A Brief Review on Test Systems Using a Ball Probe for Determination of Cooling Characteristics of Quenchants

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Abstract

A wide variety of test systems have been developed to determine cooling characteristics of quenchants. Superior systems for reliability and cost performance are widely used and adopted as domestic and international standards. This review mainly focuses on test systems using a ball probe and discusses their potential. Although ball probes are not defined in current standards, it is known that specific ones used in the past contributed to enhance the test systems in researches. Strengths and limitations inherent in ball probes have been identified from literatures. Prototypes of test systems using a ball probe produced by the author's group were reviewed briefly, which resolved problems due to a ball probe by using current technologies.

Introduction

Heat treatment quenchant has its inherent cooling characteristics, while its properties change with daily use. In order to develop and manage such quenchant, a variety of test methods have been devised to determine the characteristics [1]. The methods standardized by societies [2] are that JIS K 2526 [3] and AFNOR NF T - 60 178 [4] for a silver cylindrical probe, and ISO 9950 [5] and ASTM D 6200 [6] for an Inconel cylindrical probe, for examples. These are common in that a cylindrical probe is vertically immersed into still quenchant and a cooling curve is measured in the probe at rest, except for agitated conditions defined in the standards related to ASTM D 6200.

It is known that shapes of proposed probes have been not only cylindrical but also spherical. The introduction part of ISO 9950 [5] describes that test methods using a silver ball probe were widely identified at that time of its establishment. However Lakin [7] pointed out problems of the silver ball probes due to difficulties of fabrication and maintenance and higher conductivity than steel.

The author's latest survey of classical literature has found that small ball probes were created rationally and applied to a variety of quenchants by Engel [8] in his study on quenching. Engel stated 7 mm dia. silver and 4 mm dia. chromium-nickel balls are ideal. His work was carried out at the Kaiser-Wilhelm Institute from 1928 to 1931. Finding this literature motivated to revise the author's review on ball probes, which is included in his report on prototypes of the test system [9].

The author's group has developed prototypes of the test system using a small ball probe since 2011, initially which was performed to reproduce the concept of Tawara's apparatus [10]. Then a rotary-arm to transfer and immerse a probe was installed in the system, which is called as rotary-arm type, was developed in three phases of this project [11]. Currently, a mechanism to elevate a quenchant container with respect to a stationary probe and to cool it has been devised, which is called as elevator container type [12].

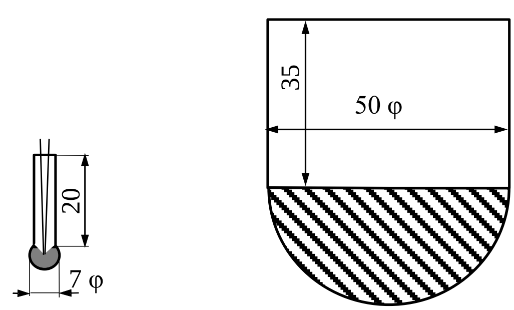
In the following, the author reviews for developing test systems with a ball probe and summarize specific features of the prototypes and results obtained. An unpublished study on the inverse heat conduction problem for the probe is depicted additionally.

Developing Test Systems Using a Ball Probe

Outline
The author reviewed studies on the test systems using ball probes in 2014, in which the Engel's work and Lakin's descriptions were not considered. The following focuses the new findings and backgrounds of standards.

Engel's work
Engel [8] evaluated former studies using cylindrical probes by Benedicks [13] and Pilling-Lynch [14], for examples, for developing his test system. These experimental works were performed to obtain cooling curves and observe micro-structures in carbon steels in probes. Engel pointed out that cooling curves of steels are induced due to latent heat of phase transformations, and then recommended to use metals without transformations for the probes.

Figure 1 shows examples of Engel's probes with 7 and 50 mm in diameter. Edges of the tapered bore in Fig. 1 (a) and the hemisphere in Fig. 1 (b) were connected to a tube. A thermocouple was made using 0.1 mm dia. platinum-platinum rhodium wires which were welded together and set in the probe. Engel informed the type shown in Fig. 1 (a) was designed based on a report by Gebhard et al. [15]



(a) 7 mm dia. *(b) 50 mm dia.*
Figure 1: Engel's ball probes.

Engel's tests were carried out using the described probes, which were applied to investigate not only characteristics of probes and quenched parts but also properties of quenchants. Therefore, chromium-nickel balls with 4, 7 and 10 mm dia. were selected for evaluating poor heat conductors. Armco iron balls with 4, 7, 10, 19 and 50 mm dia. were designed to find influences of scale formation. A copper ball with 50 mm dia. was used as an example of a good thermal conductor with scale formation. Also a 50 mm dia. carbon steel ball was applied to study a practical quenching.

Table 1 indicates physical properties of probe materials with SI units which were converted by the author. The values show that the chromium-nickel (CrNi) is a poor heat conductor. It should be noted that the chemical composition of chromium-nickel was not expressed by Engel. Also the metal was called as chromium-nickel steel which was specified in some later literatures when referring the Engel's probe as shown in the review by the author [9].

Table 1: Physical property of Engel's probe materials.

Material	Specific gravity	Specific heat kJ/(kg K)	Thermal conductivity W/(m K)	Thermal conductivity based on Cr Ni
Silver	10.5	0.233	419.	80
Copper	8.93	0.419	385.	74
Iron	7.85	0.451	41.0	8
CrNi	8.4	0.448	5.19	1

Engel clearly stated that ball probes are advantageous in that the temperature measured at its center can be regarded as the average value on the ball surface. It was also described that the appropriate diameter of the ball probe is 7 mm for silver and 4 mm for chromium-nickel so that phenomena occurring on its surface can be regarded as homogeneous.

All probes were heated to about 900 °C in an oven, and cooled in a quenchant container. Its volume varied from 500 m*l* to 5 *l* for form the smallest to largest probe size. Temperature changes of probes were recorded with a Siemens cardiograph.

Engel reported cooling rate curves which were produced from cooling curves. For examples, applied quenchants were water at six temperature levels between 0 and 100 °C, some water solutions, oils, hydrogen at three temperature levels, air, etc. Measured cooling rates using 4 mm dia. chromium-nickel and 7 mm dia. silver probes for 32 and 21 quenchants conditions, respectively, were identified in four figures concisely.

Finally Engel described temperature curves of heat flux on the probe. The flux was calculated based on an assumption that heat capacity in the probe can be lumped to its center point, which is called as the lumped heat capacity method. This technique assumes that temperature within the probe is uniform at any point during cooling process, because of the high thermal conductivity and/or small size of probes. Then 7 mm dia. silver balls was used for distilled water, hardening oil and air, and 4mm dia. chromium nickel ball was for liquid metal.

Engel explained differences in cooling characteristics of quenchants by using heat flux temperature curves. Curves of liquid metal and air show a simple upward shape, while those of water and oil have a maximum point in the middle. It was also pointed out that the temperature change occurs inside the heat treated parts due to heat flow out from surfaces; however its distribution changes depend on thermal conductivity and size of the parts.

Subsequent works at the Kaiser-Wilhelm Institute

Speith and Lange [16] changed the diameter of the Engel's silver probe from 7 to 20 mm. They explained that smaller diameter balls induced variation in phenomena during immersion and a difficulty of installing a thermocouple into them.

They considered flow and boiling phenomena around the 20 mm dia. copper ball during quenching into still quenchants mainly based on observations by photos, Schlieren photos, and movies. In order to not impede a progress of the phenomena, a support structure was attached to the bottom of the probe.

Rose applied the same 20 mm diameter silver ball probe to obtain cooling characteristics of various quenchants [17]. After heating to 800 °C, the probe was immersed into quenchants and then moved there equally about 25 cm/s. The reason to give the movement was described as adjustment to industrial conditions and avoidance of variation in the phenomenon, while the moving method was not shown clearly.

He reported the results as the form of a cooling rate curve obtained from, for example, air, water, sodium hydroxide solution, calcium hydroxide solution, mineral oil, rapeseed oil, fish oil, mixed oil, emulsion, pectin solution, water glass, and so on.

On the other hand, Rose described clearly an equation to determine the heat transfer coefficient α by applying the lumped heat capacity method:

$$\alpha = \frac{dT}{dt} \frac{\rho C_p V}{S(T_e - T)} \tag{1}$$

where T: assumed uniform temperature of probe, T_e: temperature of quenchant, V and S: volume and surface area of ball, C_p and ρ: specific heat and density of probe's material. Eq. (1) shows the method can calculate heat transfer coefficient easily if cooling late dT/dt is known. Additionally, heat flux is calculated from Eq. (1) without ($T_e - T$).

Rose created a table to summarize values of heat transfer coefficient in vapor blanket, nucleate boiling and convection stages using his data and past one, including Engel's. Table 2 is a subset of the Rose's depicted by the author after converting the unit. The results obtained from Engel's and Rose's probes may have consistency.

Table 2: Heat transfer coeff., α, W/(m^{2}K), of different quenchants by lumped heat capacity method.

Quenchant Name	Cooling Rate cm/s	Vapor blanket		Nucleate boiling		Convection		Probe	Ref.
		Temp ℃	α	Temp ℃	α	Temp ℃	α		
Water	Moderate	720	6300	550	10100			Cr–Ni ball:4φ	Engel
Water	Moderate	720	3490	200	25000			Ag-ball: 7φ	Engel
Water	25	700	3110	500	12600	90	2440	Ag-ball: 20φ	Rose
Water	10	700	1270	300	6050			Ag-ball: 20φ	Rose
Rapeseed oil	Moderate	720	2110	550	2790	300	768	Cr–Ni-ball: 4φ	Engel
Rapeseed oil	Moderate	720	1980	550	3490	200	512	Ag-ball: 7φ	Engel
Rapeseed oil	25	700	1690	500	3660	200	488	Ag-ball: 20φ	Rose
Oil heavy	Moderate	720	843	600	3190	300–200	670–372	Cr–Ni-ball: 4φ	Engel
Oil light	Moderate	720	500	500	2970	200	744	Cr–Ni-ball: 4φ	Engel
Oil heavy	Moderate	720	686	500	3490	200	599	Ag-ball: 7φ	Engel
Oil heavy	25	700	1420	550	3020	300–200	314–244	Ag-ball: 20φ	Rose
Oil light	25	700	779	450	3260	300–200	477–244	Ag-ball: 20φ	Rose

Using the same silver ball as Rose's, Schallbroch et al. [18] designed a cooling test system that the probe was immersed into quenchant flowing like a river in a tank by a gear pump. It was mentioned that advices from Kaiser-Wilhelm Institute were applied to design this device. Schematic diagram of the test apparatus included in their report was simplified further by the author as shown in Fig. 2. Although flow rate of the quenchant is not clear, how to give relative flow around the probe is known more clearly than the Rose's report.

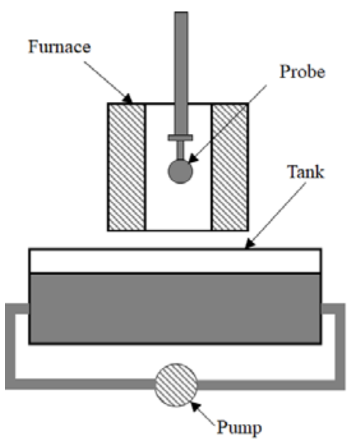


Figure 2: Schematic diagram of apparatus by Schallboch et al.

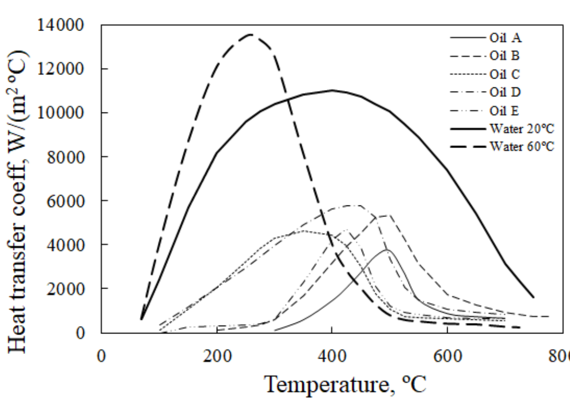


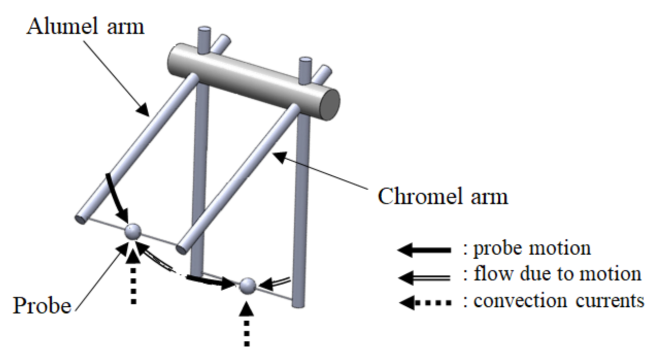
Figure 3: Temperature curves of heat transfer coefficients by silver probes.

On the other hand, Krainer and Swoboda [19] created temperature curves of the heat transfer coefficient, which were obtained from five quenching oils and two waters at different temperatures based on the research results by Rose. Original temperature curve was redrawn by the author as shown in Fig. 3.

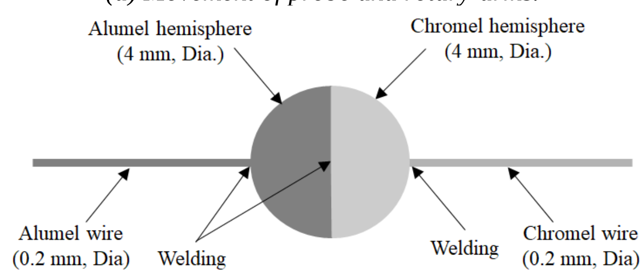
Tawara's work and Japanese standard

The author's literature survey found a unique test method reported by Tawara [10], which was developed at the materials research department of Japanese Naval Institute of Technology. A small ball probe supported with wires is rotated by arms in quenchant as shown in Fig. 4 (a) and a cooling curve is obtained during that period. This method gains not only advantages of ball probe but also effects of stirring by flow due to a rotational motion of the probe in quenchant.

Ball probe in Tawara's apparatus was produced as welded Chromel and Alumel hemispheres, 4 mm in diameter, as shown in Fig. 4(b), which was also functioned as a thermocouple at their junction. The 0.2mm diameter Chromel and Alumel lines welded to each side of the hemispheres played not only to lead wires to the thermocouple but also to support the probe.



(a) Movement of probe and rotary-arms.



(b) Structure of probe.

Figure 4: Rotary arm type apparatus by Tawra.

The ball probe is radiant heated until 850 °C by the Nichrome coils, and then moved circularly at tangential velocity of about 70 mm/s in still quenchants in a container of about 1.5 *l* by the rotary-arms.

Tawara's cooling tests were performed using tap water, saline solution, soapy water, and 21 kinds of quenching oils. Their temperatures were set at 20, 40, 60, 80, and 100 °C. Characteristic temperatures, cooling times between 700 and

300 °C, and cooling rate curves were showed as the test results, while original cooling curves were reported for some quenchants. However, heat transfer coefficient was not depicted although the small probe is suited to the lumped heat capacity method.

In Japan, a study on cooling characteristics using a silver cylinder probe was performed by Tagaya and Tamura [20] after Tawara's study. Their efforts were published in the Journal of the Japan Institute of Metals in 13 times separately as the title of "Studies on the Quenching Media" from 1951 to 1956. In their first report [20] on the subject, the reason for selecting silver for the probe material was described as minimal surface oxidation and no transformation latent heat. On the other hand, it was not clearly explained why they selected a cylindrical shape for the probe.

The probe with two thermocouples at the surface and the center was depicted in their report. A number of cooling curves measured mainly at the surface were shown in a series of their reports. While the cooling rate curve was not included there, it is also not required by the provisions in JIS K2526 [3], which was established based on their research. It should be noted that Tagaya and Tamura [20] introduced past measuring methods by Speith and Lange [16] and Rose [17], for examples, without the contents of Tawara's apparatus [10].

The method based on studies by Tagaya and Tamura was established as JIS K2526 [3] in 1965. This standard specified that a silver cylindrical probe, 10mm in diameter and 30mm length, is immersed into still quenching oils to measure cooling curves at its surface. A tube for protecting a wire connecting to a thermocouple at the surface is inserted laterally to the cylinder, and then the probe is nonaxisymmetric. JIS K2526 was merged with JIS K2242, "Heat Treating Oils" [21] in 1980.

Narazaki et al. [22] investigated effects of probe shape by immersing tests into distilled water (10 *l*) using cylindrical silver probes, 10mm in diameter and 30mm in length, with different rounded corners. It was revealed that sharp edges in a cylinder collapse a vapor film in higher temperature states, while larger rounded corners collapse it at lower temperature. Furthermore, coincident characteristic temperatures were detected in cooling curves of balls and cylinders with hemispheres. Narazaki et al. [23] suggested that these ball and cylinder with hemispheres probes should be adopted as standard since more essential phenomenon in cooling is captured using them. They concluded that the cylindrical probes including the JIS standard should be modified considering to their above finding.

When JIS K2242 [21] was revised in 2006, a silver cylinder with a thermocouple at the center was added as a probe to be used for aqueous solution quenching.

Limitations of the ball probes suggested by WHTC

Lakin, Wolfson Heat Treatment Centre (WHTC), pointed out a number of practical limitations of the silver ball probe in 1979, although a thermocouple technique was typified by the ball as follows [7]:

(a) Since the thermocouple hot junction must be located precisely at the geometric center of the ball, it is difficult to manufacture the test assemblies without introducing some probe to probe response differences.
(b) The high thermal conductivity of silver compared with steels means that the results obtained do not correspond to practical quenching conditions.
(c) It is important to maintain a consistent surface finish on the ball without affecting the diameter.

Lakin described an alternative probe proposed by WHTC as follows [7]: its material is effectively limited to the austenitic stainless steels, the AISI 310 (25%Cr/20%Ni) grade being chosen in this instance for its superior oxidation resistance. Probe dimensions are chosen at 50 mm length by 12.5 mm diameter, then the probe may be considered as a 12.5 mm diameter bar of infinite length, i.e. end effects may be ignored.

WHTC published the specification "Laboratory Test for Assessing the Cooling Characteristics of Industrial Quenching Media" in 1982 [24]. This informs WHTC set up a working party on "Testing of Quenching Media" in 1974. Contents of this document prepared by the party have a format for a standard. For examples, specified probe description is as follows: The probe shall have a diameter of 12.5 mm and a length of 60 mm, the thermocouple hot junction to be located at its geometric center. The probe shall be manufactured from Inconel 600 grade nickel-chromium-iron alloy.

Hilder describes the party of WHTC turned its attention to establishing a standard agitated test for aqueous quenchants in 1983 [25]. The first system to be evaluated consisted of a variable speed 75 mm two-bladed impeller used in conjunction with an H-shaped baffle. A second agitation system, using a variable-speed pump and orifice, has also been tested. Hilder presented some results of cooling behavior of three types of commercial polymer quenchant (PAG, PVP and polyacrylate) [26]. He emphasized the effect on cooling characteristics of concentration, temperature, agitation, ageing and contamination. Control techniques, drag-out losses and response to quenching, in terms of hardness and residual stress for a 0.45%C steel, were also considered.

Finally ISO 9950 [5] was published in 1995. Its introduction part describes "the most common method for direct testing is the so-called silver ball method" and "due mainly to difficulties concerning the silver ball probe manufacture and the assessment of test results." Materials, sizes and shapes of the probe are commented as "the probes have been made of various materials and different sizes, the shape normally being cylindrical."

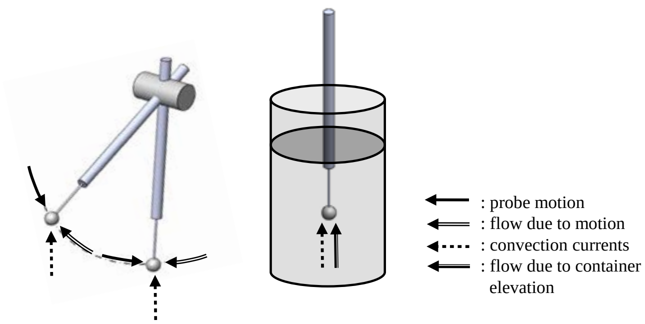
Prototypes of Test System Using a Ball Probe

Outline of prototypes and probes

The author's group has developed prototypes of test system using a small ball over phases [9, 11, 12] based on the concepts of previous systems. The rotary arm type was selected initially for the prototype based on Tawara's concept.

Tawara's original system has a ball probe which is supported from both sides with a thin wire stretched horizontally as shown in Fig. 4. The probe rotation induces flow around it, while convection currents occur due to high temperature probe in quenchant. The supporting wires show some influences on both the flow and currents.

On the other hand, the probe in the prototype of rotary-arm type is supported with a tube from one side as shown in Fig. 5 (a). This design was adapted since current contracted manufacturing technology could not restore the Tawara's probe shown in Fig 4 (b) in economic terms. Then it was decided to use a ball probe with a sheath thermocouple into the center.



(a) Rotary-arm type (b) Container elevator type

Figure: 5 Schematic diagram of probe motion, flow due to motion, and convection currents in prototypes of test system.

Strict tests of rotary-arm type using water and polymer aqueous solution revealed that turbulence may affect in repeatability of the vapor film collapse. The rotary supporting tube may produce different conditions of the flow and currents, since rotational angle of the tube varies during cooling as shown in Fig. 5 (a).

In order to avoid the problem due to angular changes of the supporting tube in the rotary-arm type prototype, a method depicted in Fig. 5 (b) was proposed as the container elevator type. The probe is fixing while elevating a quenchant container vertically. The elevation induces an axisymmetric flow and currents around the probe.

The stationary probe facilitates also to observe easily the heat flow phenomena with high resolution video. Adoption of this mechanism has become possible since electric actuators to produce precise linear motion for robotics are being distributed at economical price in recent years.

4 mm dia. ball probes for the first and second rotary-arm type prototypes were made of Inconel 600 immediately because of manufacturability. Finally the third prototype achieved to change the probe material to pure platinum for resolving the discoloration and thermal aging problems on the Inconel probe surface.

Figure 6 (a) shows a 4 mm dia. platinum ball probe which was established by using today's technology. The probe has a hole for a 0.25 mm dia. sheath of thermocouple shown in Fig. 6 (b).

Some of the problems on the previous ball probes have been resolved when using the platinum probe. This does not need to polish before testing unlike silver, and its heat conduction characteristics are closer to iron than silver. The small probe is advantageous in that the lumped heat capacity method can be used.

(a) 4mm dia. platinum probe with platinum tube

(b) 0.25 mm dia. K type sheath thermocouple
Figure: 6 Appearance of ball probe and thermocouple.

Configuration of Rotary-Arm Type Prototype
Rotary-arm type prototype was established based on experiences in three development phases. Figure 7 shows schematic diagram of the third prototype which is composed from the parts connected by wires. Transferring signals in wires are used to measure temperature and control heaters and a motor. The photographed appearance of third prototype of rotary arm type is shown in Fig. 8.

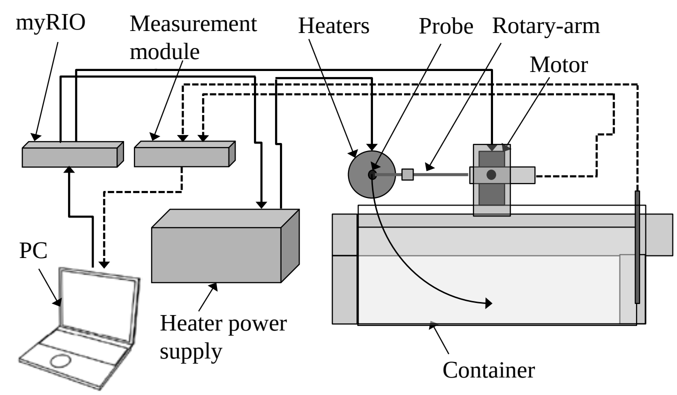


Figure: 7 Schematic diagram of third prototype of rotary arm type.

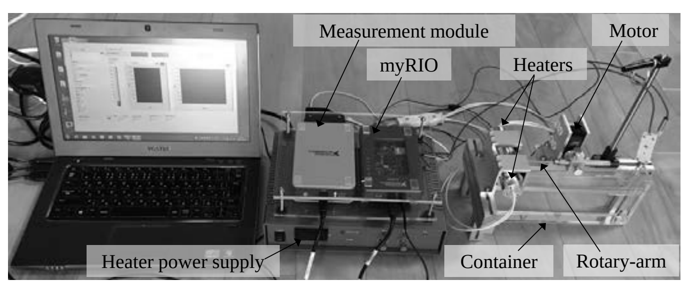


Figure: 8 Appearance of third prototype of rotary arm type.

The 4 mm diameter ball probe located at the tip of the rotary-arm is heated by a pair of the halogen lamp heaters connected with its power supply in less than one minute. The voltage of the heater power supply is controlled by the system on PC through the myRIO platform [27]. The halogen lamp has been specialized as a clean heating device although it was used for many lighting applications.

The temperature change in the probe is detected by the thermocouple in the probe and recorded by the system on PC through the measurement module. The same measuring system is applied to detect temperature at the container, which is displayed on the screen of PC for confirmation.

After heating the probe, the RC servo motor [28] rotates the rotary-arm in the quenchant container, which is controlled by the system on PC through the myRIO platform. The size specification of the container is length of 220 mm, width of 30 mm and height of 95 mm in internal dimension. Then the quenchant volume is 530 ml when the quenchant level is 80 mm.

Integrated system on PC for measuring temperature and controlling heater and motor was developed by the National Instruments LabVIEW program for the second prototype, and was adapted also to the third prototype including the replaced motor and myRIO.

The cooling curve analysis system for the second prototype was developed using LabVIEW to obtain cooling rate, heat transfer coefficient and heat flux - temperature curves, and also cooling characteristic parameters from cooling curves measured by the Inconel probe. The system was modified to fit the platinum probe in the third prototype.

The geometric relation among the probe, the heaters, the motor and the quenchant container for the third prototype is specified as shown in the front elevation in Fig. 9. The distance between the centers of the motor shaft and the probe is specified as 100 mm, which is the same as in the Tawara's apparatus. On the other hand, 35 mm distance between the initial location of the probe center and the level of quenchant surface corresponds to 40 mm in the Tawara's.

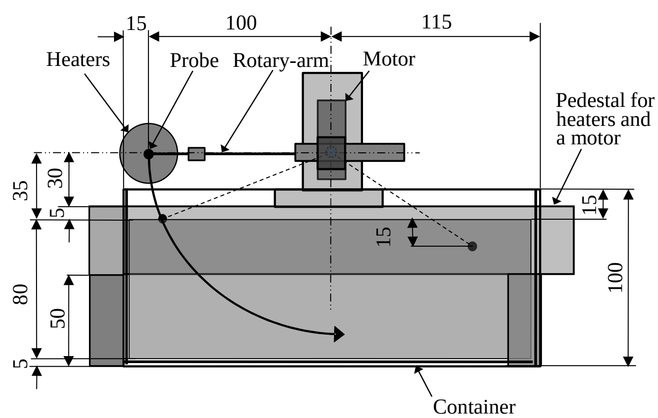


Figure 9: Front elevations of third prototype of rotary arm type.

Results Obtained from Rotary-Arm Type Prototype

Inherent shapes of cooling curves, obtained by the first prototype [9], identified clearly different types of quenchants and its temperature dependency as shown in Fig. 10 for water and polymer solution. A small temperature drop due to air cooling before immersion is seen until about 1.5 s in the curves. Trends in cooling curves of tap water agree with those in the Tawara's curves [10].

A preliminary test using two mineral oils noted as Oil A and B with the 47 mm2/s kinematic viscosity at 40 °C was also performed by the first prototype [9]. A boiling point of base oils in Oil A is higher than Oil B. Cooling and cooling rate curves for these oils were obtained as shown in Fig. 11. It is considered from these curves that differences in cooling characteristics between two oils can be identified. Similar trends of cooling and cooling rate curves obtained by Oil A and B are seen in the Tawara's results [10].

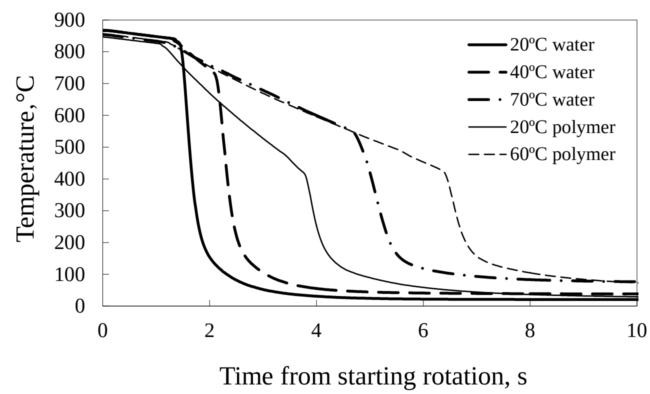


Figure 10: Cooling curves of water and polymer solution from first prototype of rotary arm type.

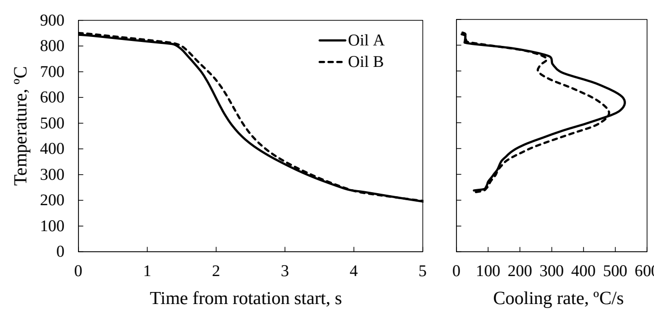
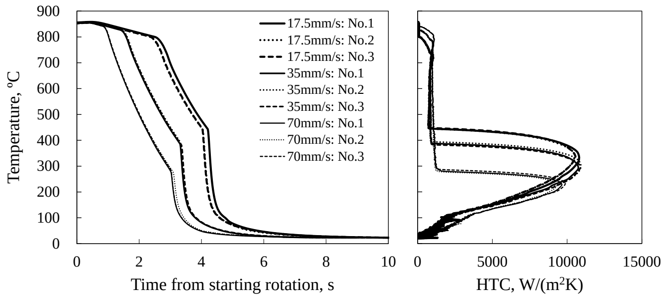


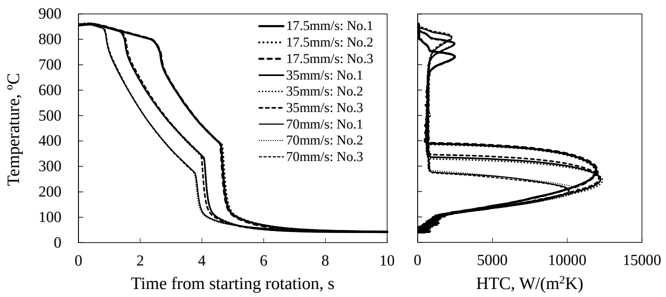
Figure 11: Different cooling characteristics between common and boiling point adjusted oils from first prototype of rotary arm type.

The third prototype using a platinum probe has been applied to similar tests performed for the second one for confirming the enhanced functions. The results described here were tested using 10% solutions of PAG polymer at 20, 40 and 60 °C temperatures and 17.5, 35 and 70 mm/s tangential speeds of circular motion of the probe. Figure 12 shows obtained cooling and heat transfer coefficient curves.

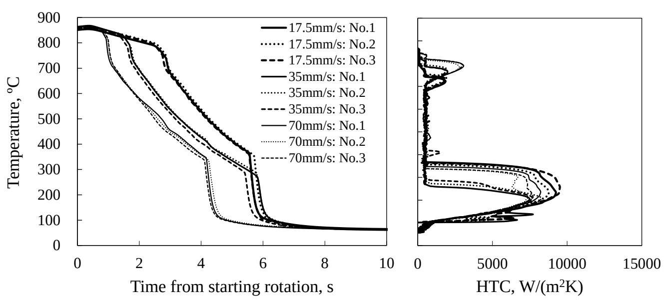
Heat transfer coefficients in between 500 and 600 °C at the probe in Fig. 12 are meaningful to clarify the characteristics in the vapor film stage of the polymer solutions. Then the average values of the heat transfer coefficient in the temperature range were obtained and plotted as shown Fig. 13. A dependency of solution temperature and tangential speed of circular motion of the probe on the heat transfer coefficient are revealed from the contour plot.



(a) 20 °C.



(b) 40 °C.



(c) 60 °C.

Figure 12: Cooling and heat transfer coefficient curves of 10% polymer solutions from third prototype of rotary arm type.

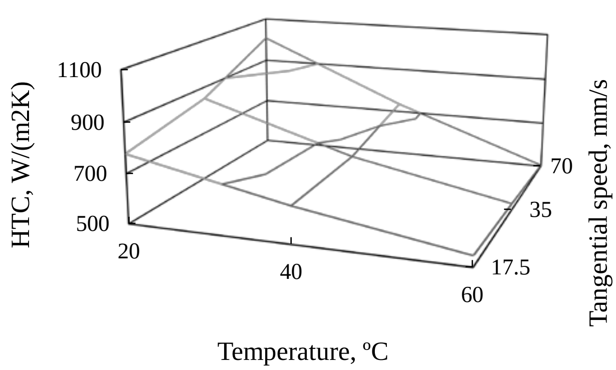
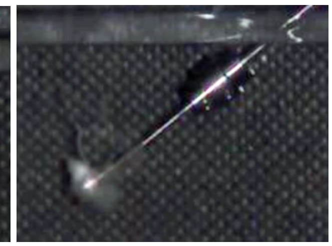


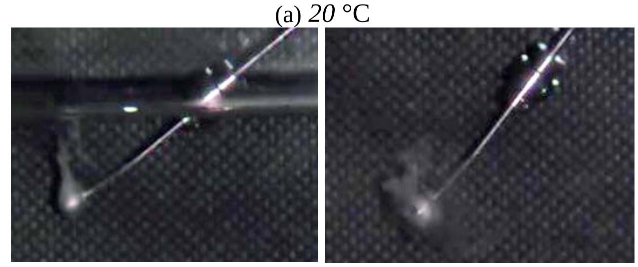
Figure 13: Average heat transfer coefficients of 10% polymer solutions at 20, 40 and 60 °C in between 500 and 600 °C probe temperature from third prototype of rotary arm type.

The rotating probe in the transparent acrylic container during testing was photographed with the High-speed Microscope VW-9000, KEYENCE Corp. Images of the probe and its surrounding during testing were grabbed from video at the vapor film and the vapor collapse stages in 10 % polymer solution at 20, 40 and 60 °C and 17.5 mm/s tangential speed as shown in Fig. 14. Different appearances of vapor around the probe are depicted well, which relate to the characteristics in the cooling and heat transfer coefficient curves in Fig. 12 and the average heat transfer coefficients in Fig. 13.

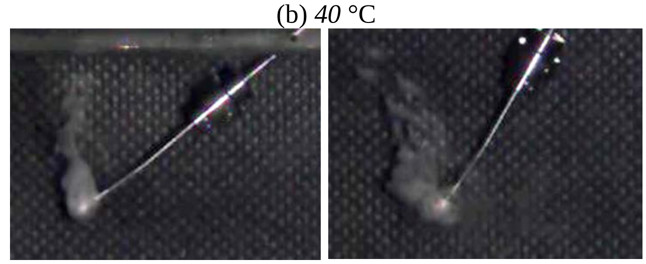
(i) Vapor film stage (ii) Vapor collapse stage

(a) *20* °C



(i) Vapor film stage (ii) Vapor collapse stage

(b) *40* °C



(i) Vapor film stage (ii) Vapor collapse stage

(c) *60* °C

Figure 14: Appearance of probe during testing in 10% polymer solution at 17.5 mm/s tangential speed from third prototype of rotary arm type.

In the third prototype, uniformity of the rotary-arm rotation was improved by changing the motor. As shown in Fig. 12, obtained cooling curves and heat transfer coefficients in the vapor film stage were almost the same in three tests conducted under the same conditions. However, starting points of the vapor film collapse were somewhat scattered.

Configuration of Container Elevator Type Prototype

Prototype of the container elevator type consists of components such as a probe, heaters, a heater retraction actuator, a quenchant container, a container elevator actuator, a temperature measuring device, a control system on PC, power supplies, as shown in the schematic diagram in Fig. 15. The appearance of the prototype is depicted in Fig. 16, which includes a control panel for control-related components and power supplies.

Firstly the probe is heated to a determined temperature with heaters which retract to a position for elevating the container after heating. Then, the probe is cooled in the quenchant in the container elevated by the actuator. Voltage changes of a thermocouple in the probe are transmitted to the PC through the temperature measurement module. This information is converted to the temperature changes by the measurement/control integration system developed by LabVIEW on PC. While, signals for controlling the heaters and the actuators are sent from the integration system through the controller to them.

The quenchant container is installed on the platform of the container elevator actuator and its temperature set at a specified value, which is measured by two thermocouples at above and below parts of the container. A video camera is installed when recording flow and boiling around the probe.

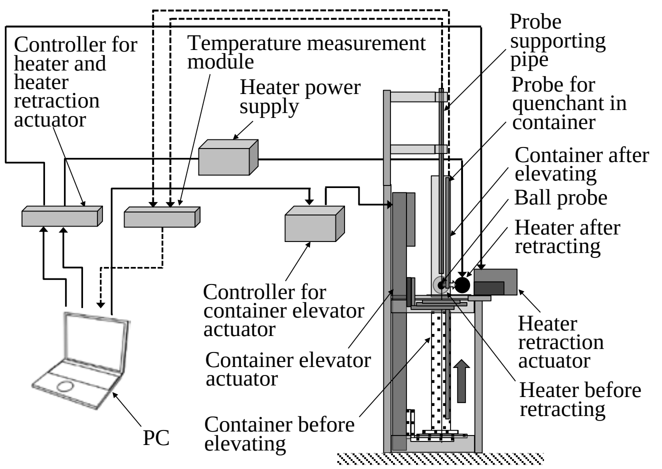


Figure 15: Schematic diagram of first prototype of container elevator type.

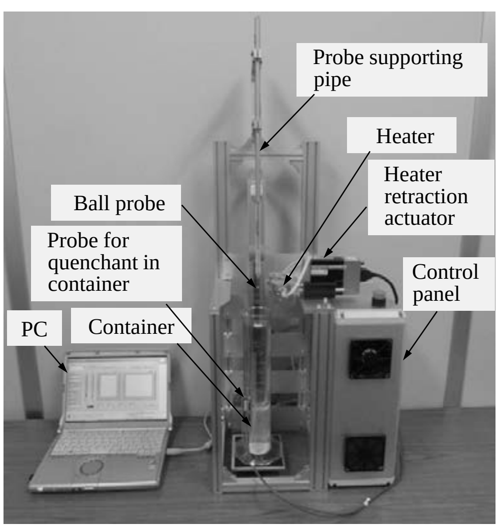


Figure 16: Appearance of first prototype of container elevator type.

The quenchant container for this prototype was considered to fit for relative elevation of the probe. A 500 ml graduated cylinder made of polymethylpentene was selected for water and polymer aqueous solution.

Heaters were retracted by IAI's actuator, EC-GD4, 50 mm in stroke and for horizontal placement. This actuator moves back and forth between heating and retracted positions. On the other hand, the container is elevated by IAI's actuator, RCP6-SA4C, 350 mm in stroke.

Results Obtained by Container Elevator Type Prototype

The first prototype with the platinum probe has been applied to the similar tests performed for the third rotary-arm type prototype for confirming its functions. The results described here were derived from tests using 10% solutions of PAG polymer at 20 °C when lifting the container at 17.5, 35 and 70 mm/s speeds.

Figure 17 shows obtained cooling and heat transfer coefficient curves from three tests conducted under the same conditions. Shapes of the curves under the same condition were almost the same except for the case of 17.5 mm/s lifting speed.

In this study, phenomena occurring around the probe during cooling were photographed by a high-speed camera. Photos for specific points in the curves, which are shown in Fig. 17, identify meanings of each cooling situation.

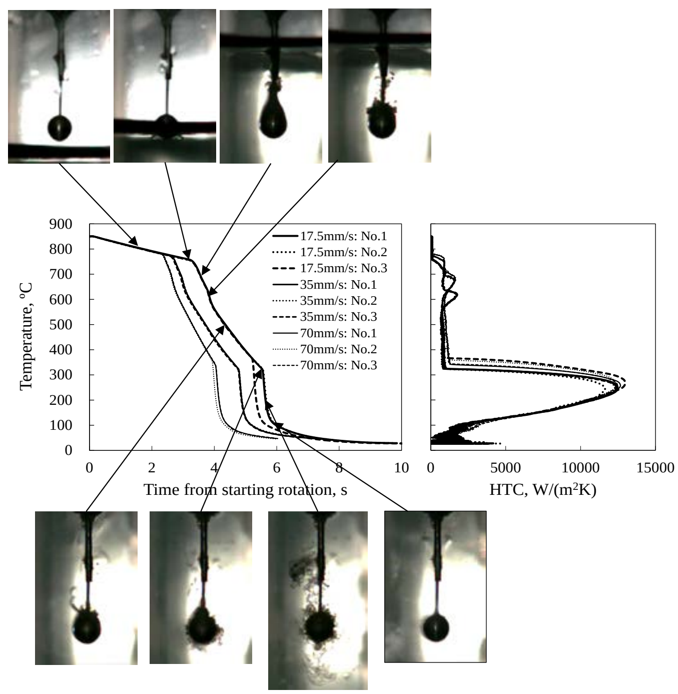


Figure 17: Cooling and heat transfer coefficient (HTC) curves of 10% polymer solutions from first prototype of container elevator type.

When comparing the results of this test with those of the same condition in the third prototype of rotary-arm type [11], it was revealed that temperatures when collapsing vapor film were different.

Inverse Heat Conduction Problem of a Ball Probe

The program IHCP1D [29] for the numerical solution of one-dimensional inverse heat conduction problem was applied to evaluate heat transfer coefficients at the probe surface. A cooling curve of the 20 °C tap water was measured at the center of the probe under the 100 mm/s elevating speed as shown in Fig. 18. A small temperature drop due to air cooling before immersion is seen until about 1.2 s in the curves.

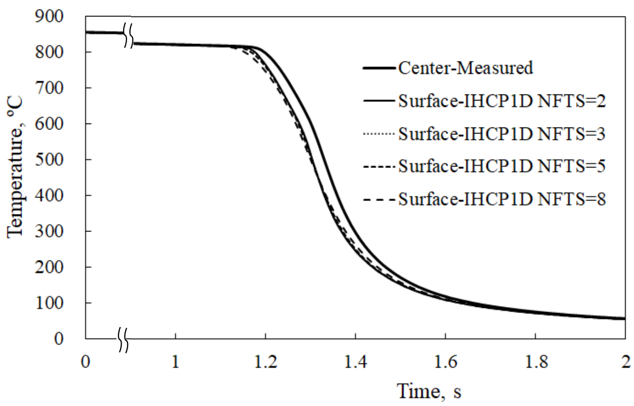


Figure 18: Cooling curves by measured and calculated by IHCP1D (under different number of future time steps)

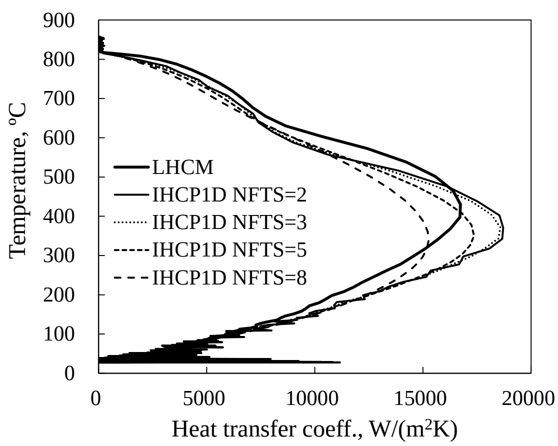


Figure 19: heat transfer coefficient by LHCM and IHCP1D (under different numbers of future time steps:NFTS)

The lumped heat capacity method (LHCM) was used to identify approximately the heat transfer coefficient on the surface as shown in Fig. 19, based on the assumption that transient temperature distributions in the probe are uniform. This calculation was performed by the system of the prototype.

Cooling curves and heat transfer coefficients at the surface were calculated by IHCP1D as shown in Figs. 18 and 19, respectively. It is noted that the number of future time steps (NFTS) [29, 30] was specified in legends for curves by IHCP1D. Peaks of heat transfer coefficient curves obtained by IHCP1D move to the lower temperature than one of LHCM. Also curves by IHCP1D are affected by numbers of future time steps.

Conclusions

Quenchants should be developed and maintained based on their cooling characteristics. A test system for this purpose is required to be compact, convenient, and reasonable. The author reviewed works on the test system and recent prototypes using a ball probe based on classical concepts. The obtained conclusions are as follows:

(1) The 4 mm dia. Cr-Ni and 7 mm dia. silver ball probe proposed in the early 1930s may be the origin of the small ball type.
(2) The small ball probes are more advantageous in that the temperature measured at its center can be regarded as the average value on the surface in the all cooling stages. Heat transfer coefficients of the probes are easily obtained using the lumped heat capacity method.
(3) Materials with extremely high corrosion resistance can be used reasonably for the probe under current manufacturing technologies because of its small size. Also the small probe can produce totally compact and short-term test system.
(4) The prototype of container elevator type functioned sufficiently so that quenchant flow around the probe become simpler for good repeatability.

It is expected that the prototype systems developed based on the classical concepts will be tried under a wide range of environments at research organizations, and their evaluation will be established after further improvements. This review also commented implicitly on the standards which exist for societies.

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