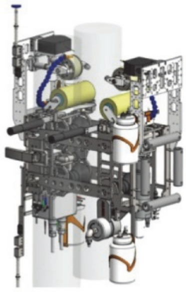
Safe and Efficient Piping Inspection Service Using Robot

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From the viewpoint of improving the operation rate and shortening the work period for regular inspections of Mitsubishi Heavy Industries, Ltd.'s (MHI) products, including plant facilities, it is hoped to establish a highly efficient inspection service. However, human inspection of plant facilities in high and confined spaces requires additional work such as erecting temporary scaffolding and removal of related equipment, and there are issues of reducing the cost and time involved and ensuring sufficient safety. Therefore, MHI has developed a robot that can self-propels and inspect the outside and inside of piping by itself. We will provide a service that uses this robot to safely and quickly inspect such facilities, diagnose the condition of plant facilities, and develop maintenance plans.

1. Introduction

Our products, including chemical (ammonia and methanol) plants and thermal and nuclear power plants, are often operated in harsh environments for long periods of time, so there are concerns about damage to the facilities as a result of aging deterioration. Some plant facilities are composed of a wide variety of piping groups that measure even several hundred kilometers in total length. If any one of these pipes is damaged, the entire plant will be suspended for several weeks, which will have a significant impact on our customers and end-users. Therefore, it is necessary to conduct more reliable inspections on a regular and thorough basis, taking into account the forms of damage that may occur in the piping equipment, and to formulate a plant maintenance plan. In addition, the increasing demand for ammonia, methanol, and electric power in recent years has led to a need to further improve the operation rate of plant facilities, which requires inspections over a wider area in a shorter period of time.

MHI has been developing a service that uses robots for plant equipment maintenance to safely and quickly inspect plant piping equipment, diagnose the condition of the equipment, and develop maintenance plans. This report presents two services we developed for chemical plants and IGCC (Integrated coal Gasification Combined Cycle) power plants.

2. Chemical plant catalyst tube inspection robot (RIDe)

2.1 Issues in maintenance and management of chemical plant catalyst tubes

MHI has developed and accumulated technologies to reform and synthesize various chemical fuels such as methane (natural gas) into cleaner and easier-to-use chemical products such as ammonia and methanol, and has led the engineering and after-sales service businesses for chemical plants that manufacture these chemical products [(1),(2)].

Figure 1 shows an example of a large-scale methanol plant we constructed. Most methanol and ammonia plants use synthesis gas, which is steam reformed from natural gas, as feedstock. This steam reforming is an endothermic reaction, and therefore the feed gas is catalytically reacted while being heated. An example of the heating method is to install a heat-resistant cast steel tube filled with catalyst in a furnace and heat the inside of the furnace with a burner. In this case, the inside of the

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catalyst tube reaches a high-temperature and high-pressure environment. The main form of damage to steam reformers in actual plants is considered to be creep rupture of the catalyst tube due to the high-temperature and high-pressure environment, which can be the weakest point of the entire plant facility, especially where localized heating (hot spots) occur due to direct burner flame or blockage in the tube. Furthermore, the risk of hot spot occurrence and the creep damage progression rate differ for each catalyst tube depending on plant operating conditions such as burner flame properties and reforming reaction rate. If inspection is not performed regularly and hot spots are overlooked, there is an increased risk of unplanned plant shutdowns due to creep rupture, resulting in a significant reduction in the facility operation rate. Therefore, TBM (Time Based Maintenance), in which tubes are replaced at regular intervals to prevent creep rupture from occurring, can be considered from the viewpoint of preventive maintenance. However, for this purpose, the replacement interval has to be shortened, which in some cases leads to excessive maintenance. Thus, it is difficult to achieve both improvement of operation rate and reduction of operating costs.

Therefore, in many cases, CBM (Condition Based Maintenance), in which the condition of the equipment is diagnosed and preventive maintenance is performed according to the results, is effective to improve the operation rate of plant equipment and to reduce the operating cost. Specifically, it is necessary to inspect all reaction tubes periodically and in a short period of time, and to diagnose the remaining life of each reaction tube in consideration of the degree of creep damage, thereby establishing a rational plant maintenance plan.

However, the reformer of a large methanol plant has more than 700 vertically mounted catalyst tubes of approximately 14 m in length, so a detailed inspection of the entire number and length of the reaction tubes requires a great deal of labor and time. In particular, when human workers inspect high areas, it is necessary to erect temporary scaffolding more than 10 m high inside the furnace, which requires time and cost. Moreover, it is not practical to search for the maximum damage location in the entire 14-m vertically mounted tubes by human workers from the viewpoint of working time and workability, and therefore, spot checks are performed, which limits the comprehensive understanding of the deteriorated condition. From the above, the problems in the maintenance and management of catalyst tubes are considered to be an increase in the inspection time due to the erection of temporary scaffolding and a decrease in the reliability of the inspection due to spot checks by human workers. To solve these problems, we have developed a robot that can inspect the entire number and length of 14-m-high vertical tubes traveling on the outside surface of them by itself without the need for temporary scaffolding.

Figure 1 Large-scale methanol plant (Delivered to: Brunei Methanol Company)

2.2 Robot performance and verification test results

In the diagnosis of the remaining life of catalyst tubes, a precise evaluation of the bulging ratio of the catalyst tube (inner diameter) is necessary, as described below. Since similar services provided by other companies cannot measure the inner diameter with the desired accuracy, we decided to develop our own robot. **Figure 2** shows the RIDe (Reformer Inspection Device), an inspection robot we developed for catalyst tubes. RIDe has a traveling bogie mechanism to move the robot up and down on the outside surface of catalyst tubes using an air motor, an outer diameter measurement mechanism using a laser sensor, and a wall thickness measurement mechanism using a tire-type ultrasonic sensor. The traveling bogie can be easily attached to and detached from both sides of the tube, and can raise and lower the robot on the reaction tube at a speed of approximately 250 mm/s. The tire-type ultrasonic sensor has a built-in probe that can focus the ultrasonic beam and can measure the wall thickness of catalyst tubes made of heat-resistant cast steel, this material that is difficult for ultrasonic waves to penetrate, with high accuracy. The equipment control and data acquisition are performed by dedicated software on a PC located outside the furnace, and profiles of the outer diameter and wall thickness can be obtained based on continuous measurement data at a pitch of 1 mm in the tube axial direction. The combination of these mechanisms makes it possible to measure the outer diameter and wall thickness of 14-m-long reaction tubes in a short time of about 5 to 10 minutes and to derive the inner diameter from these measurements.

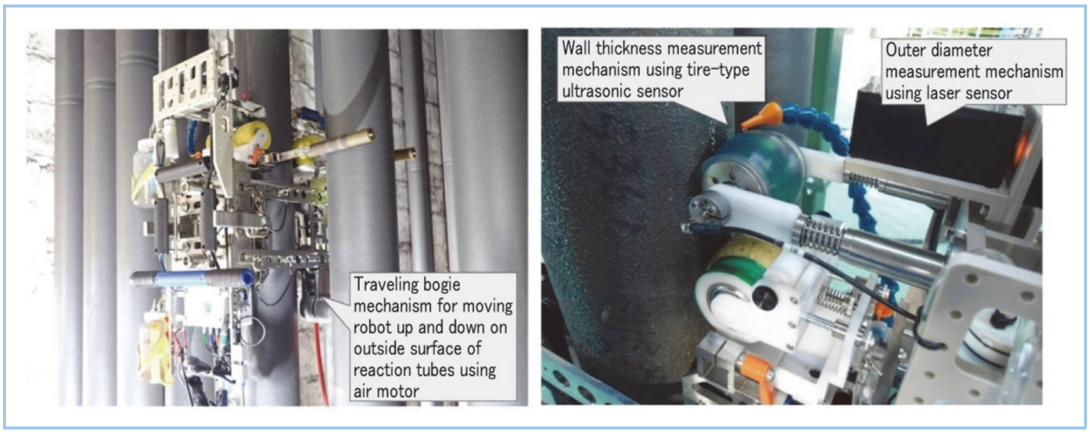

Figure 2 Catalyst tube inspection robot (RIDe)

Figure 3 shows an example of the results of tube profile measurements (outer diameter, wall thickness, and inner diameter) by RIDe of a catalyst tube that was extracted because a hot spot was found in a reformer at a methanol plant. It is indicated that the catalyst tube profile was quantified over the entire length, and that the bulged area due to the hot spot could be detected. The location where the inner diameter evaluation value by RIDe showed a large bulging ratio coincided with the hot spot location observed during operation, which demonstrated that RIDe was able to detect the area with the most damage. The runnability and measurability of the shape and dimensions of catalyst tubes have also been verified in an actual plant.

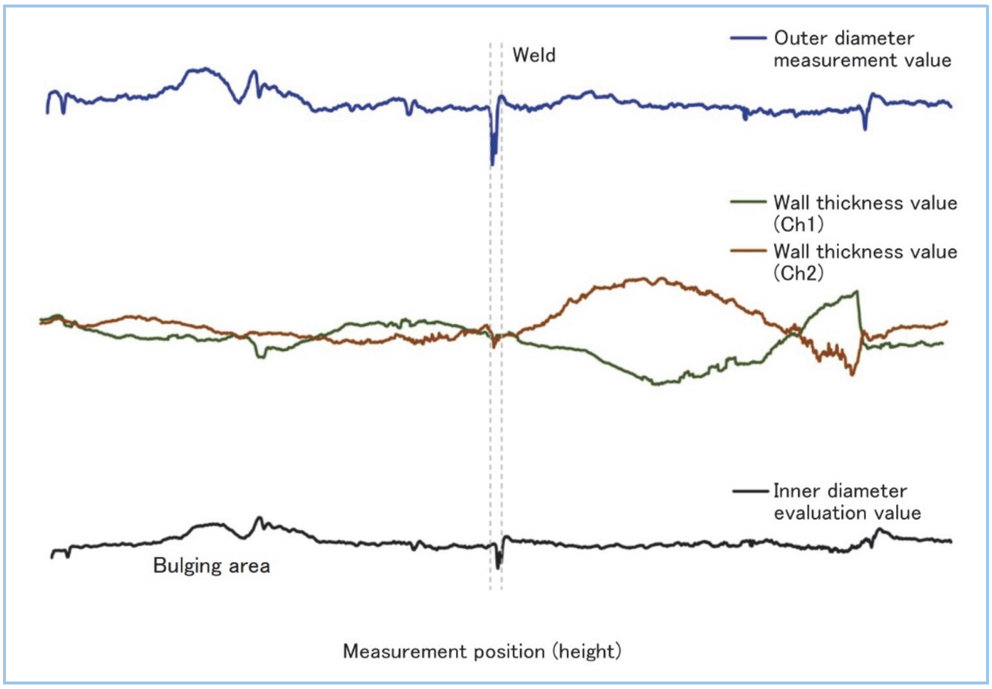

Figure 3 Result of measurement using mockup tube

Figure 4 shows a correlation diagram (for illustration purposes) between the bulging ratio and the remaining creep life of a catalyst tube. We have a great deal of knowledge on creep damage behavior and evaluation methods for various metallic materials, and by utilizing this knowledge, we have developed a method to evaluate the remaining creep life from the bulging ratio of catalyst tubes. This method enables quantitative estimation of the remaining creep life based on the inner diameter bulging rate of the entire length of the catalyst tube obtained by RIDe.

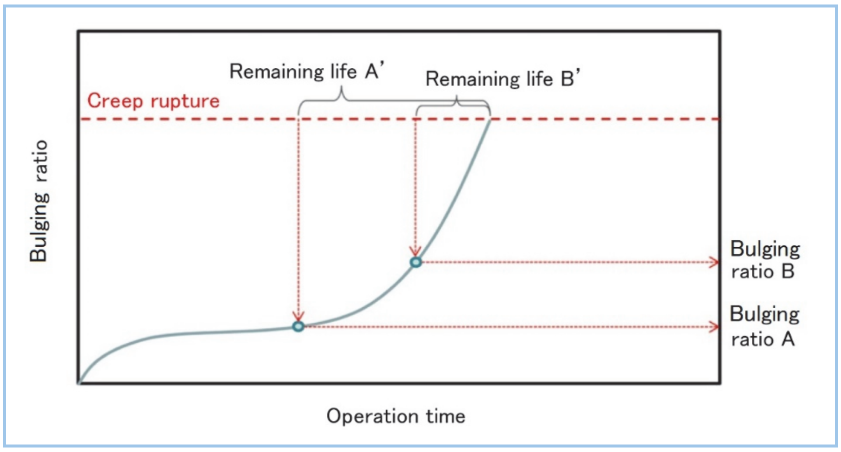

Figure 4 Line diagram of remaining creep life evaluation with respect to bulging ratio (for illustration purposes)

2.3 Value of services we provide by utilizing robots

As mentioned above, the application of RIDe enabled the measurement of the bulging of the entire length of catalyst tubes and the evaluation of their remaining life without the need for erection of temporary scaffolding. By this, the problems of long inspection periods due to the erection of temporary scaffolding and the unreliability due to sampling inspections by human workers can be solved. The RIDe can measure the bulging ratio of the entire length of catalyst tubes in a short time of 5 to 10 minutes per tube, depending on the evaluation items and local conditions, and thus can contribute to a significant reduction in the inspection period.

Next, this paragraph deals with the features of RIDe and our service by comparing them with similar inspection services provided by other companies. There are several inspection robots in practical use that, like RIDe, travel on the outside surface of catalyst tubes by themselves. Among these, robots that measure the outer diameter using a laser have the advantage of shorter inspection time compared to RIDe, and the bulging ratio of the outer diameter is obtained as the difference between the initial measurement data and the measurement data collected in each regular inspection. However, the outer surface of heat-resistant cast steel catalyst tubes is in an as-cast state and thus uneven and undulated, resulting in a large variation in outer diameter, and also tends to be oxidized and thinned during operation, so that robots that measure the bulging ratio based on the outer diameter alone cannot accurately determine the bulging ratio of heat-resistant cast steel catalyst tubes. On the other hand, the inner surface of catalyst tubes is machine-formed after the tubes are cast, which results in extremely small initial inner diameter distribution (variation) in the length direction, and is in a reducing atmosphere during operation, which results in no oxidized wall thinning. For this reason, RIDe, which can obtain the bulging ratio based on the inner diameter of the unheated part of the catalyst tube outside the furnace, has high accuracy in measuring the inner diameter and high reliability in the bulging ratio obtained from the difference in each regular inspection. There is another method of measuring the inner diameter of catalyst tubes by inserting a sensor therein. However, this method can only be used every few years when the catalyst is replaced, and the rotating movement of the sensor in the catalyst tube makes the circumferential measurement position inconsistent, making it impossible to perform fixed-point measurement in each regular inspection. Consequently, the strengths of our remaining life diagnostic service using RIDe lie in the ability to measure the inner diameter without removing the catalyst, the high reproducibility of the circumferential position, and the ability to evaluate the remaining creep life based on the inner diameter bulging ratio.

However, as shown in Figure 4, it is difficult to accurately evaluate the degradation behavior in the early stages of creep, the bulging ratio of which is very small. To deal with this, we developed a metallurgical remaining creep life evaluation method using a metal surface replica method (Suzuki's Universal Micro-Printing method: SUMP), which enables detailed remaining service life evaluation even in the early stage of creep. Accordingly, we can screen and evaluate all catalyst tubes by using RIDe, and then metallurgically evaluate the remaining life by using the replica method (SUMP) for the areas that are judged to be in the early stage of the service life or where double-checking is necessary. This enables accurate diagnosis of the remaining life for each phase from the early stage of creep to the end of the service life, and allows us to propose optimal maintenance and operation plans for the entire plant facilities to our customers.

As described above, our services can provide not only efficient measurement of the total number and length of catalyst tubes using the inspection robot RIDe, but also detailed metallurgical evaluation using the replica method, and remaining service life evaluation using the creep evaluation technology and knowledge we have accumulated over many years as a plant manufacturer. In other words, one of the features of our service is that we can provide comprehensive maintenance and operation services from multiple perspectives according to the needs of our customers and the condition of their plants. Through these services, we can prevent unplanned plant shutdowns due to catalyst tube leaks, shorten regular inspections, and optimize the catalyst tube replacement cycle, thereby contributing to the reduction of plant maintenance costs and the improvement of plant operation rates for our customers.

3. IGCC plant produced gas piping inspection robot

3.1 Maintenance issues with IGCC plant produced gas piping

Chapter 3 describes our service using the IGCC plant produced gas piping inspection robot. In the IGCC plant produced gas piping shown in **Figure 5**, unburned particles (char) contained in the gas pass through the pipe at high speed, which may lead to erosion of the inner surface of the pipe, and it is necessary to periodically understand the status of wall thinning of the pipe inner liner. A generally known method for understanding the inner wall thinning of a pipe is the ultrasonic testing (UT) method, which transmits ultrasonic from the outer surface of the pipe to measure the wall thickness and the amount of wall thinning on the inner surface. However, the UT method cannot be used from the outside of the pipe because a pipe inner liner is installed inside produced gas pipes to prevent wall thinning as shown in **Figure 6**. Therefore, to grasp the wall thinning situation from the inside of the pipe, it is necessary to partially remove the pipe to make an opening, through which human workers enter the pipe to perform inspection. This requires a great deal of time and cost for additional work such as removal of the piping and restoration after inspection, so it is desirable to minimize the number of openings as much as possible. Furthermore, in the case of piping containing vertical pipes, the accessible inspection area through the opening is limited, and there also arises a safety issue if the access to inspection areas is performed forcibly. Therefore, the challenges in the maintenance and management of produced gas piping are to reduce time and cost in inspecting the entire range of the piping and to ensure worker safety.

To solve the above issues, we have developed a piping inspection robot that can travel by itself inside pipes, including vertical pipes, to understand the pipe wall thinning status with minimal additional work, and a service that uses the robot.

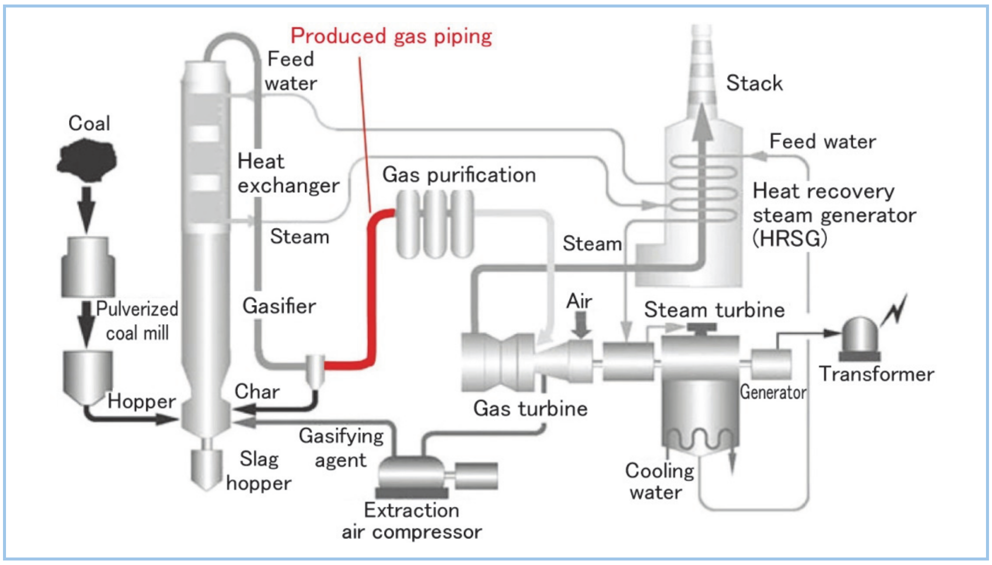

Figure 5　Produced gas piping shown in schematic air-blown IGCC system

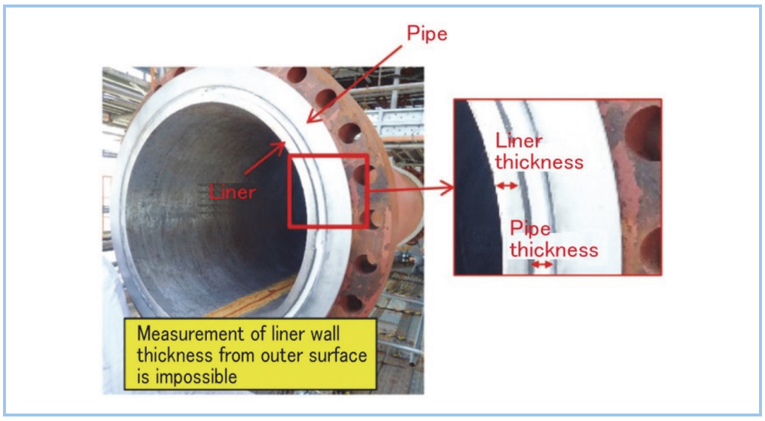

Figure 6　Appearance of produced gas piping (with flange connection removed)

3.2　Performance of robot to realize services and verification test results

3.2.1　Traveling performance of robot

Figure 7 shows the appearance information of the robot. The robot consists of three cars, and car 1 and car 2, and car 2 and car 3, respectively, are connected by arms. The robot travels by rotating the tires of each car with a motor while maintaining its posture by pressing the tires against the inner surface of the pipe by the force of the spring. By increasing the pressing force of the tires, traveling not only in horizontal sections but also in vertical sections and bends is possible. Furthermore, this robot has a steering mechanism, which turns the direction of the tires from the direction of travel (pipe axis direction) to the circumferential direction of the pipe using a motor other than the traveling motor, allowing for movement in the circumferential direction [(*1)]. If it is difficult to travel or check the wall thinning status due to char deposits on some horizontal sections or bends of the produced gas piping as shown in **Figure 8**, the robot can remove the char using the mounted suction hose as shown in **Figure 9**. This allows the robot to travel and perform inspection even if there is char accumulated on the inner surface of the pipe.

*1　In bends where the angle between the car body and the arm changes circumferentially, the tire cannot be turned circumferentially because doing so would make it impossible for the car to maintain its posture.

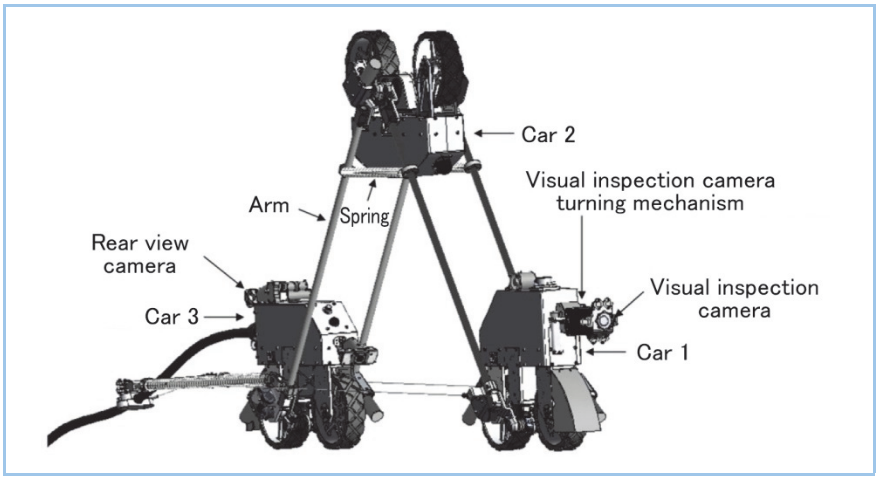

Figure 7　Appearance information of produced gas piping inspection robot

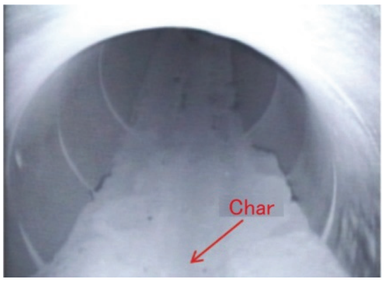

Figure 8　Char accumulated in bend section

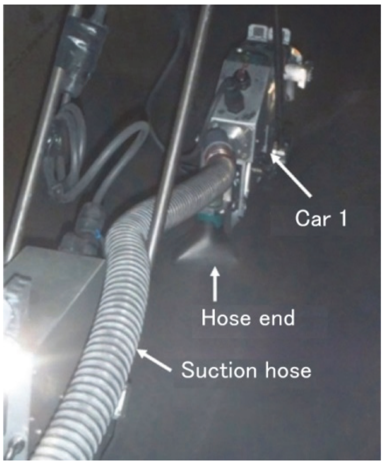

Figure 9　Suction of char

3.2.2　Inspection performance of robot

The robot performs visual inspection with a visual inspection camera mounted on car 1 shown in Figure 7. This camera can be turned in the circumferential direction of the pipe by a motor, and can visually inspect the entire circumference of the pipe even in bends where the robot body cannot turn in the circumferential direction. In addition to visual inspection by the camera, this robot has a function to quantitatively evaluate the inner surface shape of the pipe by using a laser and UT. **Figure 10** shows robot car 1 equipped with a laser device instead of the visual inspection camera. This device irradiates a ring-shaped laser beam in the radial direction of the pipe from the tip of the acrylic optical tube, and photographs it with a laser observation camera installed at the base of the tube. Furthermore, by processing the photographed images, the shape of the inner surface of the pipe can be quantified to the nearest 0.1 mm. This method makes it possible to quantitatively grasp the shape of the entire circumference of the pipe with a single measurement, which is effective for screening inspection of wall thinning [*2]. Next, **Figure 11** shows the robot equipped with a UT device. The UT device mounted on car 2 has a UT probe mounted on the tip of an air cylinder, and presses it against the inner surface of the pipe by extending and retracting the air cylinder to measure the wall thickness with ultrasonic. This UT probe uses a couplant-free probe, which enables wall thickness measurement without using a contact medium.

*2　Some areas inside bends, which are outside the range of the camera's angle of view, are not inspection-applicable with this device.

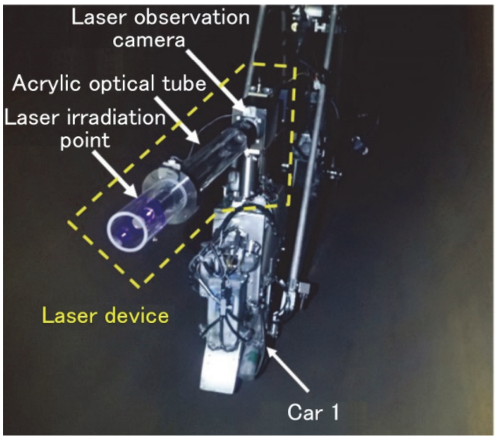

Figure 10 Laser device mounted on Car 1

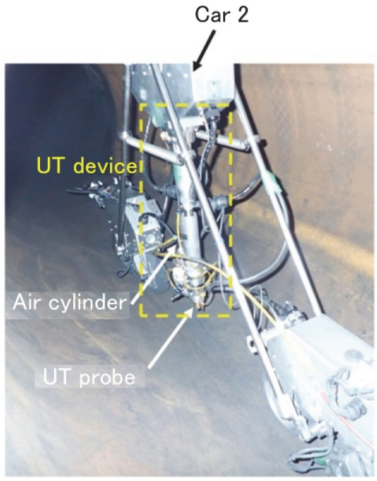

Figure 11 UT device mounted on Car 2

3.2.3 Performance verification test

We verified the traveling performance of the robot using an actual produced gas piping shown in **Figure 12** and a mock-up piping that simulates actual equipment. As a result, the robot inserted upward and downward from the opening shown in Figure 12 was able to travel the entire length of the actual produced gas piping (approximately 90 m).

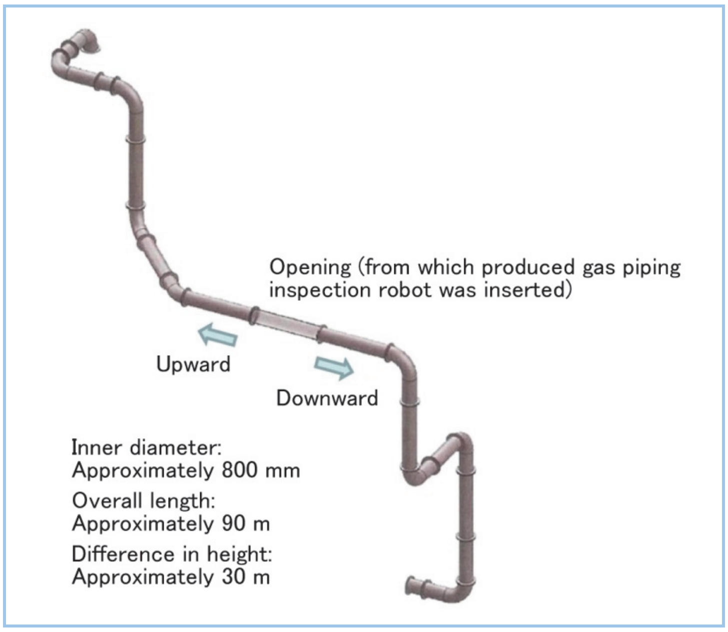

Figure 12 Produced gas piping used for verification with actual equipment

In addition, we verified whether the visual inspection camera mounted on car 1 could detect wall thinning in the actual produced gas piping. **Figure 13** shows an example of a wall thinning area captured by the camera. As can be seen from the figure, we confirmed that the visual inspection camera can detect wall thinning.

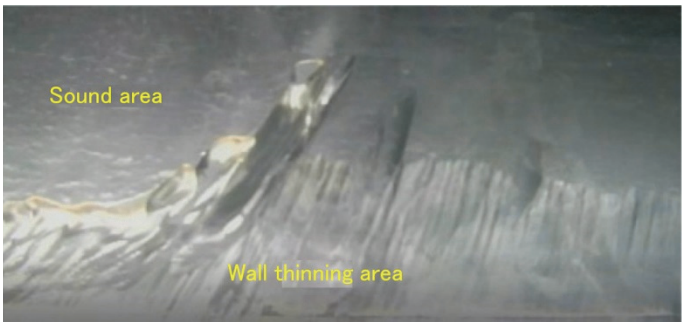

Figure 13 Wall thinning area detected by produced gas piping inspection robot

For the laser device, we performed a verification test using mock-up piping and compared the difference between the radius measured with this device and that measured with an inner micrometer. As a result, as shown in **Figure 14**, the difference between these measured values was less than ±1.4 mm. Also for the UT device, we performed a verification test using mock-up piping and compared the difference between the wall thickness measured with this device and that measured manually using a general UT device. As a result, as shown in **Figure 15**, the difference between these measured values was less than ±0.2 mm and it was confirmed that the robot was able to measure wall thickness with high accuracy. The robot is equipped with an encoder on the tire and able to record the positional information of the wall thinning points measured by the camera, laser device, and UT device, which allows for understanding of changes over time through fixed-point inspections.

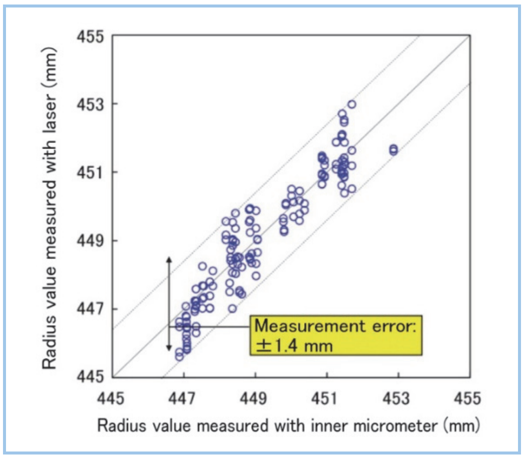

Figure 14 Laser measurement accuracy verification test result

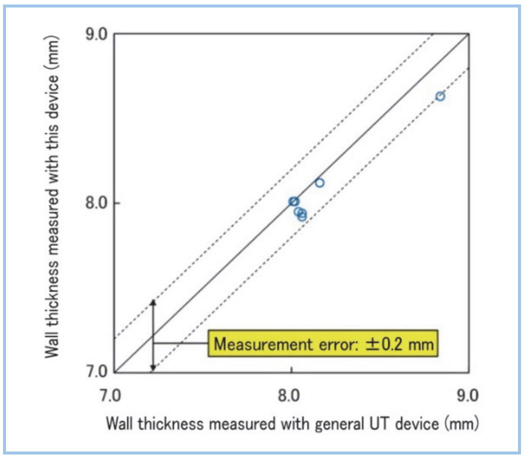

Figure 15 UT measurement accuracy verification test result

3.3 Services utilizing robot

The procedure for inspection of IGCC produced gas piping using the developed robot is shown below.

(1) Removal of char using the suction hose
(2) Screening of wall thinning using the visual inspection camera and laser device
(3) Measurement of wall thickness using the UT device

The above procedure enables thorough screening of wall thinning areas and safe grasping of liner wall thickness without needing human workers to enter the piping. In addition to general visual inspection, this robot can detect wall thinning quantitatively and thoroughly by laser measurement, thus contributing to the prevention of problems in produced gas piping. In addition, fixed-point inspection of the wall thickness of the piping with this robot makes it possible to predict the wall thinning rate. As a result, it is possible to predict when the next inspection and liner replacement should be performed, enabling planned equipment maintenance.

Furthermore, we estimated the effect of reducing the inspection period by using the robot (**Figure 16**), and found that using the robot can reduce the time required for additional work to prepare the opening, leading to a potential 10-day reduction in the overall inspection period, including the incidental work. In this way, the robot can also contribute to improving the plant operation rate.

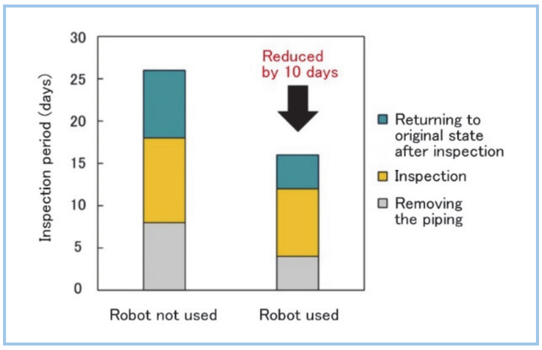

Figure 16 Effect brought by using produced gas piping inspection robot

4. Conclusion

This report presented two examples of service for our chemical plant by catalyst tube inspection robot (RIDe) and for the IGCC by piping inspection robot-based services. These original robots we developed can perform inspections of the outside and inside of piping, respectively, while traveling by themselves. They are equipped with ultrasonic sensors, and can evaluate and assess the wall thickness and inner diameter of pipes to diagnose the equipment conditions. Both of them contribute to the reduction of additional large-scale work such as erection of temporary scaffolding, and enable safe and quick inspection in high and confined spaces of plant facilities. In addition, the robots can perform full-length inspection of all piping, which has been difficult to do with human workers, enabling highly reliable life diagnosis and maintenance planning. These are condition diagnosis and maintenance services for piping equipment that utilize our robotics and ultrasonic testing technologies, as well as material life evaluation technologies and knowledge that we have accumulated over many years as a plant manufacturer. We will continue to apply these services to actual equipment in order for their further advancement and expansion of the application scope, and to provide our customers with added value such as shortening of regular inspection periods, reduction of plant maintenance costs, and improvement of operating rates.

References

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(2) Matsumoto et. al, Advanced Technology for Large Scale Methanol Plant, Mitsubishi Heavy Industries Technical Review, Vol.33 No.5 (1996) p.318~321