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Measurement and Database Construction of Heat Transfer Coefficients of Gas Quenching

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The heat transfer coefficient during the gas quenching process has a significant influence on the hardness, residual stress and distortion of the steel parts. In order to achieve the optimization of the pressurizing gas quenching processes of the steel parts, we need to know the effects of gas pressure and velocity on the heat transfer coefficients for various gases. This paper shows the heat transfer coefficient data of helium, argon, nitrogen and those mixed gases estimated by actual measurement of cooling curves of a silver rod probe. The effects of the composition of gases, gas pressure, flow rate and surface temperature of probe are confirmed. In addition, the effect of mixing of carbon dioxide gas with helium or nitrogen was also observed. The lumped-heat-capacity method was employed to estimate the heat transfer coefficient from cooling curve data of the silver probe because the uniformity of silver probe temperature was confirmed by measurement of the cooling curves. The obtained data was built in the database of heat transfer coefficients during quenching of silver probes in various quenchants.

Keywords: heat treatment, gas quenching, heat transfer, steel parts, hardness

0 INTRODUCTION

In order to achieve the optimization of the pressurizing gas quenching processes of the steel parts, we need to know the effects of gas pressure and flow rate on the heat transfer coefficients for various gases. We tried to measure the heat transfer coefficients of helium, argon, nitrogen and the mixed gases by actual measurement of cooling curves of a silver rod probe. The effects of the composition of gases, gas pressure, flow rate and the surface temperature of probe was studied. In addition, the effect of mixing carbon dioxide gas with helium or nitrogen was also observed. The lumped-heat-capacity method was employed to estimate the heat transfer coefficient from cooling curve data of the silver probe because the uniformity of silver probe temperature was confirmed by measurement of the cooling curves. The obtained data was built in the database of heat transfer coefficients during quenching of silver probes in various quenchants.

1 GAS QUENCHING TEST

Fig. 1 shows the detail of the shape and dimensions of a silver rod probe and the positions of thermocouples for measuring the cooling curves. A silver rod (15 mm in the diameter and 60 mm in height) was employed as the probe for estimating cooling power of various gases in gas quenching of hot metal. The probe has a ceramic nose cone on the upper end. This nose cone works as a thermal insulator on the upper end surface and a fairing nose for gas flow around the rod probe. In order to estimate the surface heat transfer coefficients, the cooling curves at several positions (shown in Fig. 1) were measured during the gas cooling. The sheathed thermocouples of 1.6 mm in the outside diameter were inserted in the holes of the diameter 1.7 mm vertically. These are made at the position at the geometrical centre and near the side surface of silver rod probe as shown in Fig. 1. 99.99% silver was used as the probe material to get the uniform probe temperature and to avoid the influence of the transformation latent heat and the surface oxidization. As a result, we can estimate the average heat transfer coefficient on the probe surface from cooling curve data of the silver probe by using the lumped-heat-capacity method.

1.2 Test Apparatus and Procedure

Fig. 2 shows the outline of the experimental apparatus for the gas quenching test. The honeycomb plats and contraction con was set at the upward position of the probe in order to

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make a laminar gas flow around the silver probe. The gas flow pattern was confirmed by CFD analysis. Gas quenching of the silver probe was done by the pressurized gas flow after heating up to nearly 870 ºC in an induction coil by high-frequency induction heating method. After heating, the induction current was shut down and the rotation of a fan in the blower was started. The cooling curves were measured by metallic sheathed thermocouples attached to the silver probe and recorded by PC after A/D converting of the signal of thermocouples. Gas flow rate was estimated from gas volumetric flow rate measured by a flow meter.

Nitrogen or helium gas and mixtures of the two gases were often used for gas quenching of steel parts [1]. Nitrogen, argon and helium gas were used as pure gas quenchant in this study. In addition, several mixture gases of these inert gases were employed. The mixture gas of nitrogen or helium and carbon dioxide gas was also used for examining the effect of mixing carbon dioxide to cooling power of these gases. Various gas pressures (from 0.5 to 3.0 MPa) and flow velocities (from 5 to 35 m/s) are employed in this test.

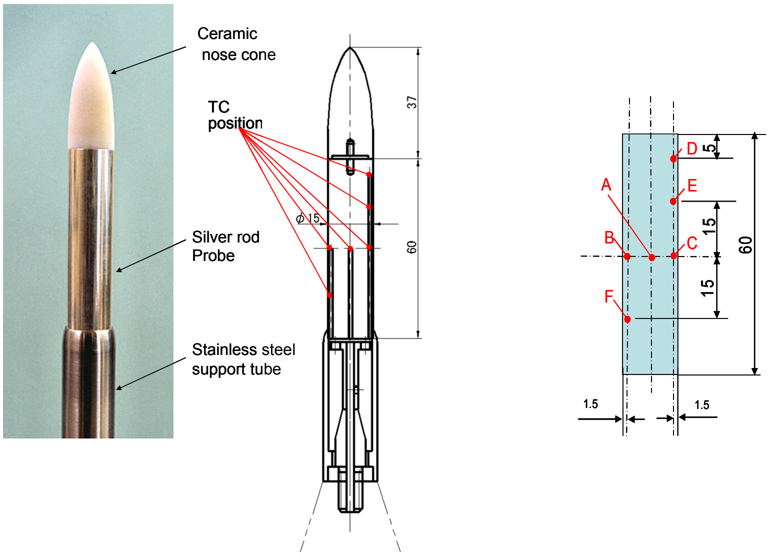


Fig. 1. *Silver rod probe and positions of thermocouples*

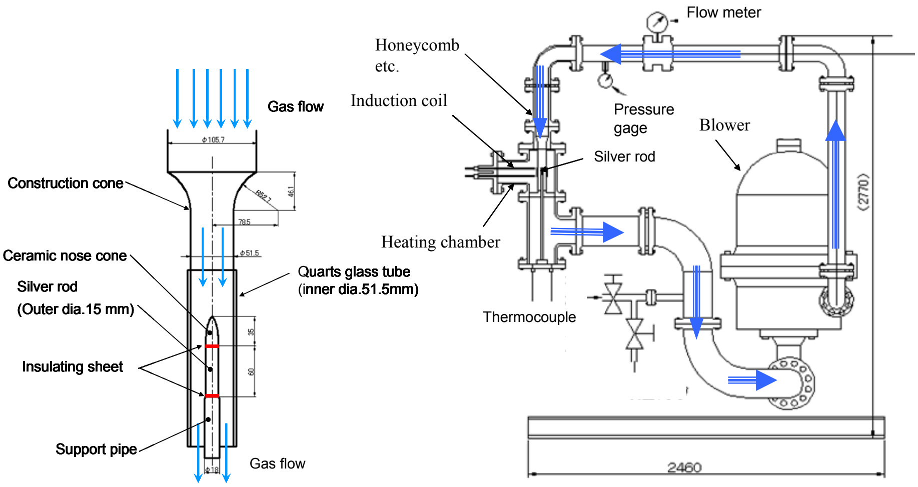


Fig. 2. *Gas-quenching test apparatus*

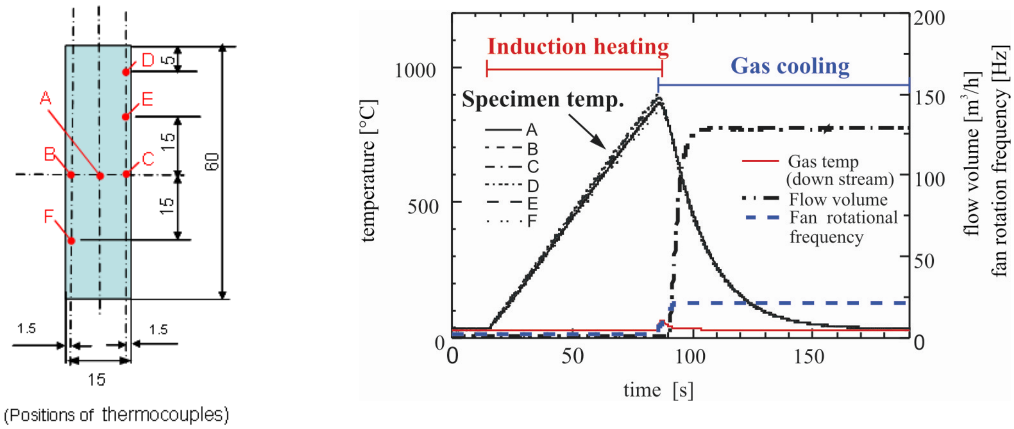


Fig. 3. *An example of measured data in heating and gas cooling of silver probe*

1.3 Measured Data

Fig. 3 shows an example of measured data in heating and cooling of the silver rod probe. The heating and gas cooling curves are almost similar despite the different positions in the probe. In particular, the temperature of the probe during gas cooling is uniform. Therefore, we can use the lumped-heat-capacity method to estimate the heat transfer coefficient on gas-cooled surface. Good reproducibility of cooling curves was confirmed by repeating the gas quenching test.

2 TECHNIQUES FOR ESTIMATING HEAT TRANSFER COEFFICIENT

2.1 Lumped-Heat-Capacity Method

The lumped- heat-capacity method can be used if we can justify an assumption of uniform probe temperature during the cooling process Holman et al. [2], Narazaki et al. [3]. The heat transfer coefficient on the gas-cooled surfaces (the side surface) was estimated by using the lumped-heat-capacity method from the gas-cooling curve data of the silver rod probe.

If the probe temperature is uniform, the heat loss from the probe Q is equal to the decrease in the internal energy of the probe. Thus,

$$Q=hA(T_p-T_l)=-c\rho V(\mathrm{d}T_p/\mathrm{d}t) \tag{1}$$

where h is the heat transfer coefficient on the probe surface, A the surface area of the probe, T_p the probe temperature, T_l the quenchant temperature, c the specific heat of the probe material, ρ the specific density of the probe material, V the volume of the probe, and t cooling time. Therefore, $\mathrm{d}T_p/\mathrm{d}t$ is the cooling rate of the probe. The side surface area of the probe is used as the value of A because we can neglect the heat transfer from the upper and lower surfaces in this case.

If the quenchant temperature around the probe T_l is uniform, the next relation is derived from Eq. 1. We use the constant value of T_l in Eq. 2, because gas temperature is almost constant during gas quenching as shown in Fig. 3.

$$q=h(T_p-T_l)=-(c\rho V/A)(\mathrm{d}T_p/\mathrm{d}t) \tag{2}$$

where q is the heat flux on the probe surface.

Here, probe weight ρV is constant, but c and A change with probe temperature. However, we can ignore the minimal change of the surface area of the probe A. Consequently, we consider only the temperature dependence of the specific heat c. Eq. 2 then becomes as follows:

$$q=h(T_p-T_l)=-c(T_p)(\rho V/A)(\mathrm{d}T_p/\mathrm{d}t) \tag{3}$$

where $c(T_p)$ is the specific heat as a function of probe temperature T_p.

Thus, the heat flux q and/or the heat transfer coefficient h can be directly calculated from the cooling rate dT_p/dt of the silver rod probe. Therefore, the preciseness of q and h values depends on the accuracy of the cooling rate calculated from measured cooling curve data. In order to avoid the effect of the noise in the measured cooling curve, our lumped-heat-capacity program "LUMPPROB" is using a polynomial curve fitting method with the leastsquares method for data smoothing and the estimation of derivative of cooling curves [3] [4] and [6].

3 REPRESENTATIVE EXAMPLES OF ESTIMATED HEAT TRANSFER COEFFICIENTS

3.1 Heat Transfer Coefficients in Inert Gas Quenching

Fig. 4 shows the representative heat transfer coefficient (HTC) for nitrogen gas cooling. The values of HTC over about 700 ºC are not accurate because the gas flow rate did not reach the steady state value because of the time-lag of fun rotation immediately after starting of fun motor. The gas-cooling heat transfer coefficients show little temperature dependence except in low temperature region. A similar result was confirmed for the other gases.

Fig. 5 shows the maximum HTC for nitrogen and helium gas. These show the value of HTC increases linearly with gas pressure and gas flow rate in both cases.

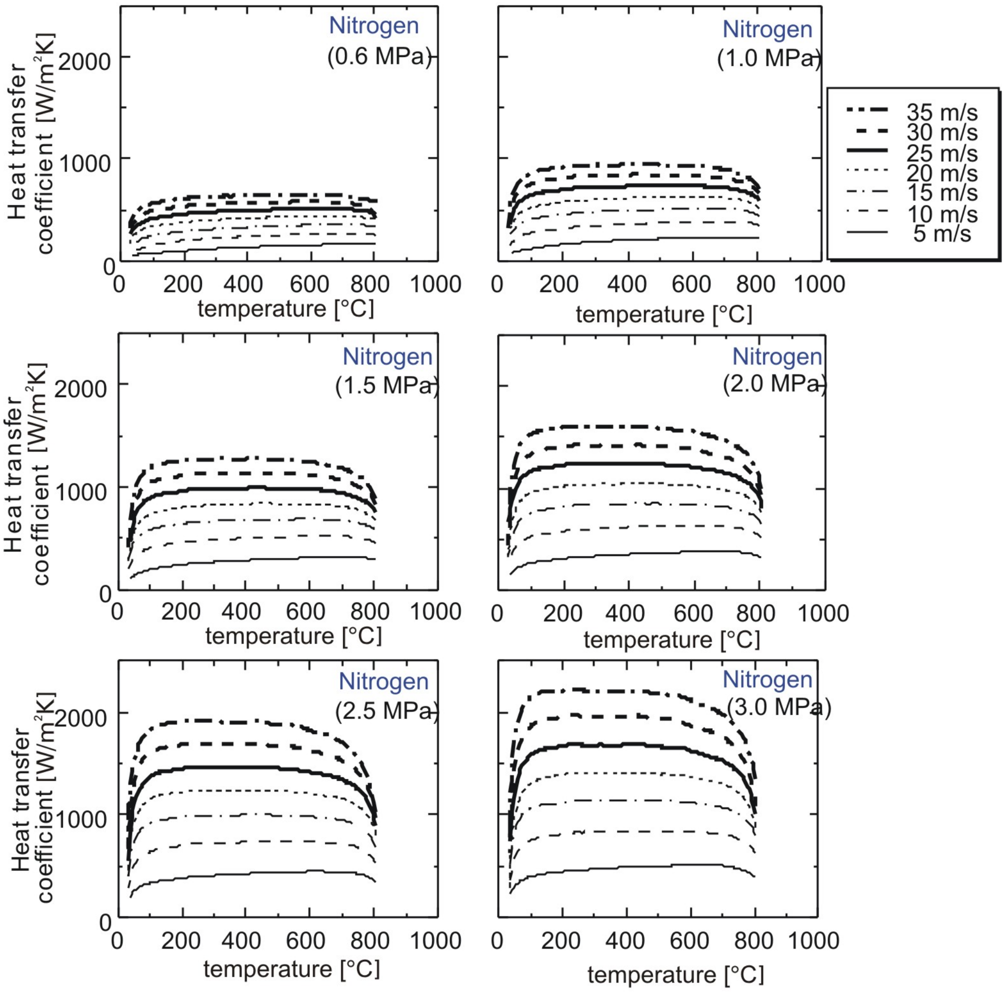
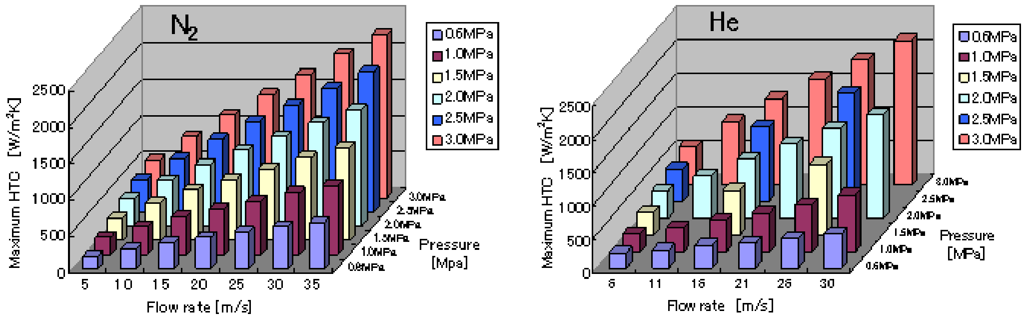


Fig. 4. *Example of heat transfer coefficients in gas quenching (nitrogen gas)*



a) Nitrogen gas b) Helium gas

Fig. 5. *Effect of flow rate and pressure on maximum heat transfer coefficient in gas quenching*

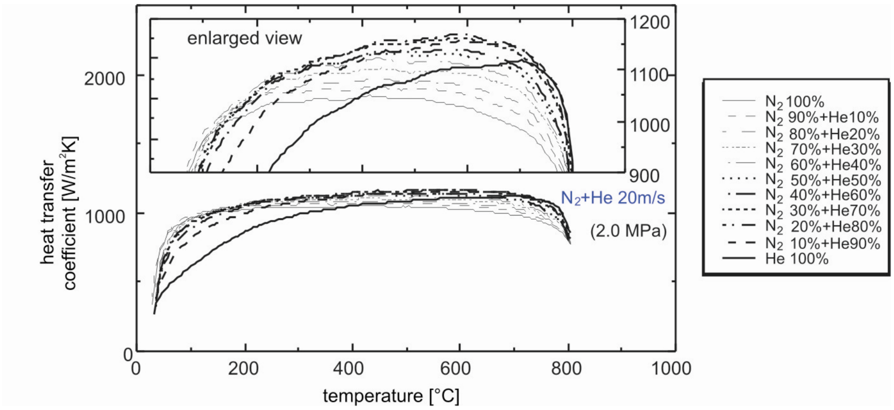


Fig. 6. *Effect of mixing rate on heat transfer coefficient in nitrogen-helium mixture gas cooling (2.0 MPa, 20 m/s)*

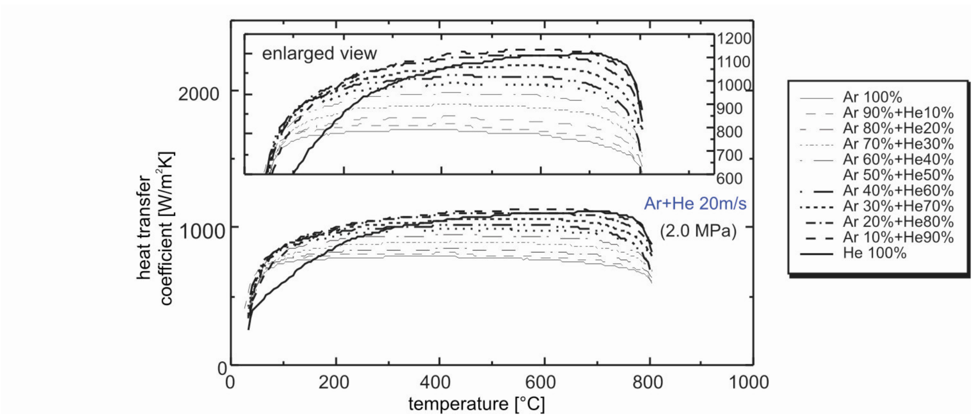


Fig. 7. *Effect of mixing rate on heat transfer coefficient in argon-helium mixture gas cooling (2.0 MPa, 20 m/s).*

3.2 Heat Transfer Coefficients in Gas Quenching by Mixture of Inert Gases

Figs. 6 and 7 show the HTC for nitrogen-helium mixture gas and argon-helium mixture gas (2.0 MPa, 20 m/s). These results show that the cooling power of nitrogen gas and argon gas increases by mixing helium gas in high temperature region. On the other hand, the cooling power of helium gas also increases by mixing nitrogen or argon gas in lower temperature region. As a result, heat treaters can choose the most suitable cooling characteristic for gas quenching by selecting the proper mixing rate.

3.3 Effect of Mixing Carbon Dioxide Gas with Nitrogen or Helium on Heat Transfer Coefficients in Gas Quenching

Fig. 8 shows the HTC for the mixture gas of nitrogen and carbon dioxide (2.0M Pa, 20 m/s). This shows that the values of HTC increase in proportion to the mixing ratio of carbon dioxide to nitrogen in whole temperature region. We confirmed a similar tendency of the different gas pressure (0.6 to 30 MPa) and flow rate (5 to 35 m/s).

Fig. 9 shows the HTC for the mixture gas of helium and carbon dioxide (2.0 MPa, 20 m/s). This shows that the value of HTC increases as the mixing ratio of carbon dioxide to helium. This tendency increases with decrease of probe surface temperature. In addition, the effect of mixing of carbon dioxide gas is remarkable in the lower mixing rate almost saturates at mixing rate 50%. We confirmed a similar tendency of the different gas pressure (0.6 to 30 MPa) and flow rate (5 to 30 m/s).

4 DATABASE OF HEAT TRANSFER COEFFICIENTS

In this study, the HTC was estimated for nitrogen, helium, argon gases and nitrogen-helium , argon- helium, nitrogen-CO_2 (up to 50%), and helium-CO_2 (up to 50%) mixture gases. The maximum gas pressure is 3.0 MPa and the maximum gas flow rate is about 30 m/s. The obtained cooling curve data and HTC data were built in the database of cooling power of quenchants that contains the data of various liquid quenchants. This database is built in cooperation with members of the working group of JSHT.

Each data sheet contains the detail of quenchant and probe, quenching condition, cooling curve data and estimated heat transfer coefficient data, etc. Fig. 10 shows an example data sheet of this database.

5 CONCLUSION

The heat transfer coefficient data of helium, argon, nitrogen and those mixed gases estimated by measurement of cooling curves of a silver rod probe and the lumped-heat-capacity method. The effects of composition of gases, gas pressure, flow rate, surface temperature of probe are confirmed. The obtained cooling curve data and the HTC data were built in the database of cooling power of quenchants.

6 ACKNOWLEDGMENTS

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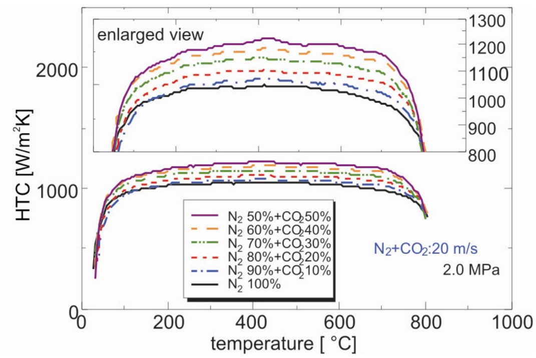

Fig. 8. *Effect of mixing rate of carbon dioxide gas on heat transfer coefficient in nitrogen and carbon dioxide mixture gas cooling (2.0 MPa, 20 m/s)*

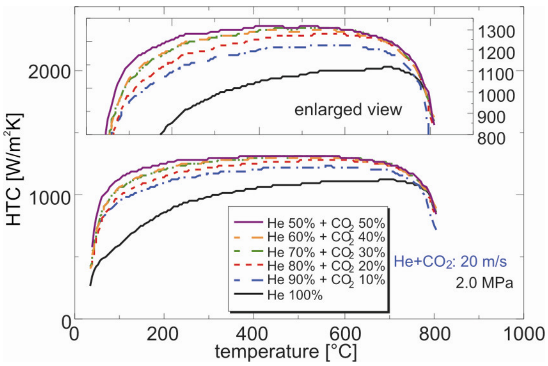

Fig. 9. *Effect of mixing rate of carbon dioxide gas on heat transfer coefficient in helium and carbon dioxide mixture gas cooling (2.0 MPa, 20 m/s)*

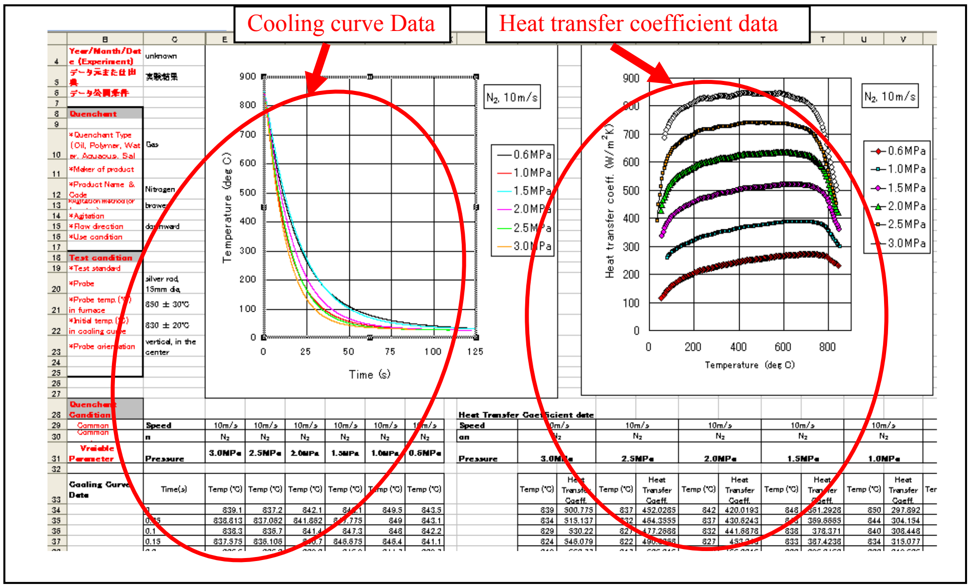

Fig. 10. *An example of data sheet in database of cooling power of quenchants*

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