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

Kyozo Arimoto

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A wide variety of test systems have been developed to determine the cooling characteristics of quenchants. Among them, rational systems with good reliability and cost performance have been adopted as domestic and international standards. This review mainly focuses on test systems using a small ball probe and discusses their development processes, features, and potential uses. Although a test system with a ball probe is not defined in current standards, it is known that specific ones used in the past contributed to enhancing the test. This literature survey found a classic test system with 7-mm-dia. silver or 4-mm-dia. chromium-nickel balls, which was created rationally for using the lumped heat capacity method, and was applied to a variety of quenchants at the Kaiser Wilhelm Institute from 1928 to 1931. The institute finally increased the diameter of the silver ball probe to 20 mm due to manufacturing problems and applied it to various quenchants, which was widely applied until the ISO 9950 standard using an Inconel cylindrical probe was established. In latter half of this report, prototypes of the test system using a small ball probe created by the author's group since 2011 were briefly reviewed. This work solved the problem in the previous small ball probes with the current technology. The latest prototype uses a 4-mm-dia. platinum ball probe with a 0.25-mm-dia. sheathed thermocouple inserted into the center. The probe heated radiantly in a fixed state with halogen lumps is cooled in the quenchant in the container which is elevated by an electric linear actuator for robotics. This container movement creates a simple relative flow of quenchant around the probe, which has not been seen in the previous test systems. The use of the small ball probe has realized the compact and short-term test system.

Keywords ball probe, cooling analysis, inverse heat conduction problem, lumped heat capacity method, quenchant

1. Introduction

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

It is known that shapes of proposed probes have been not only cylindrical but also spherical. The introduction part of ISO 9950 (Ref 5) describes that test methods using a silver ball probe were widely identified at that time of its establishment. However, Lakin (Ref 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 the classical literature has found that small ball probes were created rationally and applied to a variety of quenchants by Engel (Ref 8) in his study on quenching at the Kaiser Wilhelm Institute from 1928 to 1931. Engel stated 7-mm-dia. silver and 4-mm-dia. chromium-nickel balls are ideal for the lumped heat capacity method. 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 (Ref 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 Tawara's apparatus (Ref 10). Then, the test system with a rotary arm to transfer and immerse a probe, which is called a rotary arm type, was developed in three phases of this project (Ref 11). Currently, a mechanism has been devised to cool a stationary probe by elevating a quenchant container, which is called the container elevator type (Ref 12).

In the following, the author reviews for classic test systems using a ball probe and summarizes specific features of the prototypes and their results. An unpublished study on the inverse heat conduction problem for the ball probe applied to the prototypes is depicted additionally.

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Kyozo Arimoto, Arimotech Ltd, Osaka, Japan. Contact e-mail: kyozo_arimoto@arimotech.com.

2. Classic Test Systems Using a Ball Probe

2.1 Outline

The author reviewed studies on test systems using ball probes in 2014 (Ref 9), in which the Engel's pioneering work and Lakin's criticism for a ball probe were not introduced. The following summarizes the development of the ball probe and its subsequent positioning by using newly discovered literature content additionally.

2.2 Engel's Work

Engel (Ref 8) evaluated former studies using cylindrical probes by Benedicks (Ref 13) and Pilling-Lynch (Ref 14), for example, for developing his test system. These experimental works were performed to obtain cooling curves and observe microstructures in carbon steels in probes. Engel pointed out that cooling curves of steels are affected due to the latent heat of phase transformations and then recommended to use metals without phase transformations for the probes of the quenchant test.

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 with reference to a probe reported by Gebhard et al. (Ref 15) for finding martensite start temperature.

Engel's tests were carried out using the above-described probes, which were applied to investigate not only the characteristics of quenched parts but also the 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.

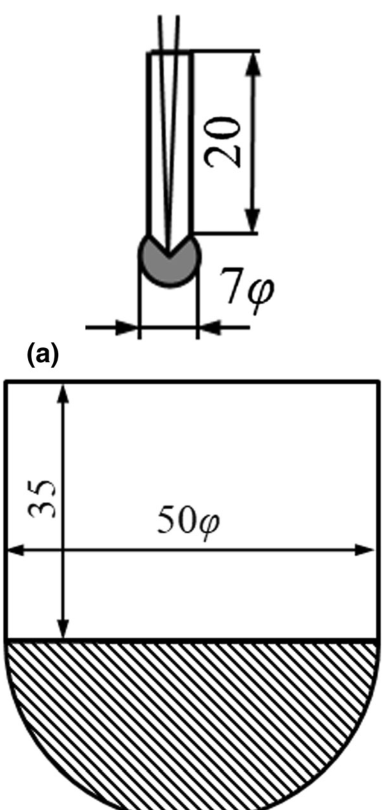

Fig. 1 Engel's ball probes. (a) 7 mm dia. (b) 50 mm dia

Table 1 indicates the physical properties of probe materials which were converted to the SI unit by the author. The values show that the chromium and nickel are a poor heat conductor. It needs to be noted that the chemical composition of chromium and nickel was not expressed by Engel. Also, the metal was called as chromium-nickel steel, which was specified in some later literature when referring the Engel's probe (Ref 16).

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 and nickel, and phenomena occurring on the surface of the probes can be regarded as homogeneous. All his probes were heated to about 900 °C in an oven and cooled in a quenchant container. The container capacity was 500 mL and 5 L for the minimum and maximum probe sizes, respectively. Probe temperature changes were recorded with equipment produced by Siemens.

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

Engel depicted 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 the cooling process, because of the high thermal conductivity and/or small size of probes. Silver balls of 7 mm dia. were used for distilled water, hardening oil and air, and chromium-nickel balls of 4 mm dia. were for liquid metal.

Differences in cooling characteristics of quenchants were expressed based on the heat flux temperature curves. Liquid metal and air show a simple upward shape in the curves, while 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.

2.3 Subsequent Works Using Ball Probes

Speith and Lange (Ref 17) changed the diameter of the Engel's silver probe from 7 to 20 mm. The changing of diameter was explained that smaller diameter balls induced variation in phenomena during immersion and 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 photographs, Schlieren photographs, and movies. To not

Table 1 Physical property of Engel's probe materials

Material	Specific gravity	Specific heat, kJ/(kg K)	Thermal conductivity, W/(m K)	Thermal conductivity ratio 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
Cr-Ni	8.4	0.448	5.19	1

impede progress of the phenomena, a support structure was attached to the bottom of the probe.

For evaluating the study by Speith and Lange, Russell (Ref 18) measured cooling curves of eight quenching oils having different properties using a 25.4-mm-dia. silver ball. Cooling curves were measured during immersing the probe vertically into still quenchants after heating it to about 850 °C. Cooling curves obtained from a silver ball in mixed oils at different temperatures showed clearly a characteristic point, which is a bending point of identifying a transition from vapor film to boiling stages. In addition, the characteristic temperature was defined as the temperature at the characteristic point. It was pointed out that the characteristic point was not significant in cooling curves measured at the center of the 20% Ni-25% Cr austenitic steel ball with the same dimensions as silver probe and 0.33% C-3.39% Cr-0.69% Ni steel cylinder with diameter of 25.4 mm and length of 50.8 mm.

Furthermore, Russell examined differences between cooling curves obtained from thermocouples provided on the bottom and the side on the silver ball. It was found that cooling rate on the bottom was higher in the early stages of cooling, while the side reached quickly to the characteristic point. This was explained by using an eddy model of flow around the silver ball. In spite of this complex phenomenon, the method using the silver ball was regarded as standard since obtained cooling curves showed good repeatability. On the other hand, it was pointed out that the Ni-Cr steel probe is not sufficient in repeatability due to scale formation. Even in the austenitic steel ball, effects of surface tarnish on cooling rate at the center were described.

Rose (Ref 19) applied the same 20-mm-diameter silver ball probe as Speith and Lange's to obtain cooling characteristics of various quenchants. 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 adjusting to industrial conditions and avoiding 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:

$$\alpha = \frac{\mathrm{d}T}{\mathrm{d}t}\frac{\rho C_p V}{S(T_e - T)} \quad \text{(Eq 1)}$$

where T is assumed be uniform temperature of probe, T_e temperature of quenchant, V and S volume and surface area of ball, and C_p and ρ specific heat and density of probe material. Equation 1 shows the method can calculate the heat transfer coefficient easily if cooling rate dT/dt is known. Additionally, heat flux is calculated from Eq. 1 without $(T_e - T)$.

Rose compiled a table of heat transfer coefficients for the vapor blanket, nucleate boiling, and convection stages using his data and previous data including Engel's. Table 2 shows a subset of Rose's, which was made by the author after converting the unit. The results obtained by Engel and Rose may not be consistent. Rose also referred to chromium and nickel as chromium-nickel steel in the original table.

Using the same silver ball as Rose's, Schallbroch et al. (Ref 20) designed a cooling test system that the probe was immersed into quenchant flowing like a river in a tank by a gear pump. Schematic diagram of the test apparatus included in their report was simplified further by the author as shown in Fig. 2. It was mentioned that an advice from Kaiser Wilhelm Institute was applied to design this system. Although the flow rate of the quenchant is not clear, how to give relative flow around the probe is described more clearly than Rose's report. On the other hand, Krainer and Swoboda (Ref 21) 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 curves were redrawn by the author as shown in Fig. 3.

Peter (Ref 22) applied a similar experimental method using the silver ball by Rose (Ref 19) to extensive conditions of a wide variety of quenchants. A liquid capacity in a vessel was described as 2 L for his tests. For example, cooling rate curves at five temperature levels between 20 °C and boiling temperature were shown for different waters such as distilled water, tap water of Dusseldorf and Clausthal, well water, and various conditions of distilled water (gas-free, nitrogen, air, oxygen saturations, and carbonated). In addition, cooling characteristics of eight quenching oils, various aqueous solutions, various metal and salt baths, and mercury were investigated.

In addition, Peter (Ref 23) reported separately about contributions of surface properties to cooling characteristics. It was described that soft iron balls with diameters of 19 and 40 mm were cooled in quenchants with a capacity of 2 and 10 L, respectively. Additional information showed that the iron balls were given a circular motion in quenchants for their relative agitation. It was clarified effects of surface oxidations and salt layer coats on the cooling rate curve. Balls with oxide film thickness of 0.08 to 0.1 and 0.2 to 0.25 mm were applied to molten salts, aqueous solutions, oils, and distilled waters.

2.4 Tawara's Work Using a Small Ball Probe

The author's literature survey found a unique test method reported by Tawara (Ref 10), which was developed at the materials research department of Japanese Naval Institute of

Table 2 **Heat transfer coeff., α, W/(m²K), of different quenchants by the lumped heat capacity method**

Quenchant			Vapor blanket		Nucleate boiling		Convection			
Name	Temp, °C	Cooling Rate, cm/s	Temp, °C	α	Temp, °C	α	Temp, °C	α	Probe	Source
Water	18	Moderate	720	6300	550	10,100			Cr-Ni ball:4φ	Engel (Ref 8)
Water	15.5	Moderate	720	3490	200	25000			Ag ball: 7φ	Engel
Water	20	25	700	3110	500	12,600	90	2440	Ag ball: 20φ	Rose
Water	8	10	700	1270	300	6050			Ag ball: 20φ	Rose
Rapeseed oil	20	Moderate	720	2110	550	2790	300	768	Cr-Ni ball: 4φ	Engel
Rapeseed oil	20	Moderate	720	1980	550	3490	200	512	Ag ball: 7φ	Engel
Rapeseed oil	20	25	700	1690	500	3660	200	488	Ag ball: 20φ	Rose
Oil heavy	20	Moderate	720	843	600	3190	300-200	670-372	Cr-Ni ball: 4φ	Engel
Oil light	20	Moderate	720	500	500	2970	200	744	Cr-Ni ball: 4φ	Engel
Oil heavy	20	Moderate	720	686	500	3490	200	599	Ag ball: 7φ	Engel
Oil heavy	20	25	700	1420	550	3020	300-200	314-244	Ag ball: 20φ	Rose
Oil light	20	25	700	779	450	3260	300-200	477-244	Ag ball: 20φ	Rose

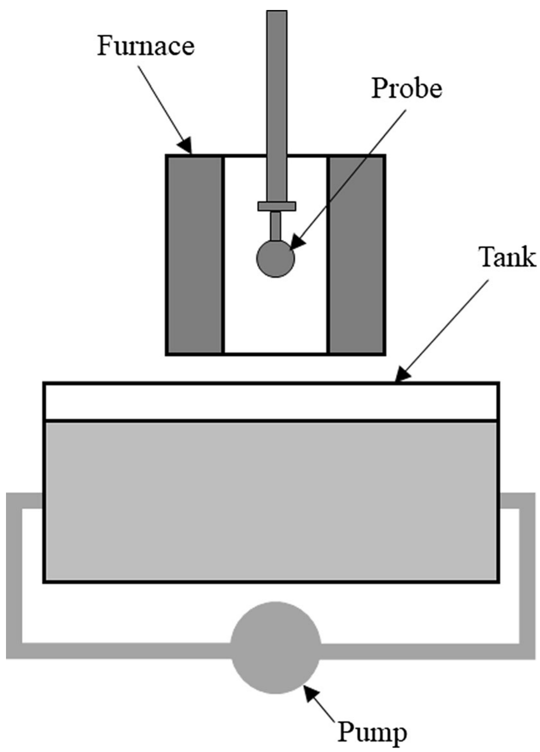

Fig. 2 Schematic diagram of apparatus by Schallboch et al

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 relative 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 0.2-mm-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 ball probe. The probe is radiant heated until 850 °C by the Nichrome coils and then moves circularly at a tangential speed of about 70 mm/s in still quenchants in a 1.5-L container.

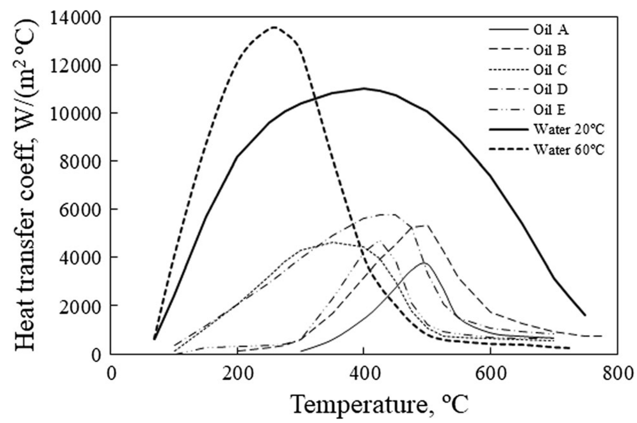

Fig. 3 Temperature curves of heat transfer coefficients by silver probes

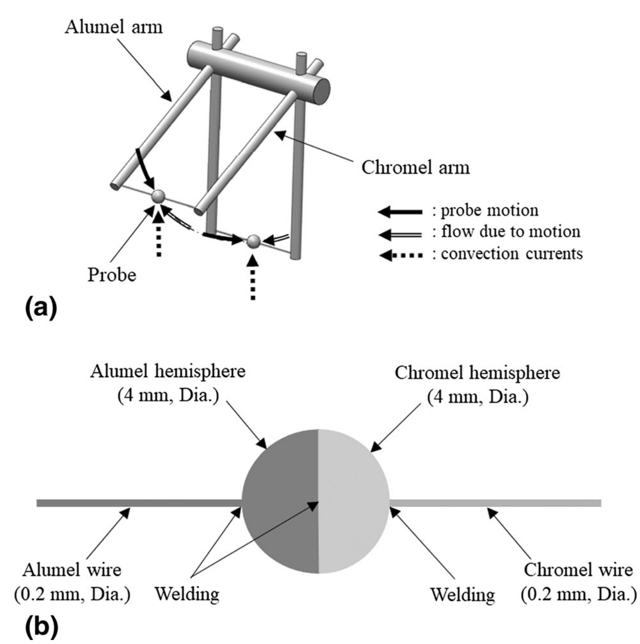

Fig. 4 Rotary arm-type apparatus by Tawra. (a) Movement of probe and rotary arms. (b) Structure of probe

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 shown as the test results, while original cooling curves were reported for some quenchants. Heat transfer coefficient was not reported, although his small ball probe is suited to the lumped heat capacity method.

2.5 Subsequent Works After Tawara's

A study of cooling characteristics using a silver cylinder probe was performed by Tagaya and Tamura (Ref 24) after Tawara's study. Their efforts were published in the Journal of the Japan Institute of Metals 13 times separately as the title of "Studies on the Quenching Media" from 1951 to 1956. It needs to be noted that they introduced past measuring methods by Speith and Lange (Ref 17) and Rose (Ref 19) without the contents of Tawara's apparatus (Ref 10). In their first report (Ref 24) 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 is not clearly explained why they selected a cylindrical shape for the probe. A number of cooling curves measured mainly on the surface of the probe were shown in a series of their reports, while the cooling rate curve was not included there.

The method based on studies by Tagaya and Tamura was established as JIS K2526 (Ref 3) in 1965. This standard specified that a silver cylindrical probe, 10 mm in diameter and 30 mm in length, is immersed into still quenching oils to measure cooling curves on its surface. Since a tube for protecting a wire connected to a thermocouple on the surface is inserted laterally into the cylinder, the probe is non-axisymmetric. The standard specification does not require reporting of the cooling rate curve. JIS K2526 was merged with JIS K2242, "Heat Treating Oils" (Ref 25) in 1980. When JIS K2242 was revised in 2006, a silver probe with a thermocouple at the center was added as a probe to be used mainly for aqueous solutions.

Narazaki et al. (Ref 26) investigated effects of probe shape by immersing tests in distilled water (10 L) using cylindrical silver probes, 10 mm in diameter and 30 mm 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 a lower temperature. Furthermore, coincident characteristic temperatures were detected in cooling curves of balls and cylinders with hemispheres. Narazaki et al. (Ref 27) suggested that these balls and cylinders with hemispheres probes needs to be adopted as standard since more essential phenomenon in cooling is captured using them. They concluded that the cylindrical probes, including the JIS standard, needs to be modified considering to their above finding.

2.6 Studies for the ISO Probe Based on Previous Ball Probes

Lakin, Wolfson Heat Treatment Centre (WHTC), pointed out the following practical limitations of the silver ball probe, although a thermocouple technique was typified by the probe (Ref 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 for avoiding the above limitations as follows (Ref 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, and then, the probe may be considered as a 12.5-mm-diameter bar of infinite length, i.e., end effects may be ignored. The positive comments on silver ball probes given by Russell (Ref 18) were not considered for this proposal. Also, the wetting phenomenon on the surface of cylindrical probes was pointed out by Tensi in his experimental work (Ref 28). It was revealed an interface between vapor blanket and nucleate boiling moves from the lower edge of the probe to its top during cooling.

After a while, WHTC published the specification "Laboratory Test for Assessing the Cooling Characteristics of Industrial Quenching Media" (Ref 29). This informs WHTC set up a working party on "Testing of Quenching Media" in 1974. This document prepared by the party includes a draft for a standard on the cooling test system for quenchants. For examples, the 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.

Hilder describes the party of WHTC turned its attention to establishing a standard agitated test for aqueous quenchants (Ref 30). 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) (Ref 31). 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 (Ref 5) was published in 1995. In its introduction part, the ball probe is described as follows: "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." Also materials, sizes, and shapes of the probe are commented generally as "the probes have been made of various materials and different sizes, the shape normally being cylindrical."

As a recent achievement of a cylindrical probe, Fried et al. (Ref 32) applied the particle swarm optimization (PSO) algorithm for inverse problem to four cooling curves at three near-surface thermocouples and one center thermocouple in a cylindrical Inconel 600 probe, 15 mm in diameter and 45 mm in length. Axisymmetric temperature distribution changes and heat transfer coefficients on the specific surface positions during the wetting phenomenon in the probe were calculated well with the algorithm. This means that cooling curves at multiple points may be required to obtain an accurate heat transfer coefficient in the ISO-type probe with wetting phenomena.

3. Prototypes of Test System Using a Ball Probe

3.1 Outline

The author's group has been developing prototypes of the test system using a small ball probe over phases (Ref 9, 11, 12) based on the concepts of previously developed systems. The rotary arm type was selected initially for the prototype based on Tawara's concept. The original system has a ball probe, which is supported from both sides with a thin wire stretched horizontally as described in section 2.4. The probe rotation induces flow around it, while convection currents occur due to high-temperature probe in quenchant as shown in Fig. 4(a). The supporting wires show some influences on both the flow and currents.

On the other hand, the probe in the prototype of the rotary arm type is supported with a tube from one side as shown in Fig. 5. This design was adapted from current contracted manufacturing technology, which 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 at the center.

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 the rotational angle of the tube varies during cooling as shown in Fig. 5. In order to avoid the problem due to angular changes of the supporting tube, a method depicted in Fig. 6 was proposed as the container elevator type.

In the container elevator type, the quench container rises vertically toward the fixed probe as shown in Fig. 6. 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 the container elevator type has become possible, since linear electric actuators have been distributed at economical prices for robotics.

The first and second rotary arm-type prototypes used 4-mm-dia. ball probes made of Inconel 600 immediately because of

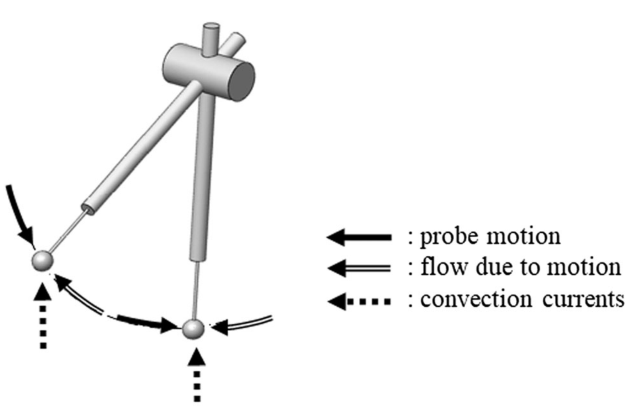

Fig. 5 Schematic diagram of motions and flows in rotary arm type

manufacturability. Finally, the third rotary arm-type prototype achieved to change the probe material to pure platinum for resolving the discoloration and thermal aging problems on the Inconel probe surface. Figure 7(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. 7(b). The platinum ball probe was used for the container elevator-type prototype.

Some of the problems on the previous ball probes have been resolved when using the platinum probe. Unlike silver, it does not need to be polished before testing, and its thermal conductivity is closer to iron than silver. The small ball probe is advantageous, in that the lumped heat capacity method can be used as described by Engel (Ref 8).

3.2 Configuration of Rotary Arm-Type Prototype

Rotary arm-type prototype was established based on experiences in three development phases (Ref 9, 11). Figure 8 shows a schematic diagram of the third prototype, which is composed of the parts connected by wires. Transferring signals in wires are applied to measure temperature and control heaters and a motor. The photographed appearance of the third prototype of the rotary arm type is shown in Fig. 9.

The 4-mm-dia. ball probe at the tip of the rotary arm is heated in less than one minute by a pair of the halogen lamp heaters with a mirror that condenses the light at one point. Halogen lamps have been specialized as clean heating devices, although they were used for many lighting applications. The heater power supply is controlled by the PC system through the myRIO platform (Ref 33).

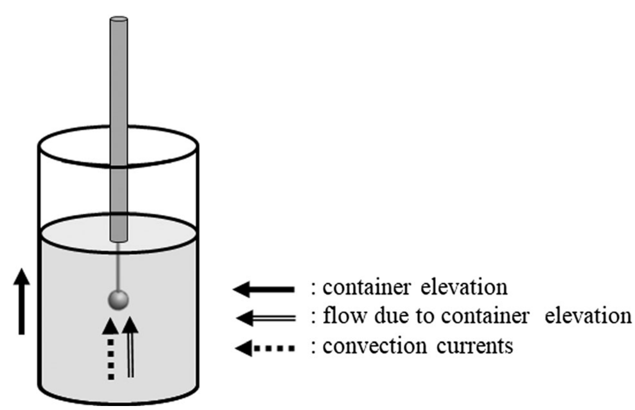

Fig. 6 Schematic diagram of motions and flows in container elevator type

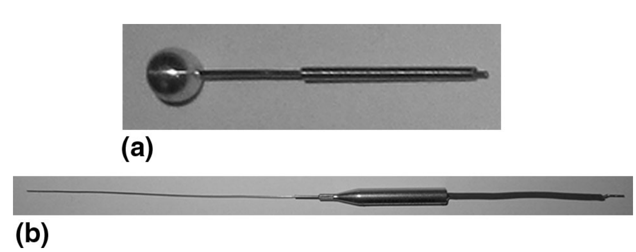

Fig. 7 Appearance of ball probe and thermocouple. (a) 4-mm-dia. platinum probe with platinum tube. (b) 0.25-mm-dia. K-type sheath thermocouple

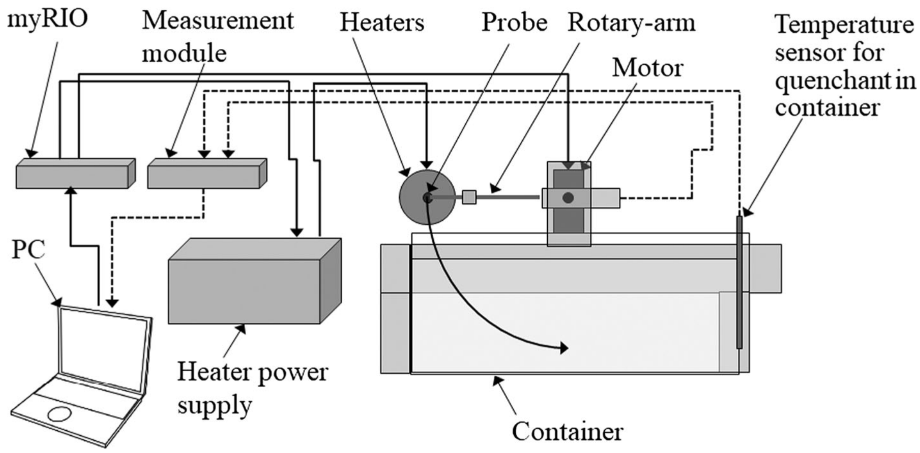

Fig. 8 Schematic diagram of third prototype of rotary arm type

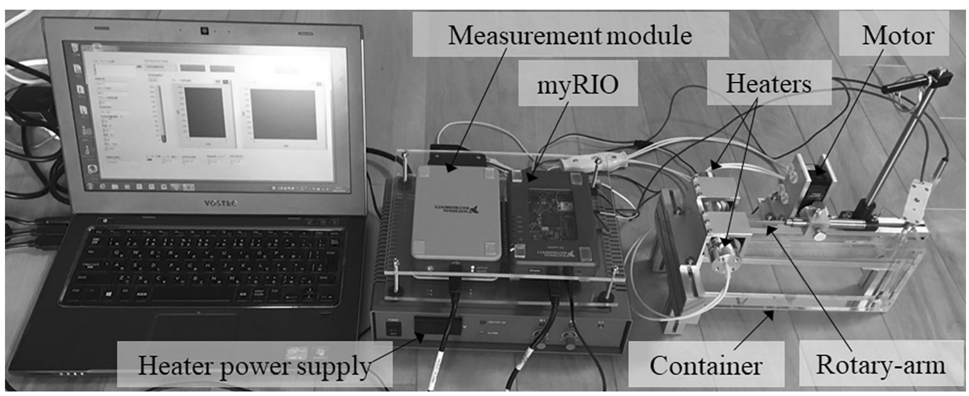

Fig. 9 Appearance of third prototype of rotary arm type

Probe temperature changes are detected by the probe thermocouple and recorded by the PC system through the measurement module. The same measurement system is applied to detect the temperature in the container and is displayed on the PC screen for confirmation.

After heating the probe, the RC servomotor rotates the rotary arm in the quenchant container, which is controlled by the PC system through the myRIO platform. The container size specification is 220 mm in length, 30 mm in width, and 95 mm in height in internal dimensions. Then, the quenchant volume is 530 mL when the quenchant level is 80 mm.

An integrated PC system for measuring temperature and controlling heater and motor was developed for the second prototype using National Instruments LabVIEW program. This system was also used for the third prototype that replaced the motor and installed myRIO. A cooling curve analysis system was developed for the second prototype using LabVIEW. The system obtains cooling rate, heat transfer coefficient, heat flux, and cooling characteristic parameters from cooling curves. Heat transfer coefficient and heat flux are calculated using the lumped heat capacity method. This 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. 10. 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.

3.3 Results Obtained from Rotary Arm-Type Prototype

Inherent shapes of cooling curves, obtained by the first prototype (Ref 9), identified clearly different types of quenchants and its temperature dependency for water and polymer solutions as shown in Fig. 11. A small temperature drop due to air cooling before immersion is seen until about 1.5 s in the curves. Trends of the cooling curves for tap water are consistent with those in the Tawara's curves (Ref 10).

A preliminary test using two mineral oils, indicated as Oil A and B with the 47 mm^2/s kinematic viscosity at 40 °C, was also performed by the first prototype (Ref 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. 12. It is considered from these curves that differences in cooling

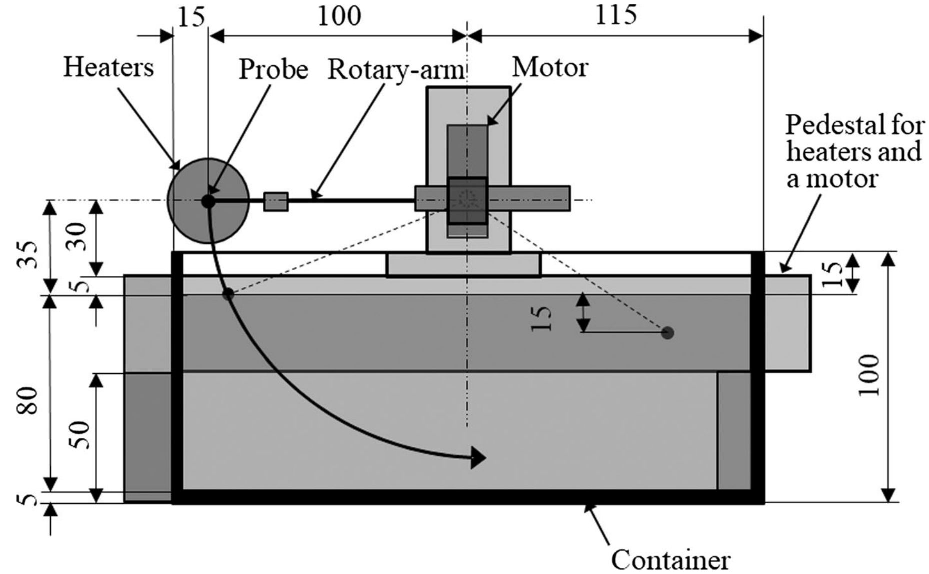

Fig. 10 Front elevations of third prototype of rotary arm type

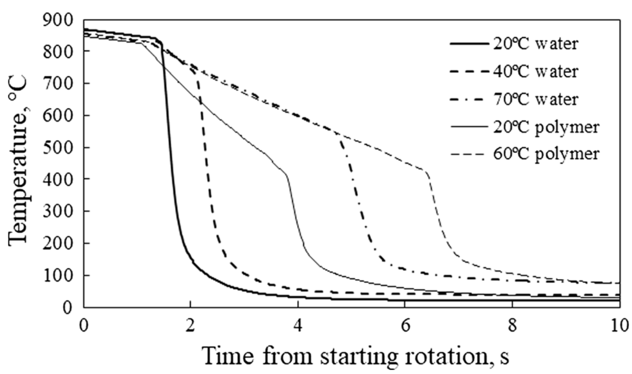

Fig. 11 Cooling curves of water and polymer solution from first prototype of rotary arm type

characteristics between the two oils can be identified. Similar trends in cooling and cooling rate curves obtained by Oil A and B are seen in the Tawara's results (Ref 10).

The third prototype using a platinum probe was applied to similar tests performed on the second one for confirming the extended functions. The results described here were tested using 10% solutions of PAG polymer at temperatures of 20, 40, and 60 °C and tangential speeds of 17.5, 35, and 70 mm/s of circular motion of the probe. Figure 13 shows the resulting cooling and heat transfer coefficient curves. The results in the vapor film stage were almost the same in three tests conducted under the same conditions, since uniformity of the rotary arm rotation was improved by changing the motor. However, starting points of the vapor film collapse were somewhat scattered.

Examining the steady heat transfer coefficient in the vapor film stage from 500 to 600 °C in the probe temperature in Fig. 13 was thought to be useful for evaluating the cooling

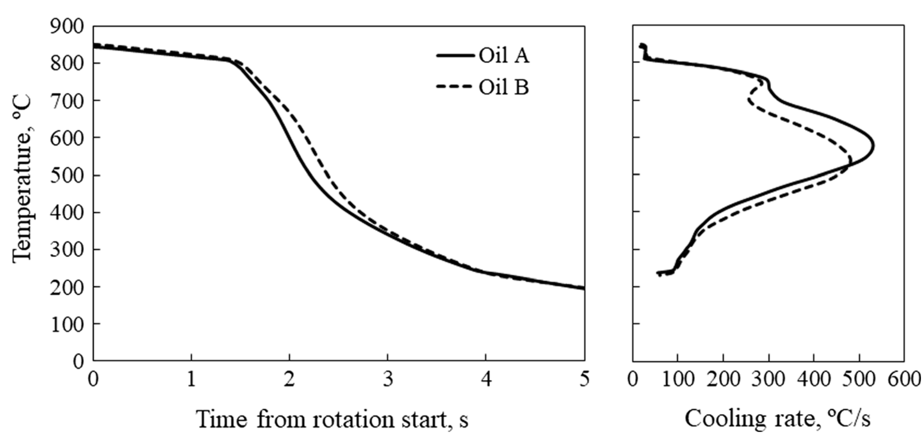

Fig. 12 Different cooling characteristics between common and boiling point adjusted oils from first prototype of rotary arm type

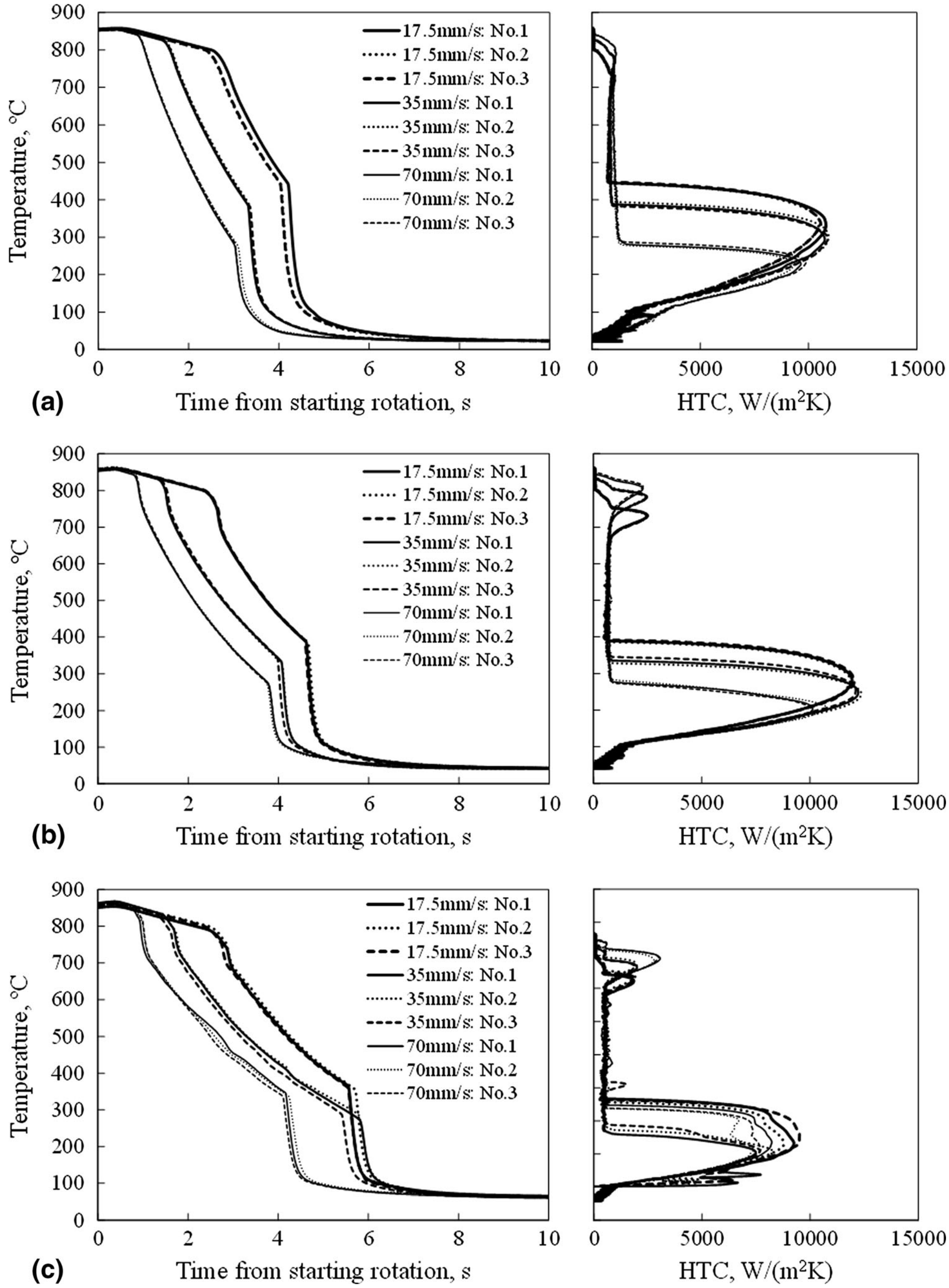

Fig. 13 Cooling and heat transfer coefficient curves of 10% polymer solutions from third prototype of rotary arm type. (a) 20 °C. (b) 40 °C. (c) 60 °C

characteristics of the polymer solutions. To make this clearer, the average values of the heat transfer coefficient over the temperature range were obtained and plotted as shown Fig. 14. The dependence of solution temperature and tangential speed of circular motion of the probe on the heat transfer coefficient are revealed from the contour plot.

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 surroundings during testing were grabbed from the 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. 15. 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. 13 and the average heat transfer coefficients in Fig. 14.

3.4 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, and power supplies, as shown in the schematic diagram in Fig. 16 (Ref 12). The appearance of the prototype is depicted in Fig. 17,

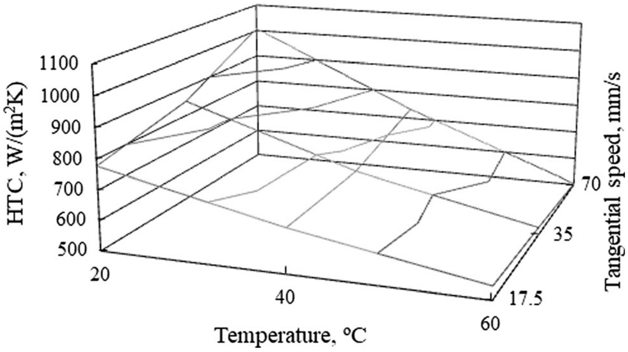

Fig. 14 Average heat transfer coefficients of 10% polymer solutions at 20, 40, and 60 °C in between 500 and 600 °C probe temperature from third prototype of rotary arm type

which includes a control panel for control-related components and power supplies.

First, the probe is heated to a determined temperature with a pair of the halogen lamp 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 signal is converted to the temperature changes by the measurement/control integration system developed by LabVIEW on PC like the rotary arm type.

On the other hand, signals are sent from the integration system to the heaters and the actuators through the controller. Retracting heaters is performed by IAI's actuator, EC-GD4, 50 mm in stroke and for horizontal placement. This actuator

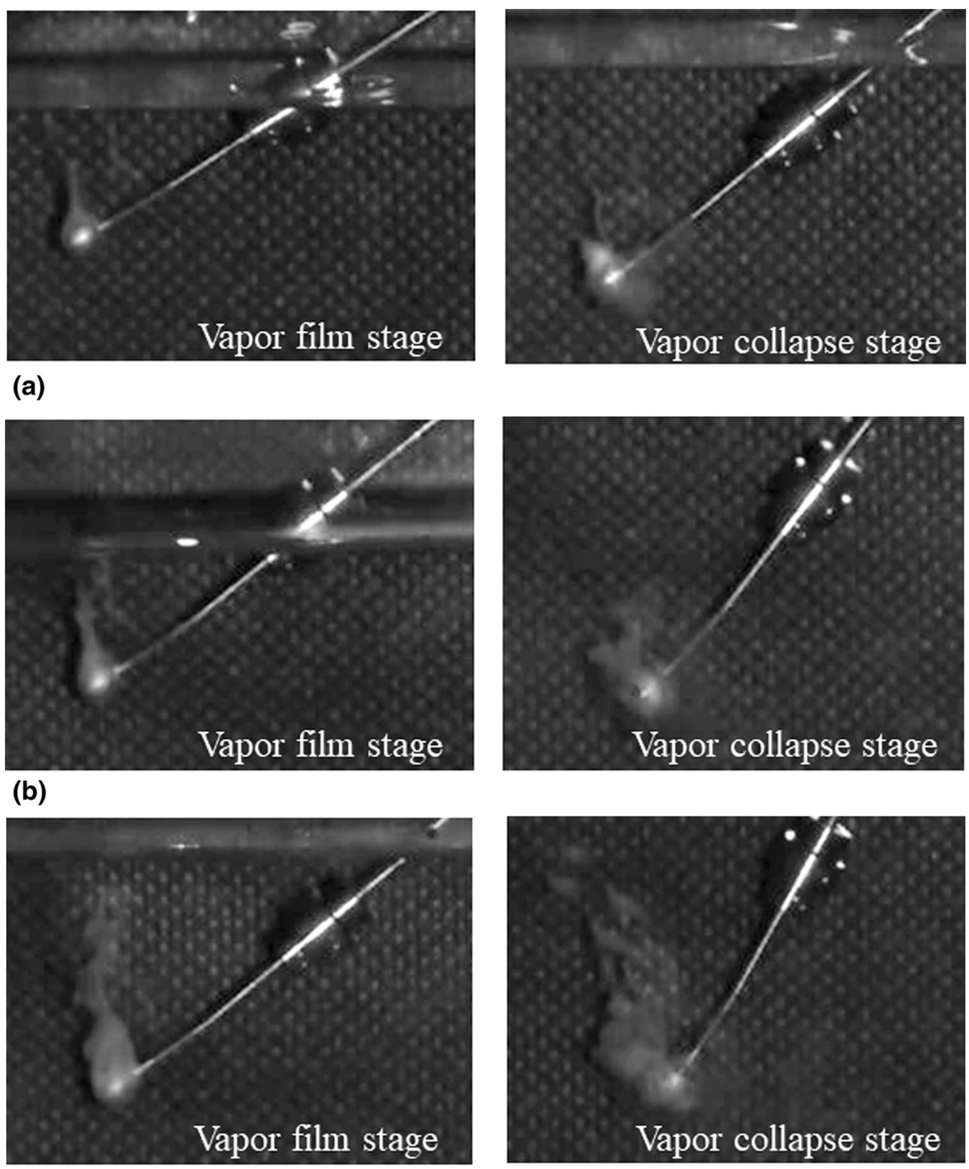

Fig. 15 Appearance of probe during testing in 10% polymer solution at 17.5 mm/s tangential speed from third prototype of rotary arm type. (a) 20 °C. (b) 40 °C. (c) 60 °C

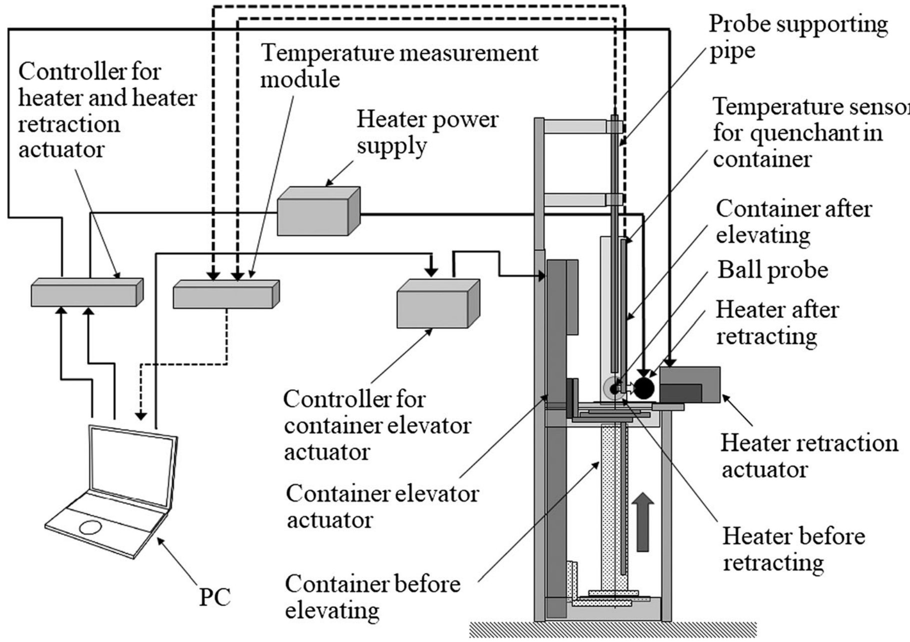

Fig. 16 Schematic diagram of first prototype of container elevator type

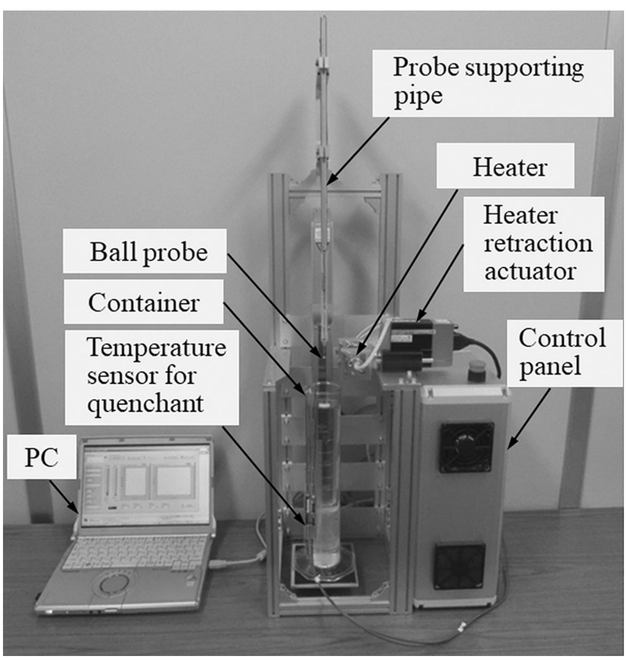

Fig. 17 Appearance of first prototype of container elevator type

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. The cooling curve analysis system for the rotary arm type was used to obtain cooling rate, heat transfer coefficient, heat flux, and cooling characteristic parameters from cooling curves.

The quenchant container for this prototype was 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 500-mL graduated cylinder made of polymethylpentene was selected for water and polymer aqueous solution. A video camera is used when recording flow and boiling around the probe.

3.5 Results Obtained by Container Elevator-Type Prototype

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

Figure 18 shows obtained cooling and heat transfer coefficient curves from three tests conducted under the same conditions. The 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. Photographs in Fig. 18 for specific points on the curve reveal each cooling situation.

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

3.6 Inverse Heat Conduction Problem of a Ball Probe

The program IHCP1D (Ref 34) for the numerical solution of one-dimensional inverse heat conduction problem was applied to evaluate the heat transfer coefficient at the probe surface. The cooling curve with 20 °C tap water in Fig. 19 was selected for this purpose, which was measured at the center of the probe

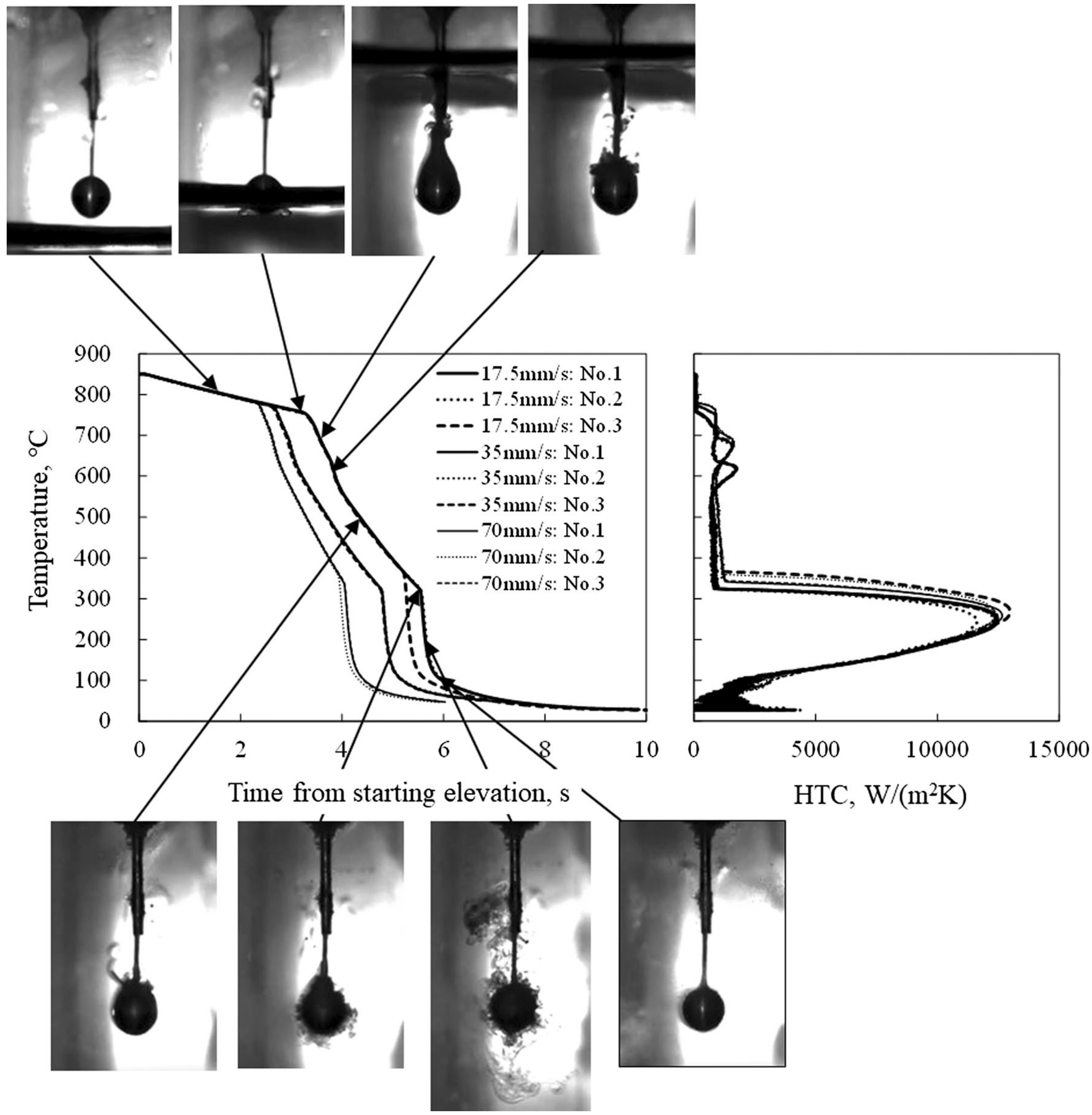

Fig. 18 Cooling and heat transfer coefficient curves of 10% polymer solutions from first prototype of container elevator type

under the 100 mm/s elevating speed using the prototype of the container elevator type. A slight temperature drop due to air cooling before immersion is observed until about 1.2 s in the curve.

Cooling curves and heat transfer coefficients at the surface were calculated by IHCP1D as shown in Fig. 19 and 20, respectively. It is noted that the number of future time steps (NFTS) (Ref 34, 35) was specified in legends for curves by IHCP1D. For comparison, the heat transfer coefficient obtained from the lumped heat capacity method (LHCM) is included in Fig. 20. Peaks of heat transfer coefficient curves obtained by IHCP1D move to lower temperature than LHCM. Also, curves by IHCP1D are affected by numbers of future time steps.

4. Conclusions

Quenchants have been developed and maintained based on their cooling characteristics. A test system to obtain the characteristics is required to be rational, reliable, compact, convenient, and reasonable. The author reviewed works regarding classic test systems and recent prototypes using a ball probe. The obtained conclusions are as follows:

(1) The origin of the small ball probe may be the 4-mm-dia. Cr-Ni and 7-mm-dia. silver balls developed rationally in the early 1930s at the Kaiser Wilhelm Institute.

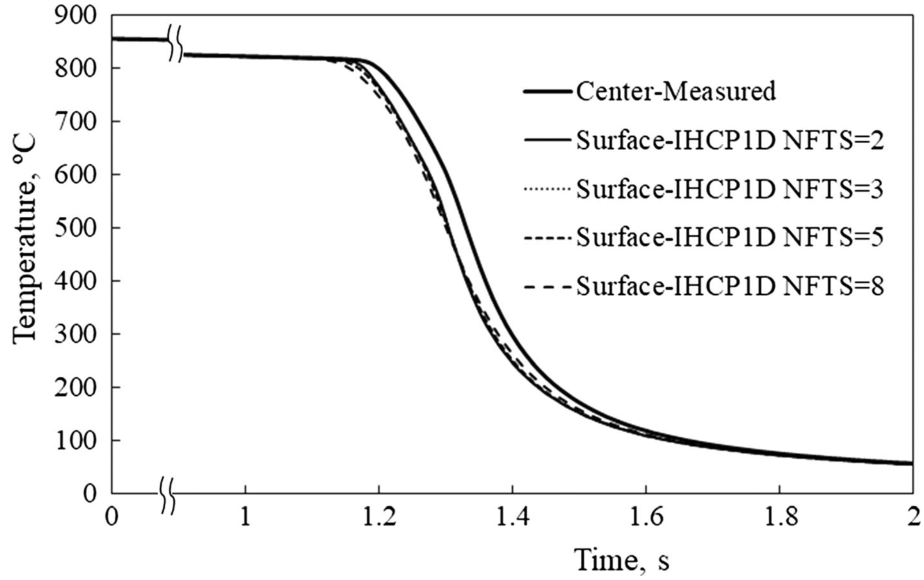

Fig. 19 Cooling curves measured and calculated by IHCP1D (under different numbers of future time steps: NFTS)

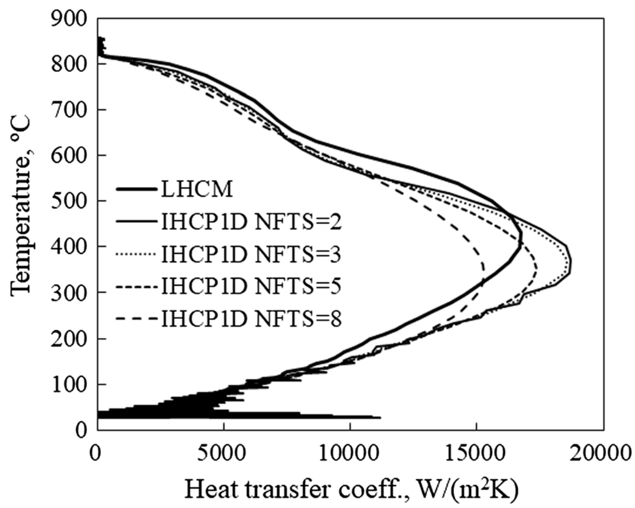

Fig. 20 Heat transfer coefficient calculated by LHCM and IHCP1D (under different numbers of future time steps: NFTS)

(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 all cooling stages. Heat transfer coefficients of the probes are easily predicted using the lumped heat capacity method and/or the numerical solution of one-dimensional inverse heat conduction problem using the cooling curve.

(3) Platinum with extremely high corrosion resistance and maintenance free can be used reasonably for the small ball probe under current manufacturing technologies. It can be heated with a couple of halogen lamps quickly. Using the small probe realizes totally compact and short-term test system.

(4) The prototype of container elevator type functioned sufficiently using the current mechatronics for robotics. Controlled quenchant flows around the probe are obtained by elevating the container, which have not been seen in the previous test systems.

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 in societies.

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