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Water Cooling Technologies for Steel Pipe Production Processes

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Abstract

Water-cooling technology is applied in various pipe heat treatment processes for high-grade pipes, especially in quench processes. Roughly 4 types of industrial water quench processes have been developed to solve the technical issues to uniformly quench pipes. Water sprays type, especially, has several merits of its flexibility and high controllability of flow rate, and so on. Nippon Steel & Sumitomo Metal Corporation has been developing the technology to quantify and to analyze the heat transfer performance. By applying the analyzed heat transfer data to the boundary condition, Nippon Steel & Sumitomo Metal has been also developing numerical simulators of pipe quenching.

1. Introduction

Steel pipe products, a group of iron and steel products, are used in various applications, such as general piping, general machinery, marine constructions, heat exchangers, various uses in the chemical and nuclear industries, oil well pipes, and line pipes. Product of optimum size, steel quality, and grade are selected to suit the intended application. In pipe production processes, steel pipes are produced independently. To realize the production of a variety of steel pipes, a variety of processes have been developed. Examples of such processes include the electrical resistance welding method, which is capable of producing high quality steel pipes at low cost, and the mandrel mill method, which is capable of producing weld-free seamless steel pipes by piercing rolling at an inclined angle.[1–3)]

When a particular strength and/or corrosion resistance are required, heat treatment is applied to as-rolled steel pipes to process them and form final products. In this article, technical issues specific to steel pipes and water cooling evaluating technologies that have been developed by Nippon Steel & Sumitomo Metal Corporation, particularly with respect to water quenching technologies in heat treatment processes, are introduced.

2. Water Quenching Technologies of Steel Pipes

2.1 Problem of water cooling and classification of cooling methods

In heat treatment processes of steel pipes, various cooling methods are used to achieve the required quenching cooling rates to obtain the desired steel material specifications (strength, toughness, sour resistance, and so on). As a cooling medium, water is used mostly due to its advantages in terms of cost and cooling rate, although gas jets or oil baths are also used depending on the heat treatment conditions. All the quenching technologies discussed below involve water cooling, unless stated otherwise.

As it is quite a different process from the manufacture of flat sheets, the following difficulties have to be considered when designing water cooling equipment for steel pipes.

(1) Asymmetry of cooling surface (inside surface vs outside surface, upper surface vs side surface vs lower surface, and top end vs bottom end)

As cooling of the inner and outer surfaces of a general long steel pipe by the same method is physically impossible, cooling means for the inner and outer surfaces have to be designed separately. To establish stabilized production, although ideal is the cooling at uniform cooling rate in circumferential direction, longitudinal direction, and inside or outside, it's practically impossible. Specifically, when a steel pipe is placed horizontally, as the direction of the main stream of the water flow and the direction of gravity differ on the top, side, and bottom surfaces, the impact pressure and the drainage characteristics vary. In the cooling of the inner surface, water tends to gather at the bottom. Furthermore, as water is only discharged from the end of the pipes, the cooling medium temperature and the ratio of the mixture of vapor and cooling medium vary in the longitudinal direction; therefore, the cooling rate is not uniform. Although this non-uniform cooling rate in the circumferential direction can be improved by rotating the pipe during cooling, it is difficult to make it completely uniform.

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(2) Non-uniformity of steel material characteristics in the circumferential direction

A general seamless pipe's wall thickness distribution in the circumferential direction is not uniform. This is considered to be attributed to the practical difficulty of piercing the exact center of a billet in the piercing rolling process. On the other hand, a welded pipe's characteristics of a welded part (seam part) are different from that of its base material, and a separate independent cooling method sometimes has to be provided. As a result of these phenomena, sometimes pipes develop cambering during cooling even if the cooling rate is uniform, resulting in problems like halting in transfer equipment or in cooling equipment in worst case.

(3) Quench crack

Steel materials used in harsh environments (high temperature, high pressure, corrosive atmosphere, vibration) have higher amounts of alloying elements like Cr and carbon added to them. These materials have high quenchability and hardness and tend to develop brittleness and thermal stress cracks during quenching in intense cooling. Therefore, in quenching these materials, it is necessary to design cooling equipment cautiously, or in other words, cooling equipment that cools the pipe at a sufficiently slow rate to avoid causing any damage, and also considering the problems highlighted in (1) and (2) above.

Four of the traditional configurations of water cooling methods are shown in **Fig.1**. These are considered to be cooling methods that are capable of solving the above mentioned problems on an industrial scale and are selected depending on their heat treatment conditions. However, as each configuration suffers from non-uniform cooling rates in the longitudinal and circumferential directions, the addition of an appropriate composition of alloying elements is also important to obtain a material that can achieve the desired cooling rate.

Immersion cooling, shown in Fig. 1 (a), is considered to be the simplest intense cooling method. However, the larger the subject pipe, the larger the load on the transfer equipment becomes. Furthermore, as there is no water inside the pipe when it is placed into the tank, problems such as the floating of the pipe and non-uniform cooling sometimes occur. In addition, to prevent a drop in the cooling rate on the outer surface on account of steam films covering the outer surface, the installation of a water stirring mechanism in the tank is preferred.

As a method to solve the shortcomings of immersion cooling which can generate intense cooling in a relatively simple manner, a laminar flow cooling method has been developed and put into practical use.[5] Among the inventions described in patents filed in the latter half of 1990s is a technology which realizes uniform intense cooling by installing a long slit of more than two in total in number as shown in Fig. 1 (b). However, as only the upper half surface is cooled intensely, installation of a pipe turning mechanism to prevent non-uniform cooling in the circumferential direction is preferred.

Immersion cooling and laminar flow cooling are designed for batch processes (stationary treatment), and the treatment speed is relatively slow because of the need for a lead time for loading and unloading of the steel pipe into and out from the equipment. Conversely, the tunnel cooling shown in Fig. 1 (c) is a method which can deliver intense cooling in a continuous process.[6] In this method, cooling uniformity in the circumferential direction and the cooling rate on the outer surface are equal to or above those of immersion cooling, and they are obtained by supplying a large water flow to a large jacket which is installed in such a way as to embrace a steel pipe, and which is sufficiently large to keep the jacket filled. However, it is difficult to supply a large amount of cooling water to the inside of the pipe while the pipe is being transferred in the longitudinal direction, and the outer surface tends to be quenched to a higher degree.

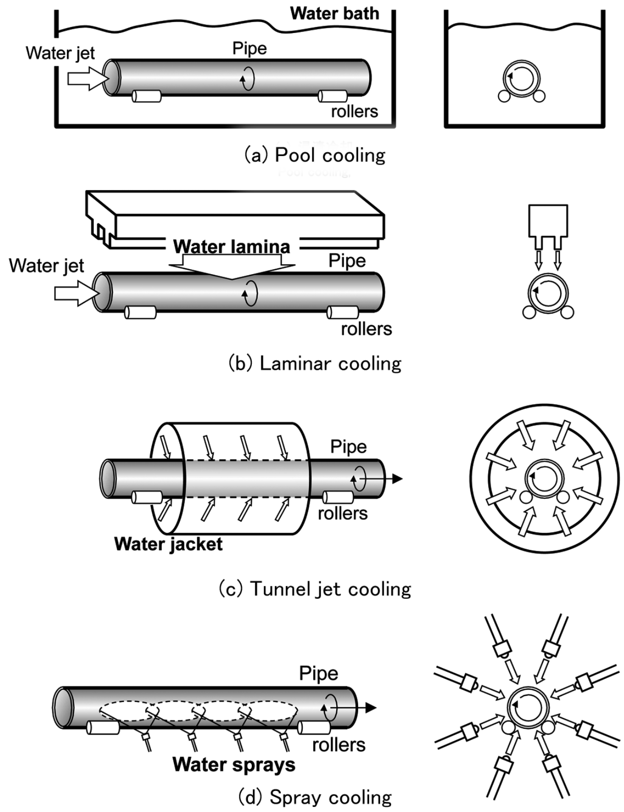

Fig. 1 Cooling methods for steel pipes

The spray cooling shown in Fig. 1 (d) is a cooling method which is applicable to either batch or continuously pipe feeding systems.[7] The flexibility in the selection of the nozzle type and layout enables the design of water cooling equipment which meets the objective of cooling, whether that be intense cooling, soft cooling or controlled cooling. On the other hand, when the nozzle arrangement is inappropriate, uniform cooling cannot be assured. Furthermore, nozzle clogging prevention measures are needed.

2.2 Trend in pipe cooling technologies overlooked through disclosed information

Academic papers on the topic of steel pipe cooling technologies are very few. This is due to the difficulty in constructing a fundamental research system in a public research organization like a university because of the asymmetry of the cooling surface, as described in the previous section, and also due to the high cost of a cooling experiment of a large diameter pipe. Furthermore, in enterprises, as the technology is coupled to production technologies, it is either patented as intellectual property, or in many cases concealed as a secret. In technical reports by domestic iron and steel manufacturers, water cooling technologies are often referred to in quite a simple manner in articles surveying steel-pipe-related technologies.[1–3]

On the other hand, a survey on the number of domestic patents concerning steel pipe cooling equipment in recent years (1990–2012) showed 67 publications which mainly concern steel pipe quenching technologies. Among such inventions, water is used mostly as cooling medium (87%), while gas jet, oil, liquefied nitrogen and solid bodies (guide rolls or the like) are occasionally used as an alternative cooling medium to water. Unless there is a particular demand for a certain cooling rate or material quality, water is used because of its low cost.

Configurations of water cooling equipment are classified into four types, as shown in Fig. 1.[4–7] These technologies have been in use for a long time, and new knowledge concerning accelerated cooling methods, uniform cooling methods (particularly intended for prevention of steel pipe cambering), and cooling rate control methods have been applied. The following technological trends have been observed from the transition in the numbers of patent applications.

(1) Patent applications on laminar flow cooling methods were concentrated in the latter half of 1990s, and it is considered that the development of this technology during this period was energetically promoted. As for the laminar flow method, there were many patent applications related to long slit laminar flow of more than or equal to two in total in number.

(2) Patent applications on spray cooling have been made continuously, with little change over time. This technology is widely used. Furthermore, any turn-down ratio in a wide range can be chosen with ease, and therefore, this technology has good compatibility with controlled cooling technology.

(3) Patent applications on immersion and tunnel cooling methods are sporadic and few. The reason for this is that this technology is used for intense cooling using large flow rates, and in many cases the addition of novel improvements like controlled cooling is difficult.

3. Steel Pipe Cooling Technologies in Nippon Steel & Sumitomo Metal

3.1 Production equipment and testing equipment of steel pipe

Representative steel pipe production equipment in Nippon Steel & Sumitomo Metal are shown in tables and process flow figures, for instance by Nishikawa.[2] Such processes comprise in part various heat treatment equipment, represented by water quenching equipment.[4–7] To evaluate the water cooling capability, the pieces of test equipment are also installed. **Figure 2** shows an example of such equipment, which has been constructed to enable researchers to conduct various small-scale-water cooling tests corresponding to the cooling mode such as immersion cooling, spray cooling, and so on. Based on the quantitatively measured cooling temperature data obtained by the experiment equipment, analytical evaluation as described in this document is conducted, and numerical simulation models of water cooling and quenching phenomena have been built up.

3.2 Cooling rate evaluating technologies

When cooling steel material with water, the cooling rate varies in a complicated manner as the way in which the water boils on the steel surface changes drastically. In Nippon Steel & Sumitomo Metal, quantitative evaluation and evaluation of boiling characteristic curves have been performed based on physical tests conducted on test equipment, as represented by the steel pipe cooling test equipment shown in Fig. 2.

Systematic research on boiling characteristic curves has its origin in the researches of Jakob and Nukiyama in the 1930s, and various researchers have built on this up to the present day.[8)] Since the state of affairs of boiling often emerges in the heat treatment of steel materials, such as in the cooling water piping of a nuclear reactor where water is used as a cooling medium, research and development in this area is very active.[8–10)]

On the other hand, the cooling mode in boiling cooling is an intensely non-linear phenomenon. Specifically, there are four modes of heat transfer: convection heat transfer, nucleate boiling, transition boiling and film boiling (**Fig. 3**). These are in the form of heat transfer modes from the surface of a solid body (steel material surface or the like) to a cooling medium, and these cooling modes transition in succession.[8)] Since the amount of heat transfer and the timing of the transition to the next cooling mode varies depending on various influencing factors (e.g., water flow density, standoff, water temperature, droplet diameter, droplet speed, air temperature, steel material surface temperature, steel material surface condition), the establishment of a boiling characteristic curve covering and including all factors is still a major challenge.

In the Heat Economy Subcommittee of the Iron and Steel Institute of Japan, a number of papers which reported on the boiling characteristics were sorted and arranged with respect to the respective cooling method, and the heat transfer coefficient corresponding to the respective boiling mode was arranged by multiple regression arrangement with respect to the influence of water flow density and temperature.[9)] For instance, with respect to the heat transfer coefficient at the impact surface in spray cooling, a multiple regression formula of an exponential function consisting of the power of water flow density and the power of the steel material surface temperature

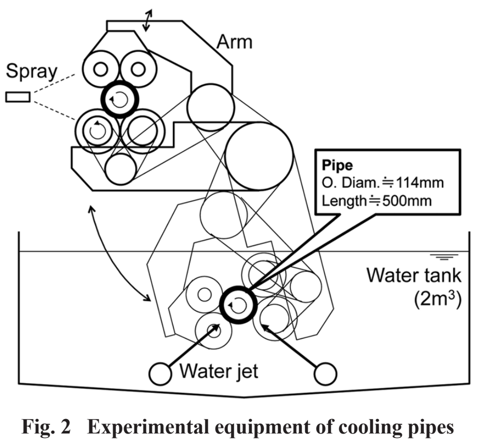

Fig. 2 Experimental equipment of cooling pipes

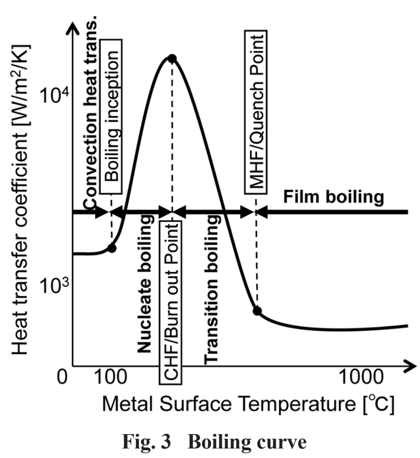

Fig. 3 Boiling curve

has been given. However, this formula does not take into account water temperature, and thus the boiling curve becomes discontinuous at the boundary temperature in the boiling state.

On the other hand, in the Japan Society of Mechanical Engineers, the results of a number of fundamental researches have been sorted with respect to boiling mode and are introduced.[8, 10] Although comprehensive arrangement is confined, in certain area of research however, the research results have general-purpose use of higher degree as a dimensionless correlation system has been worked out. For instance, to express the cooling rate in the film boiling region of a cylindrical columnar body immerged horizontally and cooled in still water, a dimensionless correlation system developed by Pitshman, et al. from the dimensional correlation system of Bromley is introduced.[8)]

When these correlation systems are used, attention must be paid to the area of application, which must be selected based on the temperature range of the steel material surface temperature (film boiling, transition boiling, nucleate boiling and convection cooling). This work is complicated and furthermore has drawbacks of collapses of consistency at the edges of the temperature regions, and the correlation system becoming not applicable if the object area of application is improperly selected.

In Nippon Steel & Sumitomo Metal, tests were carried out for measuring cooling rates in spray cooling by changing the jet water flow rate and the water temperature by the test equipment shown in Fig. 2, and the influence of water flow rate and water temperature was quantitatively evaluated. An original method of utilizing a biphasic curve for regression analysis was developed which eliminates the aforementioned complexity of sorting and selecting application regions.

A biphasic curve is a nonlinear curve defined by the following formula.

$$h = h_1 + \frac{h_2 - h_1}{1 + \exp\left(m_1 \left(T_s - T_1\right)\right)} + \frac{h_3 - h_1}{1 + \exp\left(m_2 \left(T_2 - T_s\right)\right)} \quad (1)$$

Where; h : heat transfer coefficient (W/m^2/K), T_s : steel material surface temperature (°C), and others are constant coefficients. If such coefficients are appropriately fixed, this curve is able to approximate the change in heat transfer coefficient over the entire range of steel material surface temperature, and, furthermore, has the advantage that the respective coefficients contain information directly coupled to the physical quantity of the cooling characteristics. Specifically, h_1, h_2, h_3, T_1, m_1, T_2 and m_2 correspond to; heat transfer coefficient in the neighborhood of the maximum heat flux point, heat transfer coefficient of convection heat transfer, heat transfer coefficient of film boiling, steel material surface temperature at the inflection point and its inclination in nucleate boiling, and steel material surface temperature at the inflection point and its inclination in film boiling, respectively (**Fig. 4**). Furthermore, quench temperature T_q is given uniquely by the following formula.

$$T_q \cong T_2 + {m_2}/{2} \quad (2)$$

In the conventional regression analysis method, regression analysis was made separately in each film and transition boiling region, and the separation work had to be done either manually or automatically using a suitable logic. Therefore, the regression analysis method had the drawback of calculating a different quench point depending on which engineer calculated it. Furthermore, it is difficult to deduce the physical meaning from the respective coefficient. In the biphasic curve method, as the coefficient of heat transfer in the entire temperature range is approximated by a single biphasic curve, such uncertainty is advantageously eliminated.

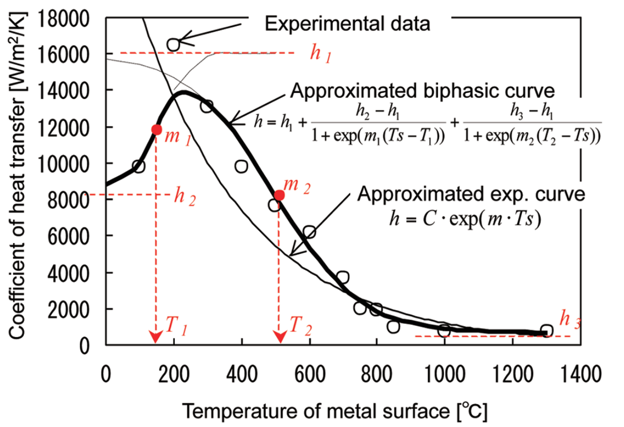

Fig. 4 Approximated boiling curve by biphasic curve

Table 1 Experimental conditions to identify heat transfer coefficients of water spray

Steel plate (test section)	Grade	SUS310S
	Size	$^{T}15 \times {}^{H}120 \times {}^{W}324$ mm
Water spray (coolant)	Water flux W	80–1 400 L/min/m^2
	Water temperature T_w	13–50 °C

In **Table 1**, the test condition range of the heat transfer coefficient measuring test is shown. As a material that does not form scale easily on its surface, SUS310S was used. The reason is to avoid remarkable deterioration in the reproducibility of the measured data due to irregularities in the surface condition of the surface scale. A sheet steel material of 15 mm in thickness was heated up to 1 000°C in an electric heating furnace and manually extracted after soaking, and cooling was started within 30 seconds. In this test sample, thermocouples are inserted from the rear side in a checker board pattern to the points below the cooled surface by 1 mm in thickness direction, measuring successive changes in temperature at each point during cooling. An oval shape spray nozzle was used as the water-cooling nozzle, and the water flow density and standoff were changed in a varying manner (equivalent to 80–1 400 L/min/m^2). Further, the water temperature was set between 13 and 50°C.

The procedure of conducting multiple regression analyses of heat transfer coefficient by utilizing a biphasic curve is shown in **Fig. 5**. Based on the results of the temperature measurements, the heat transfer coefficient at the cooled surface at each point is back calculated, and a biphasic approximated curve is worked out by a nonlinear minimum squares method. Furthermore, biphasic curve coefficients are approximated by power math function of variables in each test condition, and multiple regression analysis was conducted using formula (3).

$$\ln \mathbf{K} = \mathbf{C}_0 + \mathbf{C}_1 \ln W + \mathbf{C}_2 \ln T_w \quad (3)$$

$$\left\{ \begin{array}{l} \mathbf{K}\text{: Vector of variables} \\ \quad = (h_1, h_2, h_3\ [\mathrm{W/m^2/K}],\ T_1, T_2\ [^\circ\mathrm{C}],\ m_1, m_2\ [-])^T \\ \mathbf{C}_0, \mathbf{C}_1, \mathbf{C}_2\text{: Vectors of constants} \\ W\text{: Flux of water [L/min/m}^2\text{]} \\ T_w\text{: Temperature of water [}^\circ\text{C]} \end{array} \right\} \quad (4)$$

The mean square error between the raw data and the regression

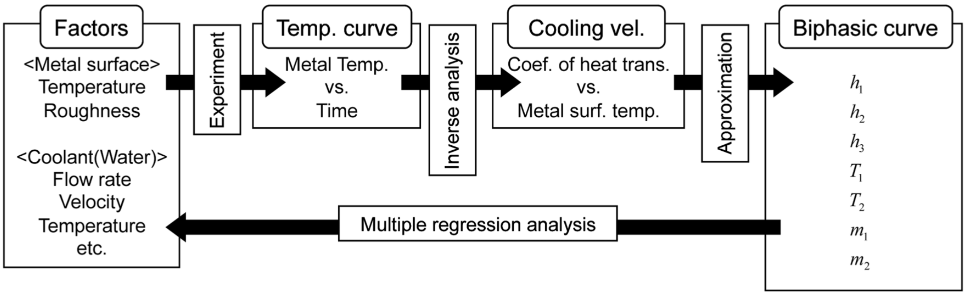

Fig. 5 Sequence of multiple regression analysis for heat transfer coefficient by biphasic curve

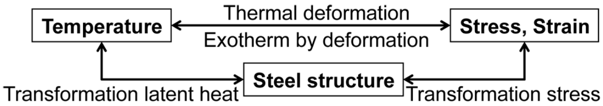

Fig. 6 Numerical analysis model of deformation

result is 24%, and the regression was completed with sufficient accuracy for practical use. By providing this result to generate boundary conditions for a quenching simulator, described in the next section, a numerical simulator capable of precise and predictive analysis of quench state distribution has been established.

3.3 Numerical simulation technology of quenching phenomena

As problems due to local excessive or insufficient quenching such as the deterioration in dimensional accuracy, high residual stress, quenching crack and quenching distortion take place if the heat treatment of steel material is inappropriate, it is very important to be able to judge whether or not a particular heat treatment can be conducted properly at the equipment designing stage. As a tool for this, a heat treatment simulator which numerically simulates heat treatment has been developed.

Based on thermal elasto-plasticity analysis software, where solution method is relatively well developed, the heat treatment simulator is designed to obtain the ratio of phase transformation, hardness, residual stress and strain as the result of coupling and solving the phase transfer of the steel material structure and the accompanying changes in thermal dynamic material characteristics, volumetric change, latent heat, and transformation plasticity (**Fig. 6**).[11, 12] This was accomplished using commercially available software (such as SYSWELD, DEFORM-HT, DANTE, GRANTAS) which had already been developed.

On the other hand, in Nippon Steel & Sumitomo Metal, a simulator has been developed by building solely-developed sub routines into an all-purpose finite element method software (ABAQUS, Marc).[13]

As an example of a simulation, water spray cooling on the outer surface of a steel pipe was simulated, and the residual stress in the wall thickness direction and the longitudinal direction after quenching were calculated, the result of which is shown in **Fig. 7**. The reversal of stress (the negative sign denotes compression and the positive sign denotes tension) on the inner and outer surfaces of a pipe, and the appearance of maximum residual stress on the steel pipe end, are confirmed.

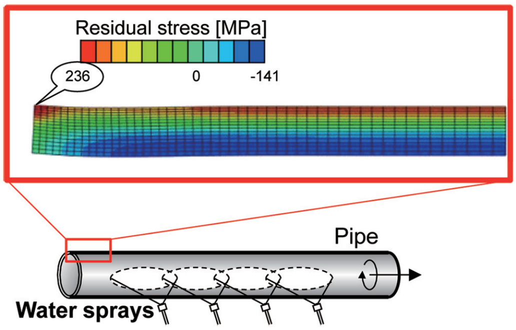

Fig. 7 Sample simulation of pipe quenching

4. Conclusion

Technical issues specific to steel pipes and general water cooling methods and the contents of technical development concerning water quenching technologies in Nippon Steel & Sumitomo Metal have been introduced. It is anticipated that the need for materials of more sophisticated function, cost reductions by lowering alloy concentration, and expectations of heat treatment technologies will only continue to grow. In order to meet these needs, it is necessary to develop cooling equipment of a more sophisticated nature by further refining and exploring in greater depth the technologies which are already in use which have been introduced in this article.

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