Developing Rotary-Arm Type Test System with a Small Platinum Ball Probe for Determination of Cooling Characteristics of Quenchants

Kyozo Arimoto
Arimotech Ltd, Osaka, Japan

Mitsuyoshi Shimaoka
National Institute of Technology, Nara College, Nara, Japan

Fumiaki Ikuta
Neturen Co. Ltd, Kanagawa, Japan

Abstract

Performances of quenchants have been enhanced and maintained based on their cooling characteristics determined by specific test systems. A rotary-arm type test system with a small ball probe has been developed for this purpose by making prototypes. Its unique concept derived mainly from a circular motion of a small ball probe in quenchants was proposed by Tawara in 1941. The prototypes have been realized by current heating, measuring and mechatronics techniques. Finally the probe material has been changed from nickel alloy to platinum for resolving the discoloration and thermal aging problems on the probe surface. The performance of the prototypes has been verified by systematic tests using specific quenchants under various cooling conditions.

Introduction

Enhancement and maintenance of quenchants have been performed using specific test methods to determine their cooling characteristics for a long time [1, 2]. Problems in the methods have been induced mainly from variations in their results depending on disturbed conditions during testing. It has been suggested that their factors may be produced from not only probe aging but also varied cooling phenomena affected by transferring a probe from a furnace to a container and maintaining it in unstable quenchants.

A rotary-arm type test system with a small ball probe has been developing for resolving the above problems by making prototypes in stages. The concept of the system was derived mainly from a circular motion of a small ball probe in quenchants, which was devised by Tawara [3] based on successful early rotary-arm type apparatuses and ball probes [4]. The circular motion is used not only to transfer the probe from a heating zone to a quenchant container but also to move it in the container during cooling.

The first prototype [4] based on current techniques rediscovered the Tawara's concept, although his ball probe was redesigned and made of Inconel 600 immediately because of manufacturability. The system for temperature measurements and arm rotation mechanisms had not been integrated well.

In the second prototype [5], the geometric relation among a probe, heaters, a motor and a container was specified more precisely for obtaining the steady results at the different places. A motor and its control system were replaced for rotating the arm more properly. Then effects of probe rotation speed on the cooling characteristics could be recognized.

Finally the third prototype achieved to change the probe material from Inconel 600 to pure platinum for resolving the discoloration and thermal aging problems on the Inconel probe surface, and also to enhance the arm rotation mechanism.

The prototypes have showed reasonable repeatability in quenchant cooling characteristics measured by systematical tests. This paper describes the contents of the third prototype with meaningful information of the previous development phases.

Developing the Prototypes

Outline
The third prototype has been established based on the experiences in the first and second development phases. It is composed from the parts connected by wires as shown in the schematic diagram in Fig. 1. Wires are used for signals for measuring temperature and controlling heaters and a motor.

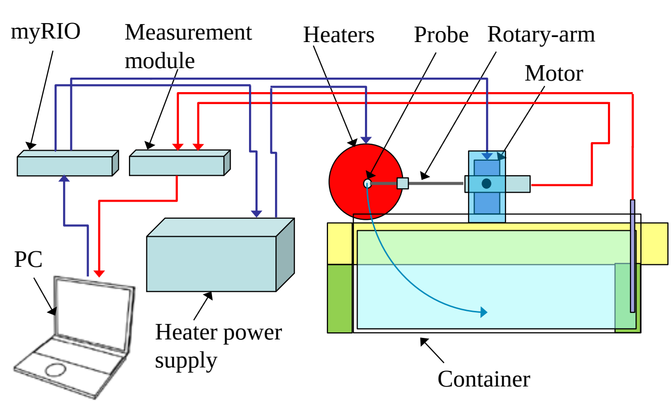


Figure 1: Schematic diagram of third prototype.

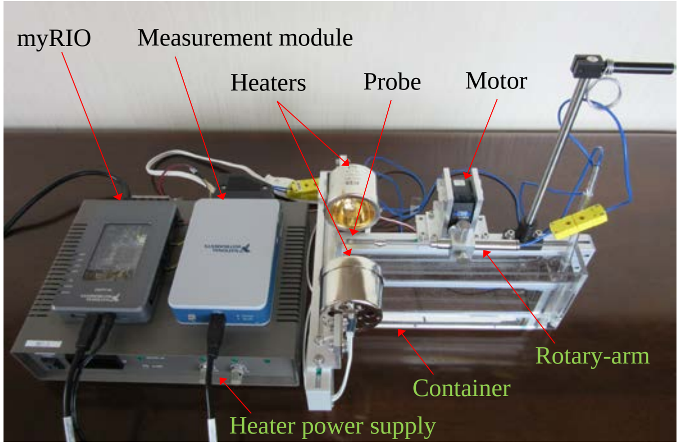
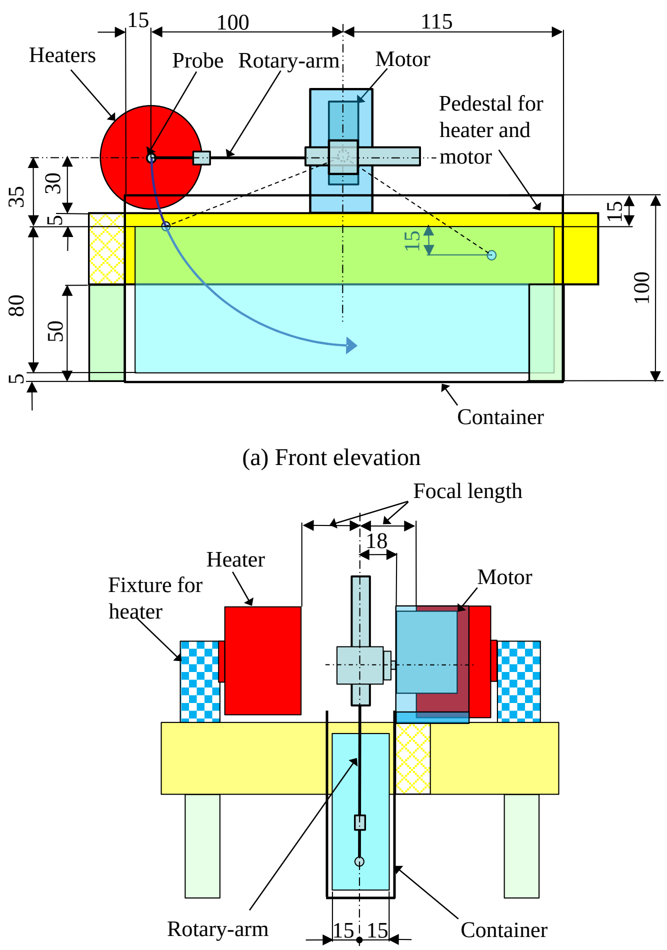


Figure 2: Appearance of third prototype.



(a) Front elevation

(b) Side elevation

Figure 3: Front and side elevations of third prototype.

The photographed appearance shown in Fig. 2 includes the 4mm diameter ball probe located at the tip of the rotary-arm. The probe is heated by a pair of the halogen lamp heaters connected with its power supply. The voltage of the heater power supply is controlled by the system on PC through the myRIO platform. After heating the probe, the RC servo motor rotates the rotary-arm in the quenchant container, which is controlled by the system on PC through the myRIO platform.

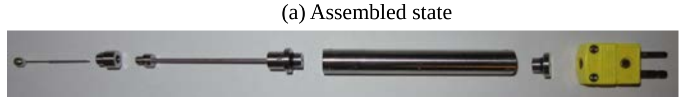
The temperature change in the probe is detected by the thermocouple in the probe and recorded by the system on PC through the measurement module. The same measuring system is applied to detect temperature at the container, which is displayed on the screen of PC for confirmation.

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 and side elevations in Fig. 3. 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 [3]. 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. Each part of the system is described in the following sections.

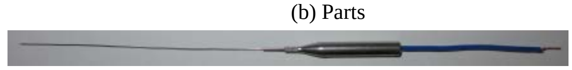
Probe and connected Rotary Arm

The appearance of the 4mm diameter platinum ball probe and the connected rotary-arm is shown in Fig. 4 (a). This product is assembled from the parts in Fig. 4 (b) and the 0.25 mm diameter sheathed K type thermocouple made by Okazaki Manufacturing Company in Fig. 4 (c). The parts in Fig. 4 (b) includes the fittings with an O-ring for liquid-tight and the thermocouple connector. The parts of the rotary-arm were made of austenite stainless steel pipe.

(a) Assembled state



(b) Parts



(c) K type sheath thermocouple

(d) Platinum probe with platinum pipe

Figure 4: Appearance of probe with rotary arm

Platinum has been selected finally as the probe material for resolving the discoloration and thermal aging problems in the previous Inconel probe. The specific range of the Inconel thermocouple sheath heated conductively from the probe was covered by the 0.5 mm outer diameter platinum pipe inserted into the center of the probe as shown in Fig. 4. (d). An appropriate hole drilled in the probe to set the pipe was provided after considering the method applied to the 9.5 mm diameter stainless steel ball probe by Kim et al. [6]. The specific range of the platinum pipe was strengthened by the 1 mm outer diameter pipe made of austenite stainless steel as shown in Fig. 4 (d).

Motor

The third prototype has selected the radio control (RC) servo motor, S3073HV, produced by Futaba Corporation, shown in Fig. 2, for increasing the positioning more accurately than the previous motors. The motor controls a rotation angle between

-90°and +90° using a corresponding pulse width generated by the pulse-width modulation (PWM) system through myRIO platform.

The RC servo motor is a compact and easiness-to-use package of a DC geared-motor associated with a position servo controller for using in small-sized robotics and RC airplanes, helicopters, cars and boats. A simple and realistic internal model of the servo motors was proposed by Wada et al. [7]. The motors for industrial use are produced by Futaba Corporation.

Heater

A pair of the halogen lamp heaters with their electric power supply, produced by Inflidge Industrial, Ltd., shown in Fig. 2, has been used since the first prototype. Its electric specification is 12 V-75 W, and the size of a reflector is 45 mm in diameter.

The location of the pair was arranged appropriately to radiant heat effectively to the probe from both sides. It takes few minutes to heat the probe to 850 °C. The halogen lamp has been specialized as a clean heating device although it was used for many lighting applications.

Quenchant Container

First and second prototypes used a square refractory glass container, length of 200 mm, width of 40 mm and height of 100 mm in internal dimension, and thickness of 3 mm, for the 230 °C service temperature. The capacity of the container is nearly 640 m*l* when the quenchant level is 80 mm.

Third prototype has prepared an acrylic container, as shown in Fig. 2, for the service temperature less than 100 °C. The size specification is length of 220 mm, width of 30 mm and height of 95 mm in internal dimension, and thickness of 3 mm for fronts and 5mm for sides. Then the quenchant volume is decreased to 528 m*l* when the quenchant level is 80 mm.

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, NI cDAQ-9171, produced by National Instruments, since the second prototype, as shown in Fig. 2. Lead wires from the thermocouples at the probe and the container were connected to the NI9213 module as shown in Fig. 1.

Signals from the probe are transformed to a time history of temperature by the integrated measurement and control system on PC, as described later, and output as Excel files separately for heating and cooling processes. The sampling interval of the inputs is specified as a rough value during heating and as 0.01 s during cooling.

myRIO Platform to Control Heater and RC servo motor

The real-time embedded evaluation platform made by National Instruments, myRIO [8], shown in Fig. 2, has been selected to control the voltage of the heaters and the movement of the RC servo motor for the third prototype. myRIO is used to develop applications that utilize its onboard FPGA and microprocessor mainly for education purpose. A previous platform has been replaced for integrity and reliability.

The connection of lead wires related to myRIO is shown in Fig. 1. The heater power input, 0 to 12 V, corresponds to the myRIO analog voltage signal, 0 to 5 V. The RC servo motor is rotated controllably by the 5 V power and the PWM signal from myRIO.

Integrated Measurement and Control System and Cooling Curve Analysis System on PC

Integrated system on PC for measuring temperature and controlling heater and motor was developed by the LabVIEW program language for the second prototype and has been adapted to the third prototype including the replaced motor and myRIO.

The system realizes six measurement and control functions as follows: (1) specifying the test conditions, (2) measuring temperature at the quenchant container, (3) measuring temperature at the probe and controlling the heater voltage during heating, (4) measuring the probe temperature and rotating the arm with the probe during cooling (5) rotating back the probe to the initial position.

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 lumped heat capacity method was used to identify approximately the heat transfer coefficient on the surface, based on the assumption that transient temperature distributions in the probe are uniform. The third prototype has modified the system to fit the platinum probe.

Experimental Results Obtained by Prototypes

First Prototype

Functions of the first prototype were tested using tap water and 10 % solutions of PAG polymer at different temperature levels after heating the Inconel probe until about 850 °C. The tangential speed of circular motion of the probe was held constant as 70 mm/s as the Tawara's apparatus in the first prototype.

A movement of the rotary-arm with the probe during cooling process in tap water at 60°C is depicted by three photographs as shown in Fig. 5. These images were obtained by extracting from a video, from which a vapor film and its collapse stage around the probe can be observed. It should be noted that these phenomena occur within a circular probe motion under the tangential speed of 70 mm/s in quenchant, which requires about 3 s.

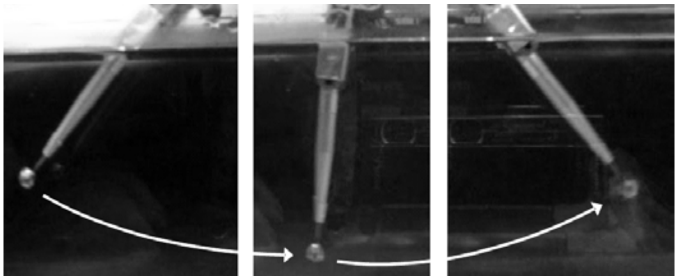


Figure: 5 Movement of rotary-arm with a probe for first prototype in 60 °C *water.*

The first prototype provided probes inserted 0.25 or 0.5 mm diameter sheathes of the thermocouple in the center without protection pipe as shown in Fig. 6. To prevent a drop of the probe, a projection provided at the insertion opening of the sheath was somewhat deformed plastically. The picture of the probe with a sheath of 0.5mm shows a discoloration to black after several oil quenching tests.

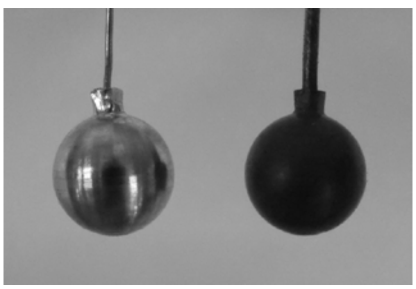


Figure 6: Inconel probes (sheath diameter: 0.25 and 0.5 mm) for first prototype.

Inherent shapes of obtained cooling curves clearly identified different types of quenchants and its temperature dependency as shown in Fig. 7 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 [3, 4].

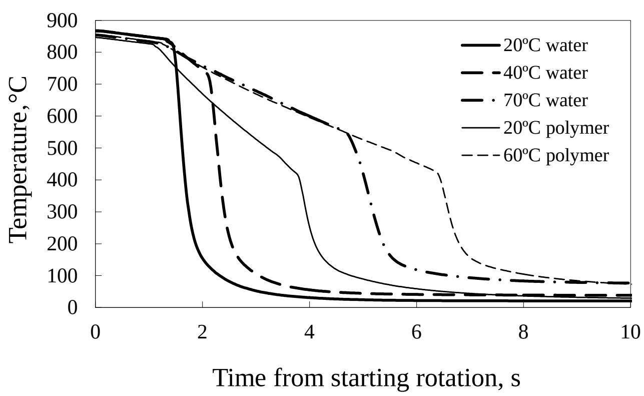


Figure 7: Cooling curves of water and polymer solution.

A preliminary test using two mineral oils noted as Oil A and B with the 47 mm^2/s kinematic viscosity at 40 °C was also performed by the first prototype [4]. 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. 8. 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 [3].

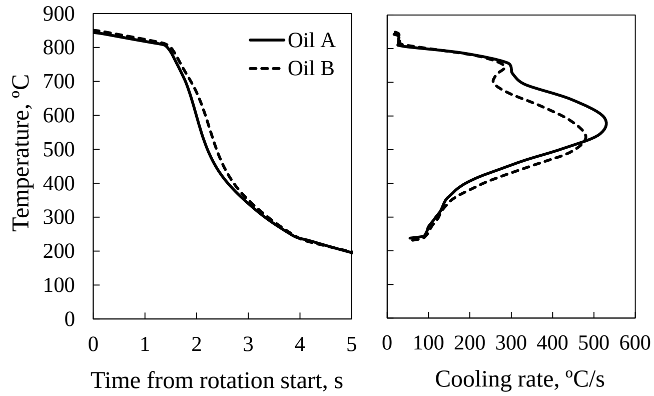


Figure 8: Different cooling characteristics between common and boiling point adjusted oils.

The first prototype was also applied to a systematical test of the used and new 27 % solutions of PAG polymer at three temperature levels, 10, 20, and 30 °C. In order to confirm the repeatability, the test was performed three times for individual cases.

The results in the case of 30 °C are shown in Fig. 9 as an example. The horizontal axis in cooling curves show the time measured from the starting point of immersion. Although variations are seen somewhat in the obtained cooling curves, differences of cooling characteristics of solutions in between new and used solutions can be identified.

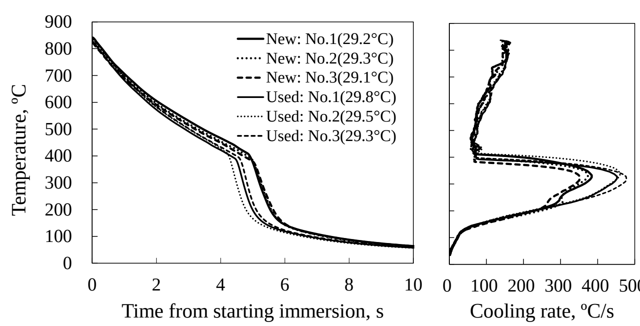


Figure 9: Cooling and cooling rate curves of new and used polymer solutions at 30 °C

One of the reasons to select the polymer solutions for the above preliminary test was derived from the fact that the quenchants cause repeatability problems in their still conditions, as pointed out by Totten et al. [2]. Two different types of agitation devices for the Inconel cylindrical probe were standardized as ASTM D6482 [9] and ASTM D6549 [10] to resolve the problems.

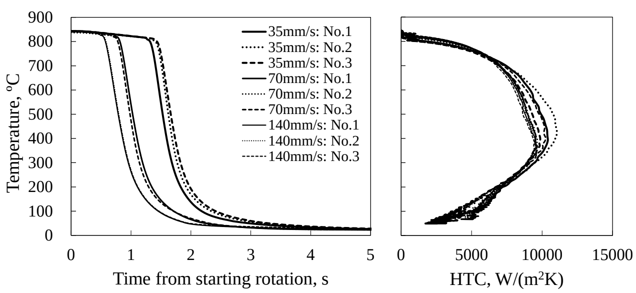
Average velocities of flow near the surface of the probe in the two standard apparatuses were predicted by Banka and

MacKenzie [11] as 90 and 70 mm/s, respectively, by CFD simulation using normal water as fluid. Since the predicted velocities are the same level as the tangential speed of circular motion of the probe, about 70 mm/s in Tawara's apparatus [3], the relative flow around the ball probe is expected to induce the same effect as the agitations [4].

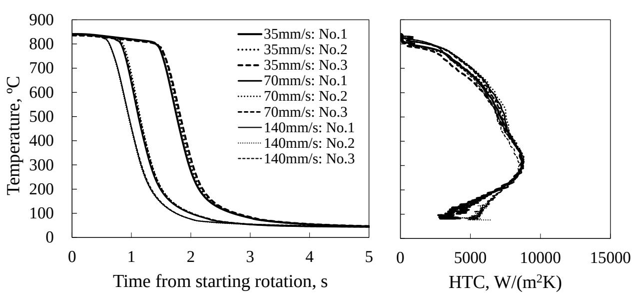
Second Prototype

The second prototype became possible to give different rotation speeds to the Inconel probe [5]. Several tests were performed to confirm effects of the tangential speed of rotating probe. Cooling curves of the 20, 40 and 60 °C tap water were obtained under the 35, 70 and 140 mm/s tangential speeds, which derived their heat transfer coefficient curves, as shown in Fig. 10. Each test was performed three times for confirming repeatability.

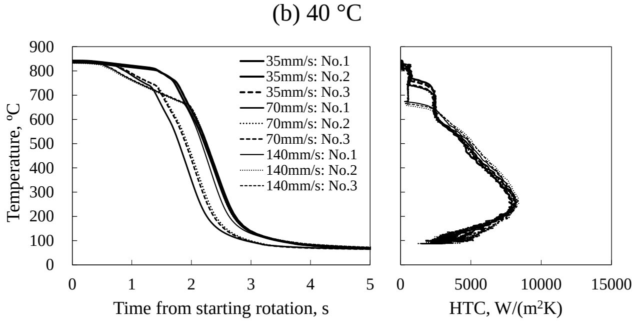
It is revealed that the curves obtained from the 60 °C tap water are affected from different tangential speeds. The cooling curves show that the beginning immersion of the probe in the 140 mm/s is earlier than in the 35 and 70 mm/s. This may affect the trend of the curves.



(a) 20 °C



(b) 40 °C

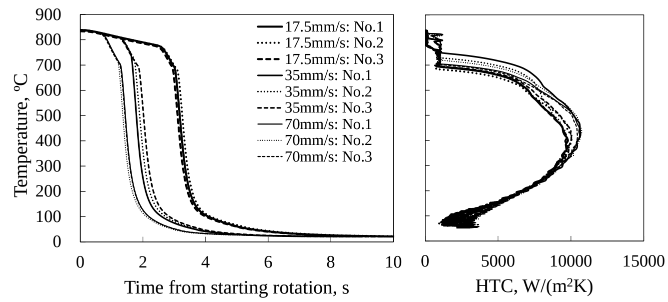


(c) 60 °C

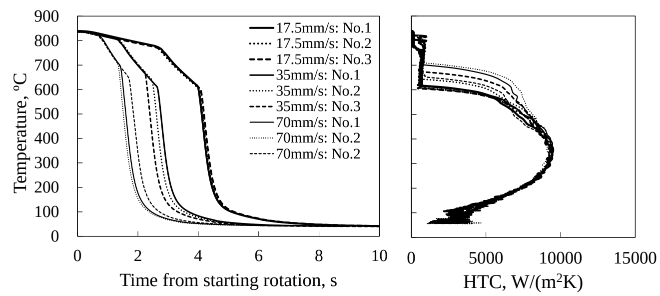
Figure 10: Cooling and heat transfer coefficient curves of water at 20, 40 and 60 °C.

The 5, 10, 15 and 30% solutions of PAG polymer were tested under the 20, 40 and 60 °C temperatures and the 17.5, 35 and 70 mm/s tangential speeds. Each test was performed three times for confirming repeatability.

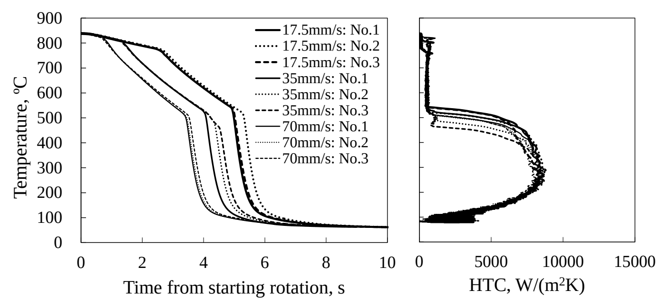
Figure 11 shows cooling and heat transfer coefficient curves of 5% polymer solutions at 20, 40 and 60 °C. It is revealed that the characteristics temperature is increased at 20 and 40 °C, while decreased at 60 °C.



(a) 20 °C



(b) 40 °C

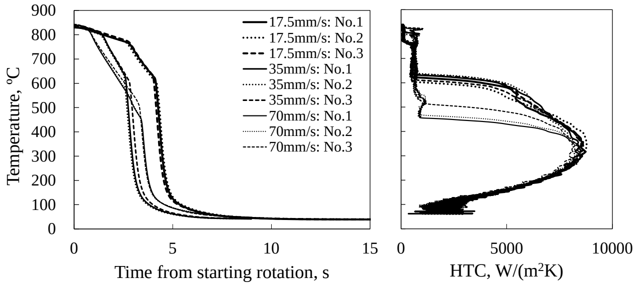


(c) 60 °C

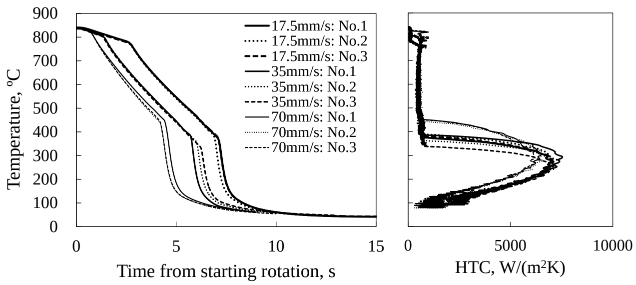
Figure 11: Cooling and heat transfer coefficient curves of 5% polymer solutions at 20, 40 and 60 °C.

Cooling and heat transfer coefficient curves were obtained for the 10, 15 and 30% polymer solutions at 40 °C for studying effects of the solution concentration on the cooling characteristics as shown in Fig. 12.

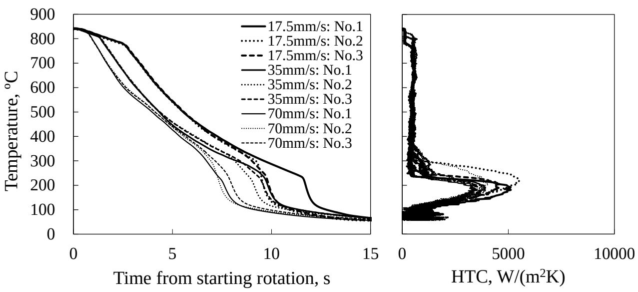
The figure shows that the characteristic temperature decreases and heat transfer coefficient in the vapor film stage [1] is slightly down with increasing their concentration. Heat transfer coefficients in the boiling stage decrease overall with the increased concentration. Other trends are induced in the effects of tangential speed of probe at each concentration level.



(a) 10% polymer solution

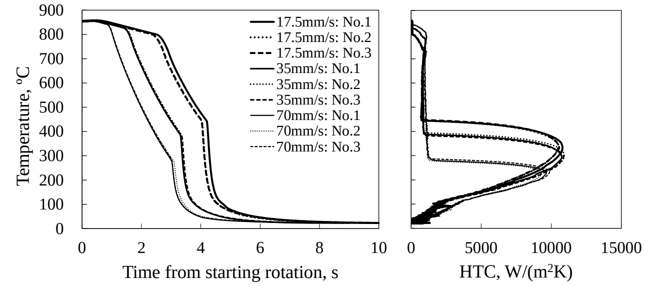


(b) 15% polymer solution

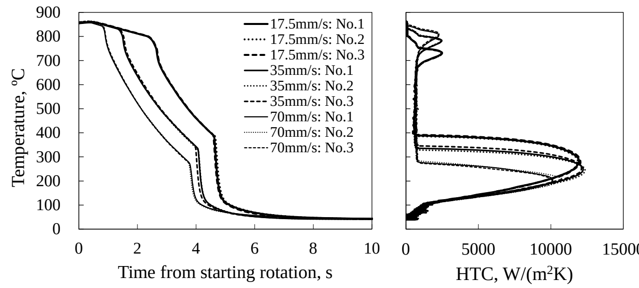


(c) 30% polymer solution

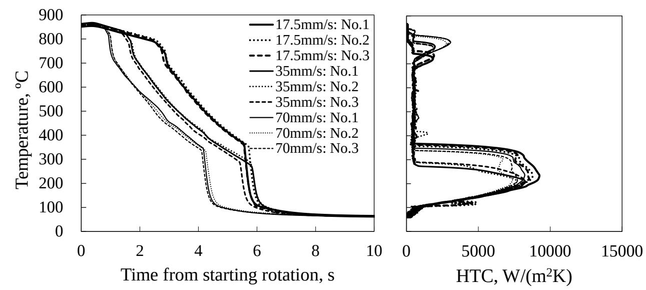
Figure 12: Cooling and heat transfer coefficient curves of 10, 15 and 30% polymer solutions at 40 °C.



(a) 20 °C



(b) 40 °C



(c) 60 °C

Figure 13: Cooling and heat transfer coefficient curves of 10% polymer solutions at 20, 40 and 60 °C.

Third Prototype

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 13 shows obtained cooling and heat transfer coefficient curves.

Curves in Fig. 13 (b) for the 10% polymer solutions at 40 °C corresponds to those in Fig. 12 (a) obtained with the second prototype. The differences between the two figures may be derived from the change of the probe material. Also the projection shown in Fig. 6 on the probe for the second prototype was removed as shown in Fig. 4 (d) for the third one.

Heat transfer coefficients in between 500 and 600 °C at the probe in Fig. 13 are meaningful to clarify the characteristics in the vapor film stage of the polymer solutions [1]. Then the average values of the HTC in the temperature range were obtained and plotted as shown Fig. 14. A dependency of solution temperature and tangential speed of circular motion of the probe on the HTC are revealed from the contour plot.

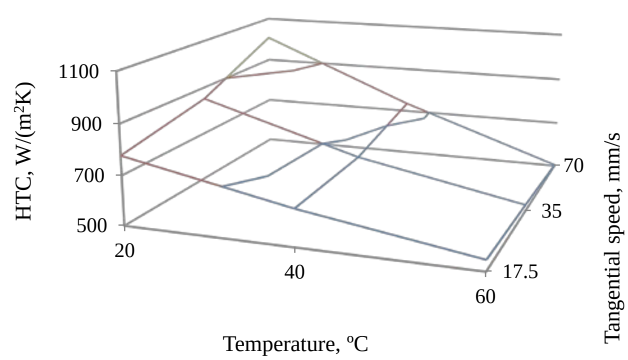
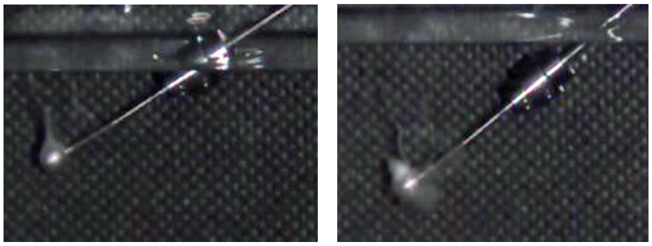


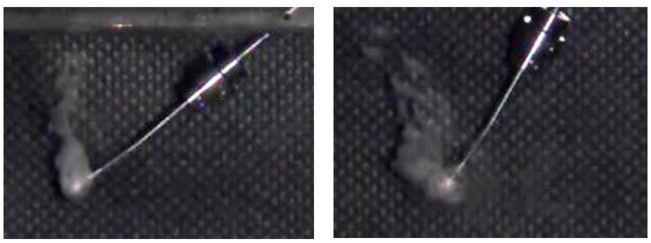
Figure 14: Average heat transfer coefficients of 10% polymer solutions at 20, 40 and 60 °C *in between 500 and 600* °C *probe temperature.*

The rotating prove 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 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.



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

(a) 10% polymer solution at 20 °C.



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

(b) 10% polymer solution at 60 °C.

Figure 15: Appearance of probe during testing at 17.5 mm/s tangential speed.

Conclusions

Advantages of Tawara's concept come from inheritances of successful early rotary-arm type apparatuses and ball probes. Since the third prototype has realized the platinum ball probe and improved the arm rotation mechanism, the fundamental problems in the previous prototypes have been reduced. Therefore the current prototype system can be used for evaluation purpose. Especially, the integrated measurement and control system developed by LabVIEW is distributed easily. Results from faithful reproductions of the prototype in different institutions are meaningful to confirm reproducibility of the test. A more enhanced system to develop and maintain quenchants at each worksite will be made from a corroborative works based on the prototypes.

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