used to release the sphere, which dropped through a stainless steel tube into a wire basket, C, submerged in the quenchant. Austenitic stainless steel items were used because of their non-magnetic properties.

Cooling time was measured by an electric timer. A diagram of the timer circuit is shown in Figure 5. When switch D in Figures 3 and 5 was turned on, 110 volts activated the solenoid relay, E, which released the sphere. At the same instant, the timer circuit was completed by switch D and the

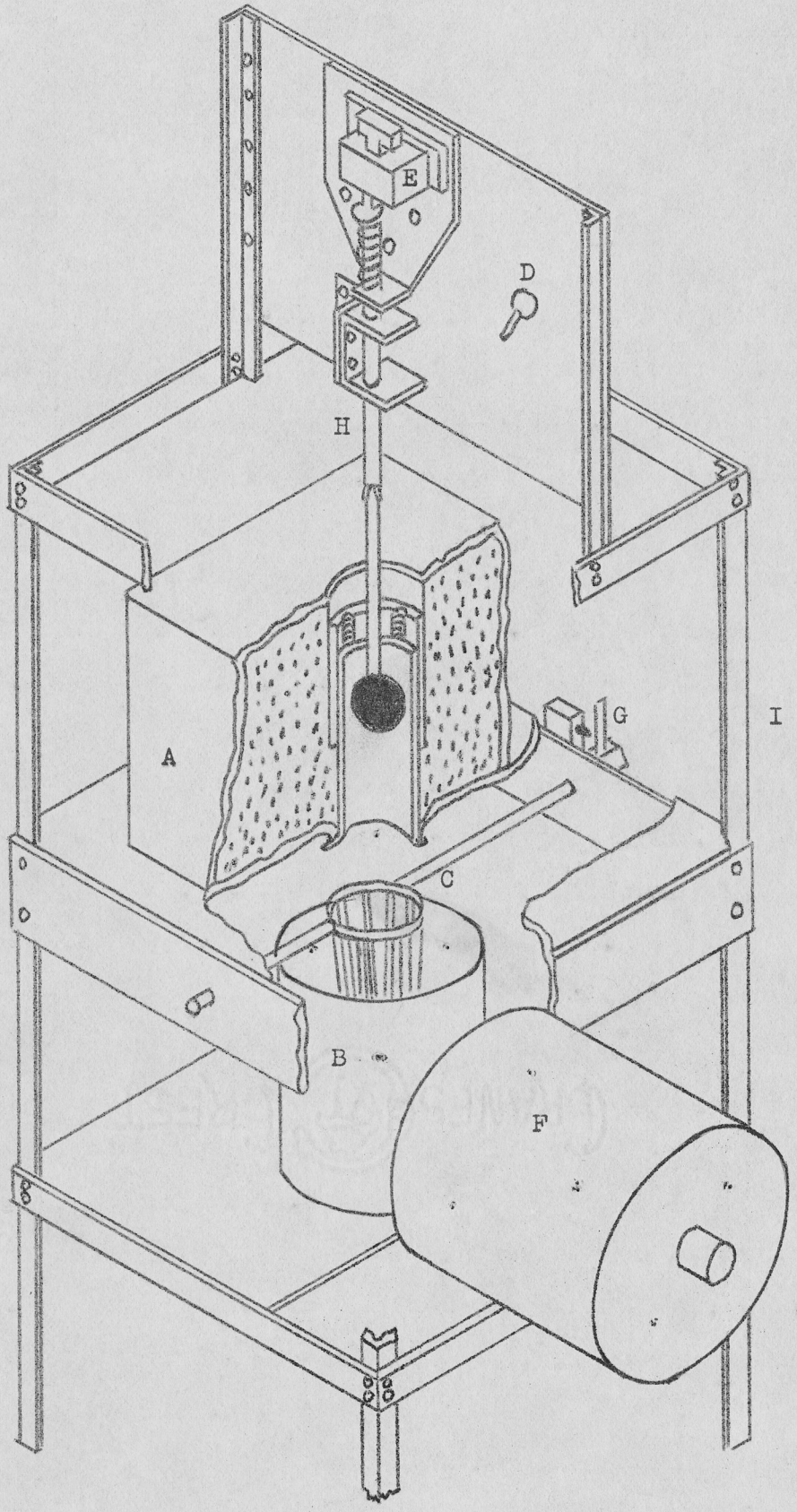

Figure 3. Cut-Away Sketch of Magnetic Quenchometer
(For identification of parts see page 13)

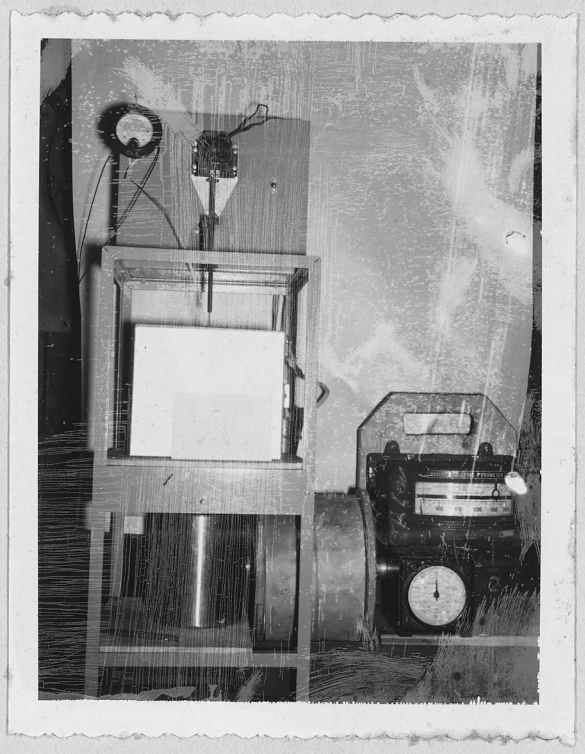

Figure 4. Photograph of Equipment, Front Overall View

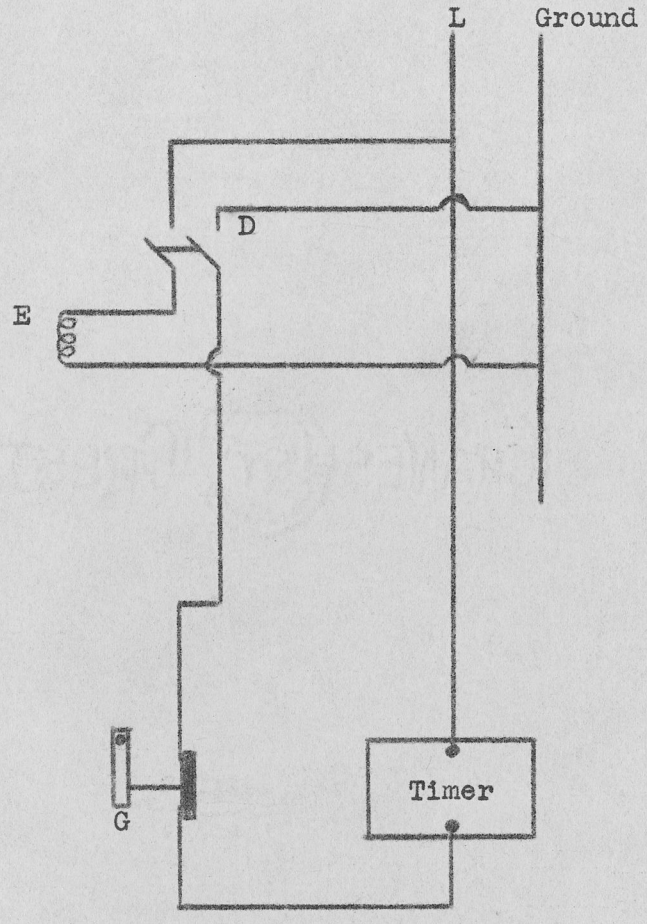

Figure 5. Schematic Diagram of Timer Circuit

timer started. When the sphere cooled to 670° F it became magnetic and was attracted to electromagnet F. Three and 8/10 amperes were supplied to the electromagnet by a 70-volt D. C. generator. The swing of the basket and sphere activated microswitch G, which opened the timer circuit and stopped the timer.

Figure 6 is a front view of the equipment with the beaker removed. It shows the sphere being attracted to the magnet and a side and bottom view of the furnace, A. The rear view in Figure 7 shows how the microswitch made contact and opened the timer circuit when the magnet attracted the sphere.

A list of parts as identified in Figure 3 is as follows:

A. Furnace, 9-1/4 x 9-1/4 x 8 inches
B. Stainless Steel Beaker, 3000 ml capacity
C. Stainless Steel Wire Basket, 5-1/2 inches deep
D. Sphere release switch
E. Solenoid relay
F. Electromagnet, 1-3/8 inch diameter core, 9-1/8 inches long
   9-1/2 inch diameter coil, 7-1/4 inches long
G. Microswitch
H. Finger clamp
I. Steel framework, 12-5/8 inch front, 14-1/4 inch side, 41 inch height.

Other parts shown in Figure 4 but not in Figure 3 are:

1. Temperature indicator attached to thermocouple, upper left of photograph
2. Electric timer, bottom right
3. Furnace temperature controller, directly above timer

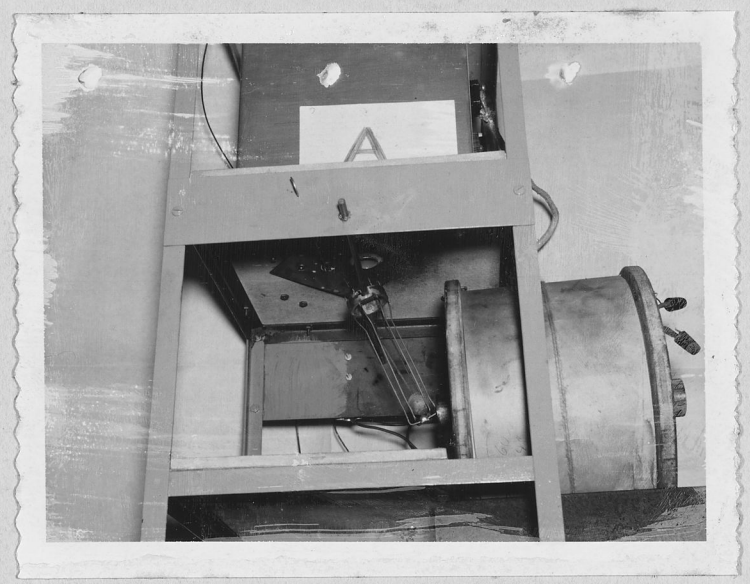

Figure 6. Photograph of Equipment, Magnet Attracting Sphere

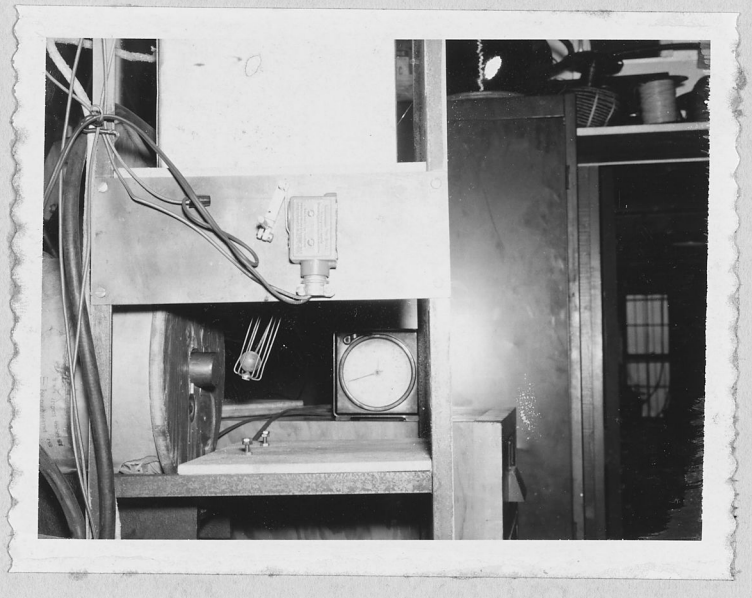

Figure 7. Photograph of Equipment, Microswitch in Open Position, Rear View

CHAPTER IV

EXPERIMENTAL PROCEDURE

Preliminary steps required for operation of the equipment involved turning on the furnace and timer circuit power supply and zero-adjusting the furnace temperature controller to 1600° F. (Tests with a thermocouple indicated that at equilibrium the actual furnace temperature was 1350° F). Another preliminary step was to start the D. C. generator which powered the electromagnet. Approximately 45 minutes were required for the cold furnace to reach 1350° F.

Actual operation included the following items for each run:

a. Insertion of the sphere and thermocouple into the furnace (It was found that the sphere reached 1350° F in approximately 15 minutes.)

b. Placing the stainless steel beaker containing quenching medium in position beneath the furnace

c. Removing the radiation shield from the opening at bottom of furnace

d. Zeroing the timer

e. Throwing switch to drop sphere from oven into quenching medium and start timer (When the sphere cooled to its Curie point, 670° F, it was attracted by the magnet and a microswitch activated to stop the timer.)

f. Recording cooling time

g. Removing sphere from wire basket, cleaning it, and reinserting it in the furnace (After each run the sphere was dried and any film which formed was removed with fine sandpaper.)

h. Readjusting temperature of quenching medium for subsequent run.

The average time required for each run was approximately 20 minutes.

CHAPTER V

RESULTS AND DISCUSSION

The results of this study are summarized in Table 1. Each value for cooling time represents the average of 8 to 10 runs. The results are represented graphically in Figures 8, 9, and 10. Figure 8 illustrates the effect of agitation and additives on quenching time for three oils. When each of the three oils was mildly agitated, quenching time was reduced by 8.2 per cent for Super Quench 70 oil, 1.19 per cent for naphthenic oil and 20.2 per cent for paraffinic oil. Super Quench 70 oil contains additives that increase wetting power and make cooling time shorter. The naphthenic and paraffinic oils do not contain these additives.

A comparison of cooling times for the three oils without agitation, also shown in Figure 8, revealed that Super Quench 70 oil cooled the sphere 26.8 per cent faster than naphthenic oil and 46.5 per cent faster than paraffinic oil.

The effects of bath temperature and an additive on cooling time for water are shown in Figure 9. Decreasing water temperature from 75° F to 32° F caused the cooling time to drop from 3.56 seconds to 1.72 seconds--a decrease of 56 per cent. The combined effect of an ionic solute and lower bath temperature was demonstrated by the cooling time of 0.69 second recorded for the saturated brine solution at 22° F. The 80.6 per cent shorter average cooling time in iced brine

Quenching Medium	Temp. °F	Time, Seconds (No Agitation)	Avg. % Deviation	Time, Seconds (Agitation)	Avg. % Deviation	% Decrease Due to Agitation
Super Quench 70	75	11.72	5.70	10.76	3.26	8.20
Naphthenic Oil	75	16.00	7.17	15.81	3.50	1.19
Paraffinic Oil	75	21.99	1.67	17.56	2.25	20.20
Water	75	3.56	3.34	2.59	3.62	27.20
Ice and Water	32	1.72	3.64			
Ice and Brine	22	0.69	0.02			
Air	75	311.54	0.34			

Table 1. Times Required to Cool Nickel Sphere from 1350° F to 670° F in Various Quenching Media and the Effect of Agitation

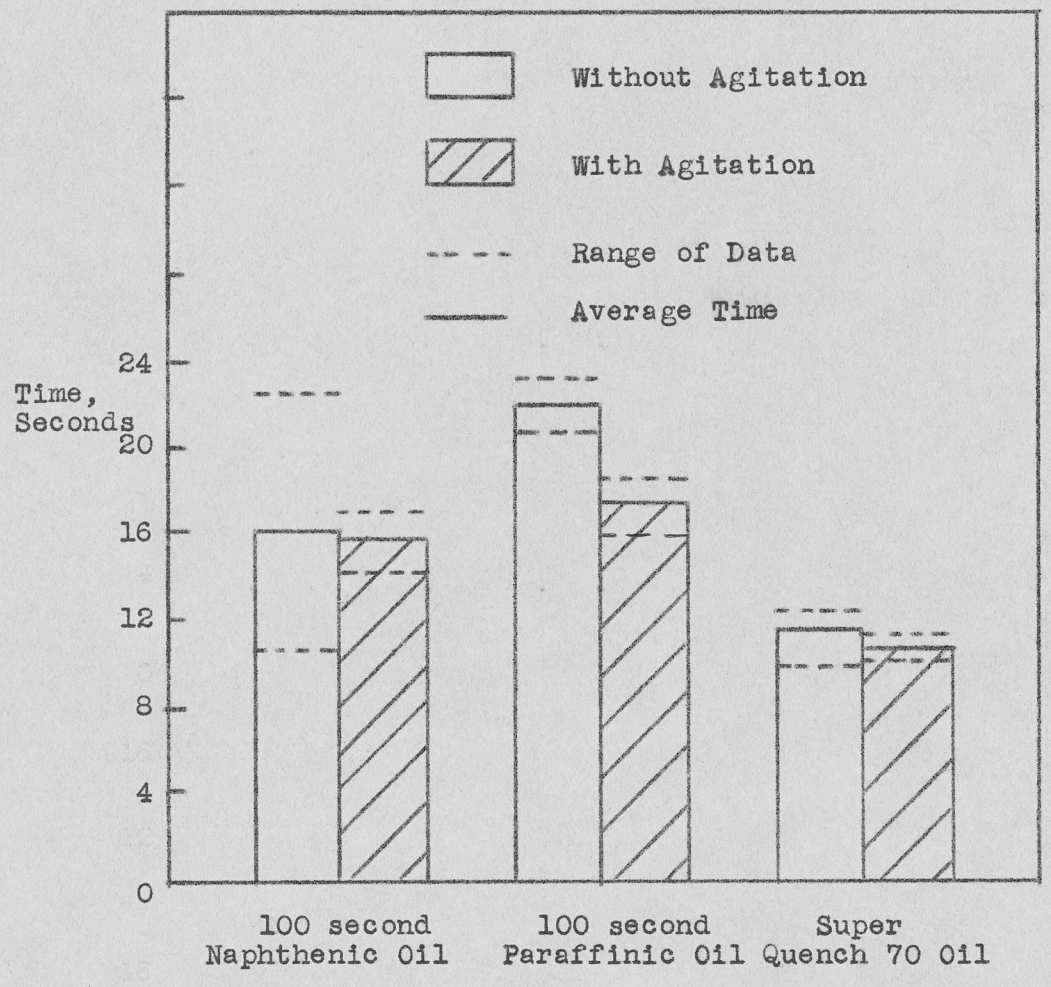

Figure 8. Comparison of Cooling Times for Quenching Oils

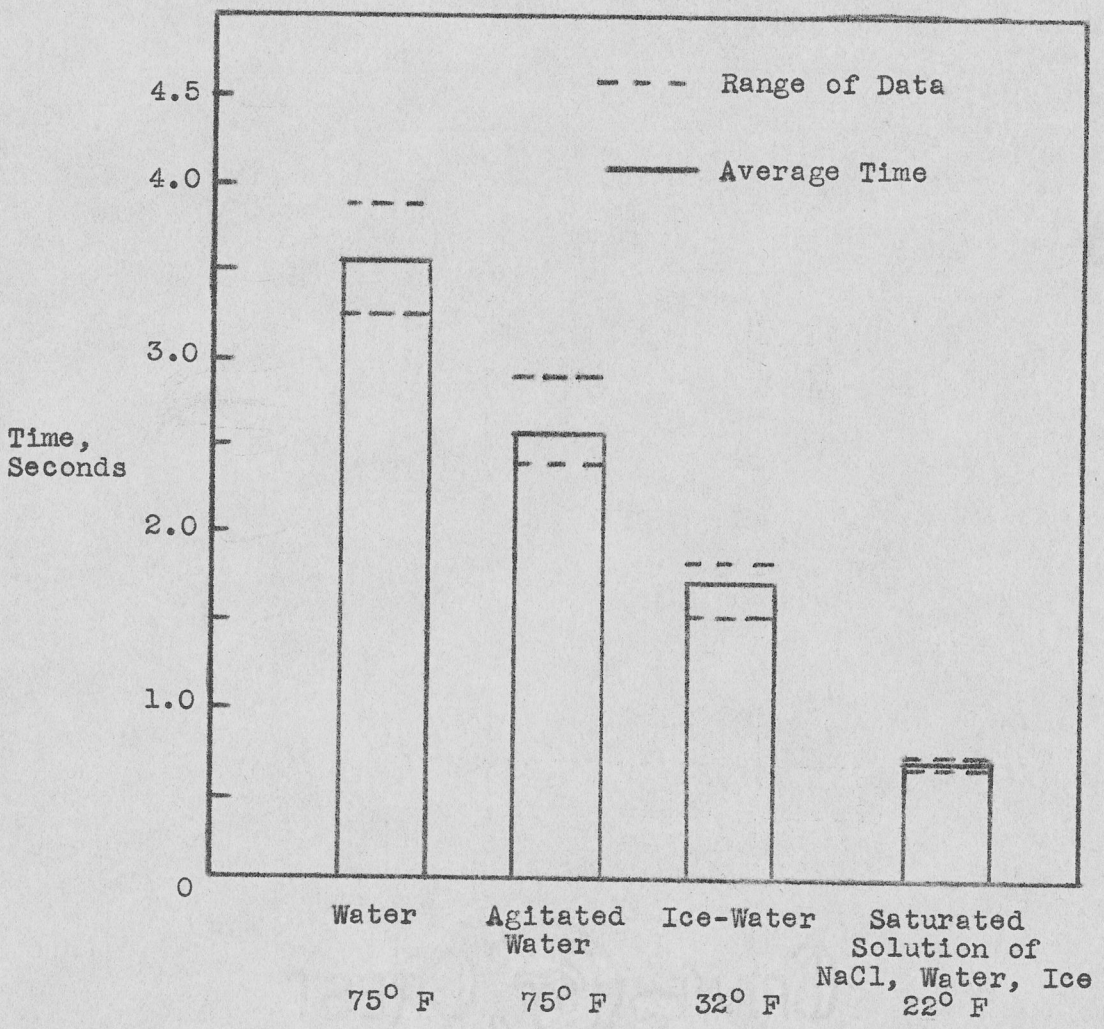

Figure 9. Comparison of Cooling Times for Water

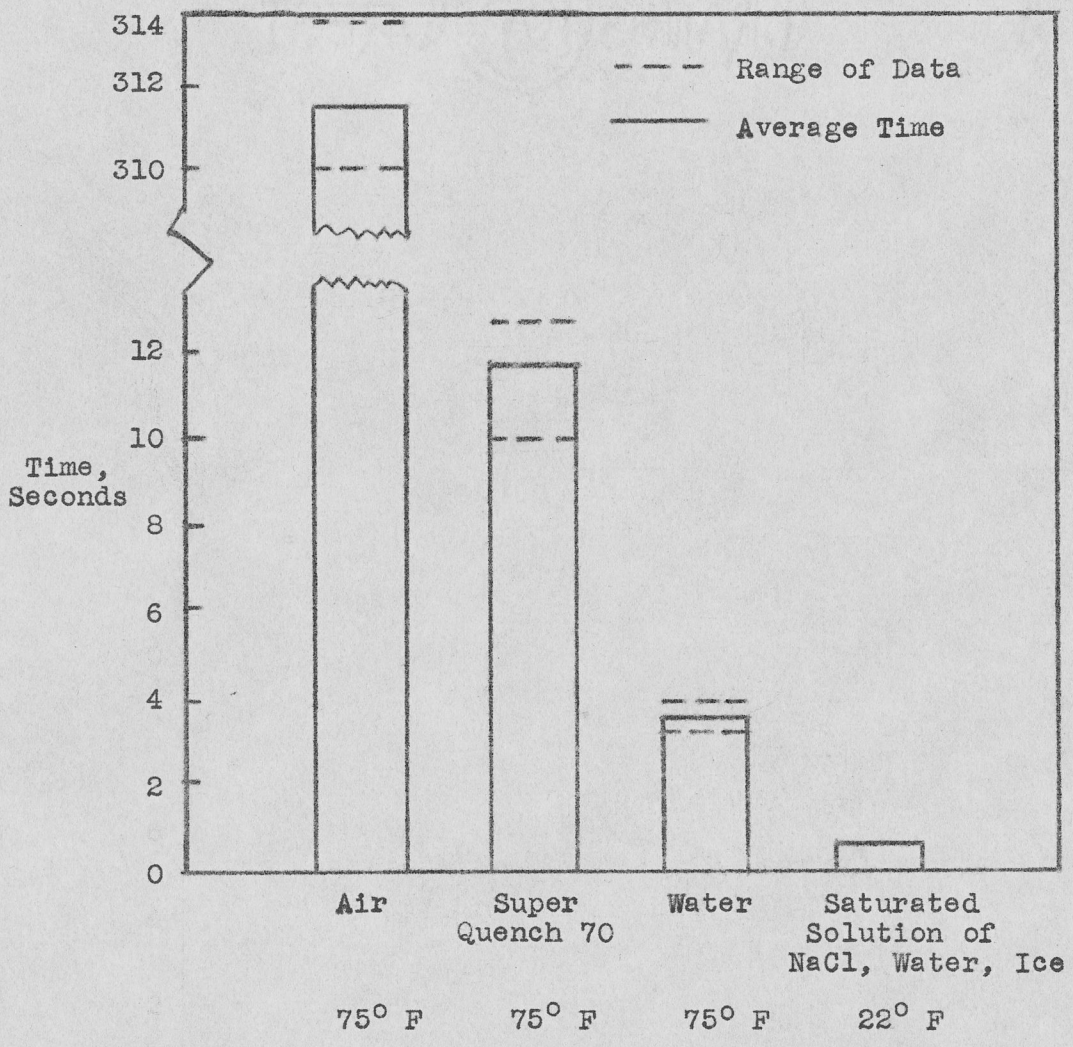

Figure 10. Comparison of Cooling Times for Air, Water, Oil

at 22° F, compared to unagitated water at room temperature, is due to both the lower bath temperature (larger driving force for heat transfer) and to the better heat transfer properties of the ionic salt solution.

A comparison of quenching rates in air, Super Quench 70 oil, water, and iced brine are represented graphically in Figure 10. The average percentage deviation of all readings for each quenching medium was calculated as a measure of the reproducibility of data obtained with the equipment. The results, shown in Table 1, indicate that the equipment performed satisfactorily, with an average deviation not exceeding 5.7 per cent for any one set of readings, except those on naphthenic oil. On three different days data taken on the unagitated naphthenic oil were inconsistent, while other oils and water run immediately preceeding or following the naphthenic oil gave consistent results. Therefore, it was concluded that the widely varied data obtained with naphthenic oil were not caused by faulty equipment.

A tightly adherent oxide scale and surface pits were observed to form on the nickel sphere during the ice-brine studies. Since these had the effect of gradually increasing the cooling times, the ice-brine studies were terminated after 5 runs. Other results were not affected by the deterioration of the sphere since iced brine was the last quenching medium studied.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

It can be concluded from the data obtained in this investigation that:

1. The equipment used provides a convenient and satisfactory method of comparing the heat extraction powers of quenching media.
2. The use of additives and agitation produces significant increases in the cooling rates of liquid quenching media.

Recommendations

It is recommended that further studies be made to determine causes for the inconsistencies in quenching time observed for 100 second naphthenic oil. The equipment used in this investigation could be applied to a determination of the effect of quenching-media temperature on cooling rate.

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APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval that the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn herein, but approves the thesis only for the purpose for which it is submitted.

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