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First Prototype of Container Elevator Type Test System Using a Small Ball Probe for Determination of Cooling Characteristics of Quenchants

Kyozo Arimoto[1,a *], Mitsuyoshi Shimaoka[2,b] and Fumiaki Ikuta[3,c]

[1] Arimotech Ltd., Osaka, Japan.

[2] National Institute of Technology, Nara College, Nara, Japan.

[3] Neturen, Co., Ltd., Kanagawa, Japan.

[a] kyozo_arimoto@arimotech.com, [b] shimaoka@ctrl.nara-k.ac.jp,
[c] f-ikuta@k-neturen.co.jp

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Abstract. Cooling characteristics determined by specific test systems for quenchants have been used to enhance and maintain their performance. A rotary-arm type test system with a small ball probe had been developed for this purpose through three phases of prototypes. Its unique concept derived mainly from a circular motion of a small ball probe in quenchants was proposed by Tawara in 1941. Although the prototypes had been realized by current heating, measuring, and mechatronics techniques, its repeatability was not fulfilled strictly for aqueous polymer solutions. In order to eliminate the problem, a new concept for the test system was discovered based on experiences of developing the prototypes. The same ball probe is stationary on this occasion, while a quenchant container is elevated toward the probe to cool it down. Since the elevation was realized by using a popular electric actuator for the current robotics applications, an axisymmetric flow was ideally induced around the probe. Platinum ball probe was used in the same way to the previous prototype for resolving the discoloration and thermal aging problems on the surface. The authors' literature survey revealed that a classical study identified advantages of small ball probes. The functions of the new prototype have been confirmed by tests using a quenchant under some cooling conditions.

Introduction

Heat treatment quenchant has its inherent cooling characteristics, while its properties change with daily use. In order to manage such quenchant, a variety of test methods have been developed to investigate 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. These standards 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. Introduction part of the ISO 9950 [5] describes that test methods using a silver ball probe were widely identified at the time of its establishment. However Lakin [7] pointed out problems of the silver ball probe due to difficulties of fabrication and maintenance and higher conductivity than steel.

It should be noted that the lumped heat capacity method [8] to predict the heat transfer coefficient cannot be applied to cooling curves obtained from the Inconel cylindrical probes because of its low conductive performance, unlike the silver probes. Furthermore, Narazaki et al. [9] found that corners of cylindrical silver probes induce locally preceding collapses of vapor film of quenchants based on tests by comparison with spherical and hemispherical silver probes. They concluded that the cylindrical probes including the JIS probe should be modified considering to their above finding.

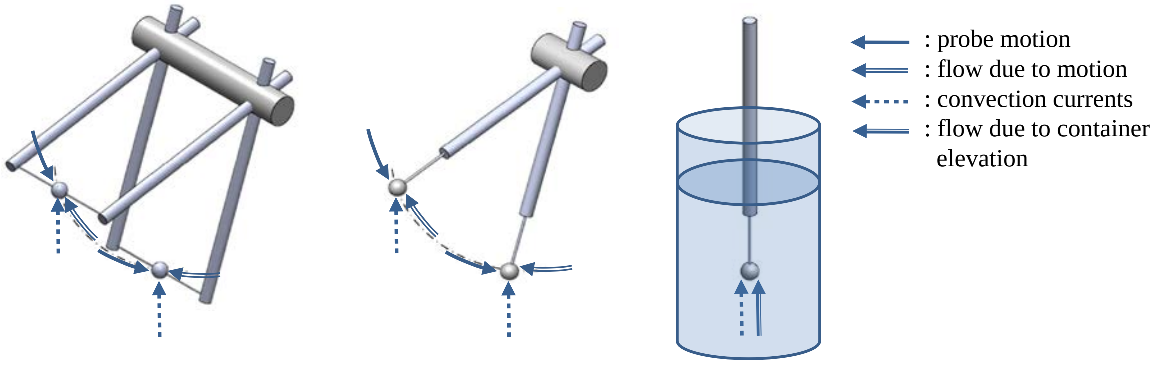
One of the authors conducted a literature survey on this field and found a unique test method reported by Tawara [10], in which a small ball probe supported with an arm is rotated in quenchant and a cooling curve is obtained during that period. This method gains not only advantages of the ball probe but also effects of stirring by flow due to a rotational motion of the probe in quenchant. Prototypes have been developed over three stages [11,12] in order to evaluate functions based on the Tawara's system since its unique concept might have an idea to solve problems in the current test systems.

Strict tests of water and polymer solutions using the third stage of prototypes revealed a question of repeatability in vapor film collapse occurrence [12]. The reason was considered to be that a heat flow near supporting position of the probe changes due to an angle variation of the support arm produced by the probe rotation. In order to eliminate the problem, a mechanism to elevate a quenchant container with respect to a stationary probe and to cool it has been devised, which is called here as “elevator container type”. Since this new prototype merely replaces the movement of the probe from rotational to linear, it can be regarded as an extension of the Tawara’s concept.

In the following, the authors describe specific features of the prototype and the results obtained by using it.

Concepts of Test System Using Small Ball Probe

Prototypes using the small ball probe is explained here based on the conceptual diagram shown in Fig. 1. In the Tawara’s original system, the ball probe is supported from both sides with a thin wire stretched horizontally as shown in Fig. 1 (a). The probe rotation induces flow, while its high temperature produces convection currents in quenchant. Although the supporting lines seem to influence both the flow and currents, induced turbulence may be bilateral symmetric. On the other hand, in the rotary-arm type prototype, the probe is supported with a tube from one side as shown in Fig. 1 (b). This rotating tube produces turbulence of the flow and currents, which varies with change in the rotational angle of the supporting tube. Strict tests using water and polymer aqueous solution revealed that this turbulence may affect in repeatability of the vapor film collapse.



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

Fig. 1 Schematic diagram of probe motion, flow due to motion, and convection currents

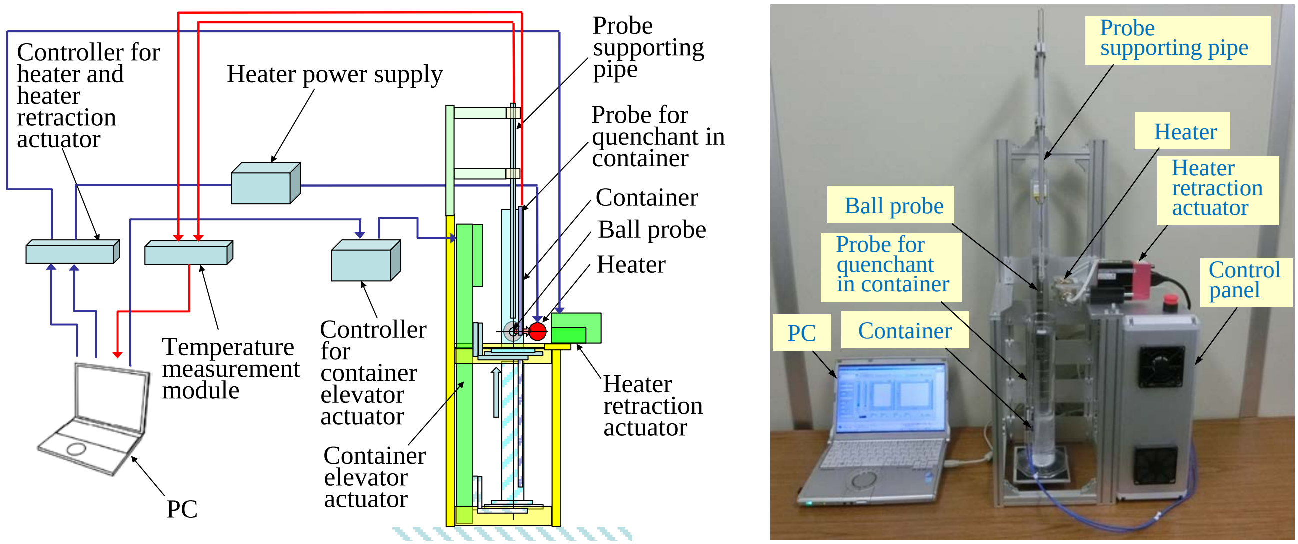
In order to avoid the problem due to angular changes of the supporting tube in the rotary-arm type prototype, the authors devised a method of fixing the probe, while elevating a quenchant container vertically to induce an axisymmetric flow as suggested in Fig. 1 (c). The stationary probe facilitates 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.

Outline 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. 2 (a). The appearance of the prototype is depicted in Fig. 2 (b), 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. 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 NI USB-6002 control device 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.



(a) Diagram (b) Appearance

Fig. 2 Prototype system of container elevator type

Components in the Prototype

Probe and Supporting Pipe. The appearance of ball probe and thermocouple is shown in Fig. 3. The probe is the 4mm diameter platinum ball with the 0.5 mm outer diameter platinum tube as shown in Fig. 3 (a). The platinum tube was strengthened by the 1 mm outer diameter tube made of austenite stainless steel. Platinum was selected as the material for resolving discoloration and thermal aging problems. The thermocouple shown in Fig. 3 (b) is the 0.25 mm diameter sheathed K type made by Okazaki Manufacturing Co., which was inserted into the probe center. The ball probe tube was connected to the 10 mm outer diameter supporting pipe made of acrylic resin and austenite stainless steel tubes by a connector with O-rings. The supporting pipe covers the thermocouple.

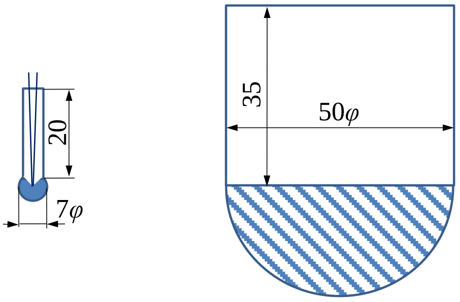
(a) Platinum probe with platinum tube (b) K type sheath thermocouple

Fig. 3 Appearance of ball probe and thermocouple

Our survey of classical literature found that small ball probes were used by Engel [13] in his study on quenching. He clearly stated that the ball probe is 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 minimum 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.

A silver ball with 7 mm dia. was chosen by him as the most ideal probe for the experiments, and chromium-nickel balls with 4, 7 and 10 mm dia. were used for evaluating poor heat conductors. Armco iron balls with 4, 7, 10, 19 and 50 mm dia. were designed to investigate influences of scale formation. Also a copper ball with 50 mm dia. was used as an example of a good thermal conductor with scale formation.

Figure 4 shows Engel's probes with 7 and 50 mm dia. Edges of the tapered bore in Fig. 4 (a) and the hemisphere in Fig. 4 (b) were connected to tube. The tube walls were made as thin as possible. A thermocouple was made using 0.1 mm dia. platinum-platinum rhodium wires which were welded together and set in the probe. Engel indicated physical properties of probe materials without specifying units as shown in Table 1. While the unit of the thermal conductivity may be "cal/(cm s °C)", the values show that the chromium-nickel is a poor heat conductor. It should be noted that the chromium-nickel probe was referred as the chromium-nickel steel probe in later literatures as shown in the report by the authors [11].



(a) 7 mm dia. (b) 50 mm dia.

Fig. 4 Ball probes by Engel

Table 1 Physical property of Engel's probe materials

Material	Specific gravity	Specific heat	Thermal conductivity	Thermal conductivity based on Cr Ni
Silver	10.5	0.0556	1.000	80
Copper	8.93	0.100	0.92	74
Iron	7.85	0.1078	0.098	8
CrNi	8.4	0.107	0.0124	1

Cooling curves and cooling rates obtained from the ball probes were reported by Engel [13], which were applied to evaluate cooling characteristics of water at six temperature levels between 0 and 100 °C, some water solutions, oils, hydrogen at three temperature levels, air, etc.

Although the subsequent development of the research using the silver ball probes was reviewed by one of the authors [11], the essence of the report is described here to clarify a background of the standardized probes. The diameter of the Engel's silver probe was changed from 7 to 20 mm by Speith and Lange [14]. They explained that smaller diameter balls induced variation in phenomena during immersion and a difficulty of installing a thermocouple into them.

The same 20 mm diameter silver ball probe was applied to obtain cooling characteristics of various quenchants by Rose [8]. 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. Using the same silver ball as Rose's, Schallbroch et al. [15] designed a cooling system that the probe was immersed into quenchant flowing like a river in a tank by a gear pump after heating it to 800 °C in an electric furnace. 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.

Finally, the test methods using silver ball probes were widely identified as described in the introduction part of the ISO 9950 [5]. However, a number of practical limitations of the silver ball probe were pointed by Lakin [7], which has been found through our survey of literature, as follows:

(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.

Some of the above problems have been resolved when using the platinum ball probe produced by today's technology. Also, the platinum probe 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. There may be a problem with production cost; however this may be canceled by its long life.

Heater. A pair of halogen lamp heaters, produced by Fintech Co. Ltd., was applied, which is 12 V-110 W and 35 mm in a reflector diameter. The halogen lamp has been specialized as a clean heating device. Distance of the pair was arranged appropriately for effective heating of the probe from both sides. Cosel product, PBA 300 F-12, AC 85 to 264 V in rated input, 300 W-12 V in rated output, was installed for a power supply for two heaters.

Quenchant Container. 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. Also, an acrylic rectangular container, with compatible volume of the graduated cylinder, was used for video photography.

Actuators for Heater Retraction and Container Elevator. IAI's actuator, EC-GD4, 50 mm in stroke and for horizontal placement, was installed to retract the heaters. This actuator moves back and forth between heating and retracted positions. As a power supply for the actuator, Cosel product, PBA 150 F-24-N was applied.

IAI's actuator, RCP6-SA4C, 350 mm in stroke, was installed to elevate the container. For controlling the actuator, IAI's controller, PCON-CB, was applied. The power source for the heater retraction actuator is also worked for a power supply of the container elevator actuator.

Measurement Module for Temperature at Probe and Container. Temperature signals have been processed by the high-density thermocouple input module, NI9213, with the 1-Slot USB chassis, produced by National Instruments, since the previous rotary-arm type prototype. Lead wires from the thermocouples at the probe and the container were connected to the module. The sampling interval of the inputs is specified as a rough value during heating and as 0.01 s during cooling.

Integrated Measurement and Control System and Cooling Curve Analysis System on PC. Integrated system on PC for measuring temperature and controlling heaters and actuators was developed by LabVIEW. The system realizes five measurement and control functions as follows: (1) specifying the test conditions and moving the heaters to the heating position, (2) measuring temperature at the quenchant container, (3) measuring temperature at the probe and controlling the heater, (4) after heating the probe, retracting the heater to the initial position, and elevating the container during cooling (5) moving back the container to the initial position.

The cooling curve analysis system 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 platinum probe. The lumped heat capacity method [8] was used to identify approximately the heat transfer coefficient on the probe surface.

Experimental Results Obtained by 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 5 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.

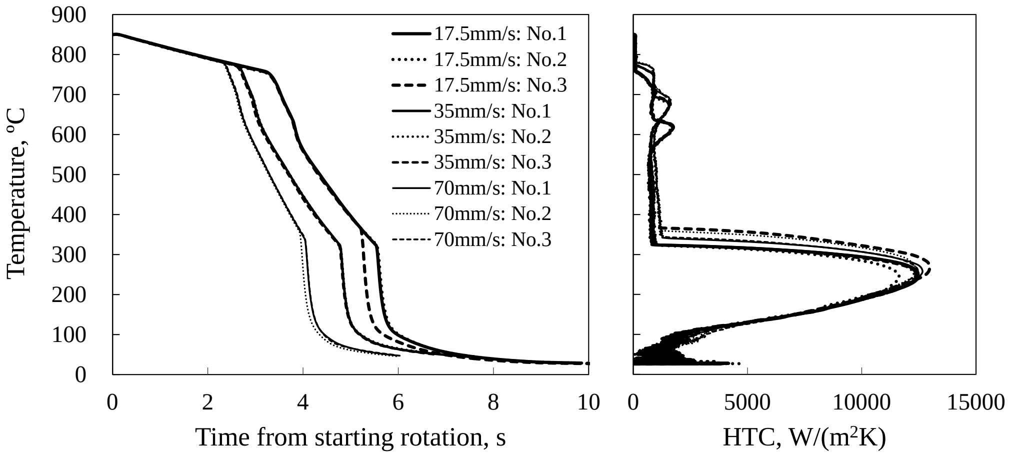


Fig. 5 Cooling and heat transfer coefficient curves of 10% polymer solutions at 20 °C

When comparing the results of this test with those of the same condition in the third prototype of rotary-arm type [12], it was revealed that temperatures when collapsing vapor film were different. However explanation of this cause is our future task. In this study, although phenomena occurring around the probe during cooling were photographed by a high-speed camera, their examinations have not been achieved. On the other hand, as an analytical study of phenomena, FEM was used to predict the temperature distribution changes inside the probe when specifying the obtained heat transfer coefficient. Furthermore, the program IHCP1D [16] for the numerical solution of one-dimensional inverse heat conduction problem was applied to evaluate exactly the heat transfer coefficient of the surface. These analytical results are omitted here because of the page limitation.

Summary

The authors confirmed that the newly developed prototype of container elevator type functioned sufficiently so that quenchant flow around the probe became simpler. As a result, the prototype systems including the rotary-arm type have been achieved. In both types, the platinum small ball probe is currently used.

On the other hand, an additional literature survey found the history of the 4 mm dia. Cr-Ni ball probe reported in the early 1930s. This showed clearly the intention of developing the small ball probe. Furthermore, according to another document, it was understood that the development of the ISO probe in the 1970s was carried out to overcome some problems of the silver ball probe used at that time. The problem of the silver ball probe has been solved by using the platinum small ball probe created by the studies. This probe can be regarded as an idealization of the original Cr-Ni small ball probe.

However, these prototype systems have not been comprehensively tested for a variety of quenchants and under their conditions. Therefore, data for evaluating the two prototype systems has not been collected sufficiently. 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.

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References

[1] Totten, G. E., Bates, C. E. and Clinton, N. A., “Handbook of Quenchants and Quenching Technology,” ASM International, Materials Park (1993)

[2] Totten, G. E., Tensi, H. M. and Liscic, B., “Standards for Cooling Curve Analysis of Quenchants,” Heat Treatment of Metals, Vol. 4, pp. 92-94 (1997)

[3] JIS K 2526, “Testing Method for Cooling Ability of Heat Treating” (1965)

[4] AFNOR NF T60-178, “Petroleum products - Quenching oils - Drasticity - Silver sensor test in static” (1989)

[5] ISO 9950, “Industrial quenching oils - Determination of cooling characteristics –Nickel -alloy probe test method” (1995)

[6] ASTM D 6200, “Standard Test Method for Determination of Cooling Characteristics of Quench Oils by Cooling Curve Analysis” (1997)

[7] Lakin, J. J. “Testing of quenching media”, Heat Treatment of Metals, Vol.6, pp. 59-62 (1979)

[8] Rose, A., “Cooling Capacity of Steel Quenchants”, Arch. Eisenhüttenwes., Vol. 13, pp. 345-354 (1940) (in German)

[9] Narazaki, M., Fuchizawa, S., and Usuba, M., “Effects of Specimen Geometry on Characteristic Temperature during Quenching of Heated Metals in Subcooled Water”, Tetsu- to- Hagane, Vol. 75(4), pp. 634-641 (1989) (in Japanese)

[10] Tawara, S., “Experimental Research on the Cooling Power of Various Quenching Media Report I”, Tetsu-to-Hagane, Vol. 27, pp. 583-599 (1941) (in Japanese)

[11] Arimoto, K., Ikuta, F., and Yokota, H., “First Prototype of Rotary-Arm Type Test System Using a Small Ball Probe for Determination of Cooling Characteristics of Quenchants”, Materials Performance and Characterization, Vol. 3, No. 4, pp. 405-426 (2014)

[12] Arimoto, K., Shimaoka, M., and Ikuta, F., “Modified Prototypes of Rotary-Arm Type Test System Using a Small Ball Probe for Determination of Cooling Characteristics of Quenchants”, Materials Performance and Characterization, Vol. 8, No. 2, /doi.org/10.1520/MPC20180016 (2018)

[13] Engel, N., “Studies on Steel Hardening”, Ingeniorvidenskabelige Skrifter. A. no. 31 (1931) (in German)

[14] Speith, K. G. and Lange, H., “The Quenching Capacity of Liquid Quenchants”, Mitt. Kais. -Wilh. -Inst. Eisenforschg., Vol. 17, pp. 175-184 (1935) (in German)

[15] Schallbroch H., Bieling, W. and Blank, J., “The Quenching Capacity of Various Quenchants”, Technische Zeitschrift fur praktische Metallbearbeitung, Vol. 52, 1941, pp. 77-82. (in German)

[16] Beck, J. V., “User’s Manual for IHCP1D: Program for Calculating Surface Heat Fluxes from Transient Temperatures inside Solids”, Beck Engineering Consultants Company, Okemos, Michigan (2006).