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Innovation of Fog Emulation Technology: Reproduction of Fog Environment by Testing and Verification System for Autonomous Vehicles

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Autonomous driving systems are being vigorously developed worldwide and are expected to exhibit dramatic improvements in capability and widespread adoption in the future. To guarantee their safety and robustness, it is necessary to verify that sensors and systems function normally under diverse natural environments (fog, rain, light, snow, etc.). Anticipating the growing need for such verification, Mitsubishi Heavy Industries Machinery Systems, Ltd. is developing "Adverse Weather Automated-driving Research Environment" as an evaluation system for autonomous mobility. This report describes a control system and method for fog emulation technology, for which achieving and maintaining a uniform environment is highly challenging. Through a simple approach, the system can generate and maintain any visibility from 10 to 200 m with an accuracy of ±10-15%.

1. Introduction

In nature, fog environments occur when moisture-laden air reaches saturation, such as when it is cooled. When fog forms, fine water particles obstruct the view, leading to a reduction in visibility. Fog concentration (the amount of moisture in the air) and visibility have an inverse relationship, and an approximation formula (hereinafter referred to as the visibility conversion formula) has been proposed [(1)].

There are various types of fog emulation devices. A method that humidifies outside air introduced into a test chamber using a steam boiler requires a large amount of energy to generate fog, and has difficulty in forming a uniform fog within the chamber. As another method, there are systems that generate and maintain fog by cooling pre-humidified air with air conditioning equipment; however, as the test chamber becomes larger, these systems require higher-capacity air conditioning units accordingly. Meanwhile, simple methods for generating fog include nozzle-based spraying systems. These systems commonly use two-fluid nozzles that use compressed air to atomize fog particles. Since fog generated by two-fluid nozzles can achieve a mean droplet diameter of 10 μm or less, it has a low sedimentation velocity and remains suspended in the space for a long time; consequently, controlling visibility requires intermittent spraying through on-off control. However, such systems are easily affected by the external environment (temperature and humidity), and the time constant of visibility change in response to nozzle spraying is large, making it difficult to generate and maintain the specified conditions required as a testing device through feedback control. Thus, fog emulation test devices are required to create a fog environment at low cost without complicating the configuration, while also controlling for uniform visibility.

This report introduces a control system and method developed by Mitsubishi Heavy Industries Machinery Systems, Ltd. to solve the aforementioned issues, which can stably generate and maintain a fog environment with a desired visibility through a simple configuration.

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2. Fog environment emulation system

The developed fog formation and visibility control system (**Figure 1**) consists of fluid nozzles, solenoid valves for spray pattern commands, a control processor, temperature and humidity sensors, a visibility meter, and an operation unit; the control results are monitored by the visibility meter within the test chamber. As shown in **Figure 2**, the test space has a non-sealed structure that allows the inflow and outflow of air. The system calculates the amount of air leaking to the outside and the amount of moisture consumed to bring the air flowing in from the outside with less than 100% humidity to 100% humidity. Using these processing results as boundary conditions, the spray flow rate and spray pattern of the nozzles are determined so that the visibility within the space reaches the target value.

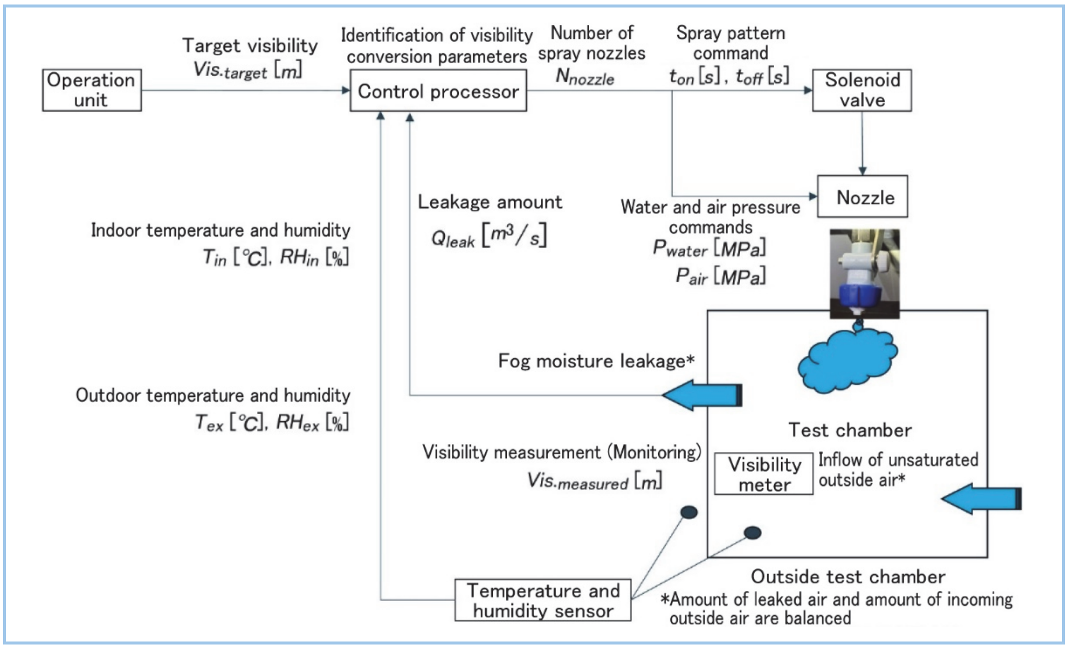

Figure 1 Fog generation and visibility control system
Block diagram of system components (including input/output data)

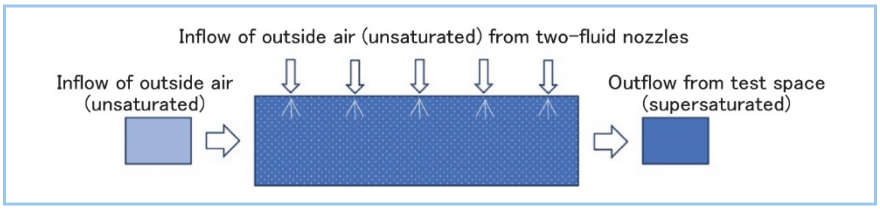

Figure 2 Inflow of outside air and outflow of fog in test space
Reduction of fog moisture due to inflow and outflow of air with different humidity levels

3. Control method

One of the general methods for controlling concentration, temperature, and humidity is feedback control, which operates based on the deviation from a target value. In contrast, the method applied in this study (hereinafter referred to as the developed control method) is feedforward control of fog visibility (more accurately, concentration) based on a mathematical physical model. **Figure 3** shows the specific control procedure. Based on the target visibility, the number of spray nozzles N_{nozzle}, the water pressure loaded on the nozzles P_{water}, the air pressure P_{air}, and the spray pattern (spray time t_{on}, stop time t_{off}) are determined. A correspondence table between the time-averaged spray flow rate m_{nozzle} and the fog concentration C in the space is created based on these physical quantities, and visibility is feedforward-controlled via the visibility conversion formula. Therefore, the visibility meter is used only for monitoring measured values. Note that to calculate the fog concentration in the test chamber, the fog concentration outside the test chamber C_{ex} is required. C_{ex} is estimated from the outdoor temperature, humidity, and the leakage air volume Q_{leak}. There are several methods for estimating the leakage amount, such as estimating it from the change in visibility meter readings over a certain period, calculating it from the amount of air leaking into the atmosphere based on the measurement of the internal-external pressure difference using a nozzle with a throttle mechanism installed from the test space toward the outside (open air), or introducing outside air using a blower with a known airflow rate.

In addition, to control the visibility Vis using the developed control method, calibration is required to identify the parameter α of the visibility conversion formula before the test. At that time, the required mean particle diameter of fog particles D_p is determined by the water and air pressure of the nozzle; therefore, manufacturer specifications or pre-measured values are used.

Furthermore, since the developed control method uses point mass (zero-order) approximation of the space, spatial variations in visibility cannot be controlled. Therefore, to achieve uniform concentration (visibility) in a large space, it is also necessary to consider the arrangement and spray direction of the nozzles, as well as the inlet/outlet (ventilation positions) for leaked air. Additionally, as the diameter of the generated fog particles increases, the effect of concentration reduction due to sedimentation on the floor surface becomes more significant. Particularly under conditions where no airflow is generated in the space, the effect of natural sedimentation becomes prominent. As such, adopting a spray pattern with a short intermittent cycle is effective since its short stop time mitigates the impact on concentration.

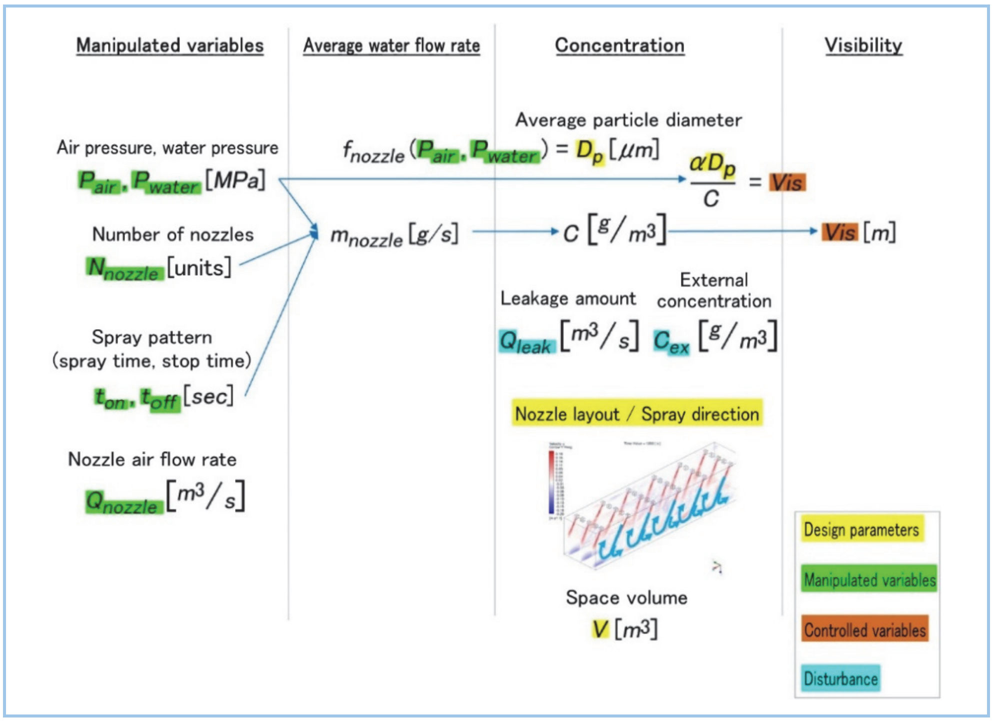

Figure 3 Fog visibility control procedure
Diagram of physical quantity input/output relationship

4. Verification results

This chapter shows the results of verifying the effectiveness of the developed control method by comparing simulation results based on this method with actual measurements in two cases: a small space and a large space.

4.1 Verification using vinyl tent

The following shows the results of verification using a highly airtight vinyl tent (**Figure 4**, 9 m^3 in volume). The vinyl tent has opening/closing systems at the entrance and the top; each was partially opened, and a blower was installed at the entrance, while a fog nozzle was placed in the center of the interior. While the blower introduced outside air, the nozzle was operated with intermittent spraying. Thus, the temporal change in visibility within the tent was measured. **Figure 5** shows the results of feedforward control using the spray stop time as the manipulated variable, with the spray flow rate and the duration of a single spray (10 seconds) fixed. It can be confirmed that as the stop time (on the horizontal axis) increases, the fog concentration becomes lower, and the visibility (on the vertical axis, as a 3-minute time-average value) increases. Comparing the results of the test (orange) with the pre-simulation using the developed control method (gray), for example, under the condition of a 50-second stop time, the difference between the measured value and the target value is -4%. For all other stop times, the differences are 10% or less, confirming the effectiveness of the developed control method in a small space. Note that the reason the visibility in the test results for the 79-second stop time alone is higher than the simulation is thought to be that the concentration in the space became lower than the simulation due to the effect of particle sedimentation caused by the long stop time. Although the spray time was fixed at 10 seconds in these cases, the deviation between the simulation and the test can be improved even under low fog concentration conditions by changing the spray pattern to a shorter cycle while maintaining the duty ratio.

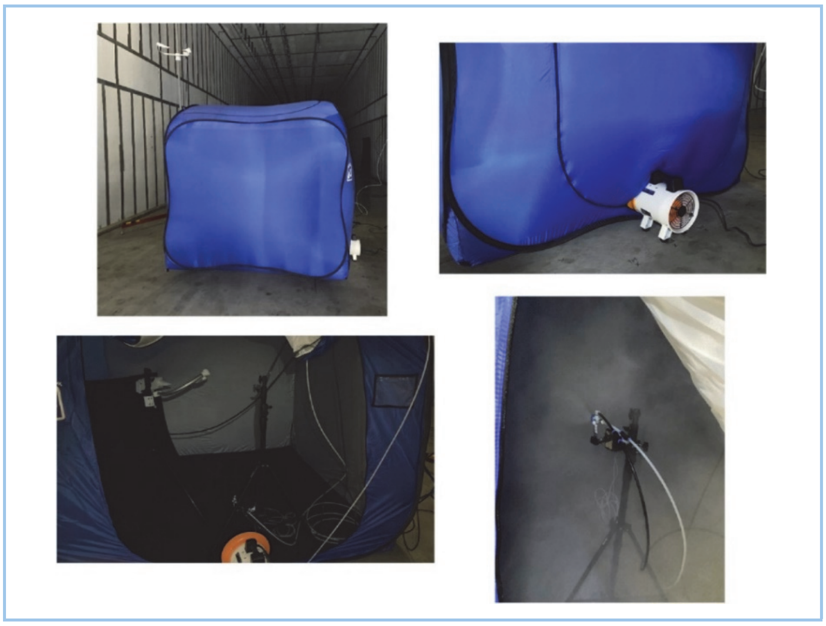

Figure 4 Vinyl tent
Tent used to verify effectiveness of developed control method and equipment layout

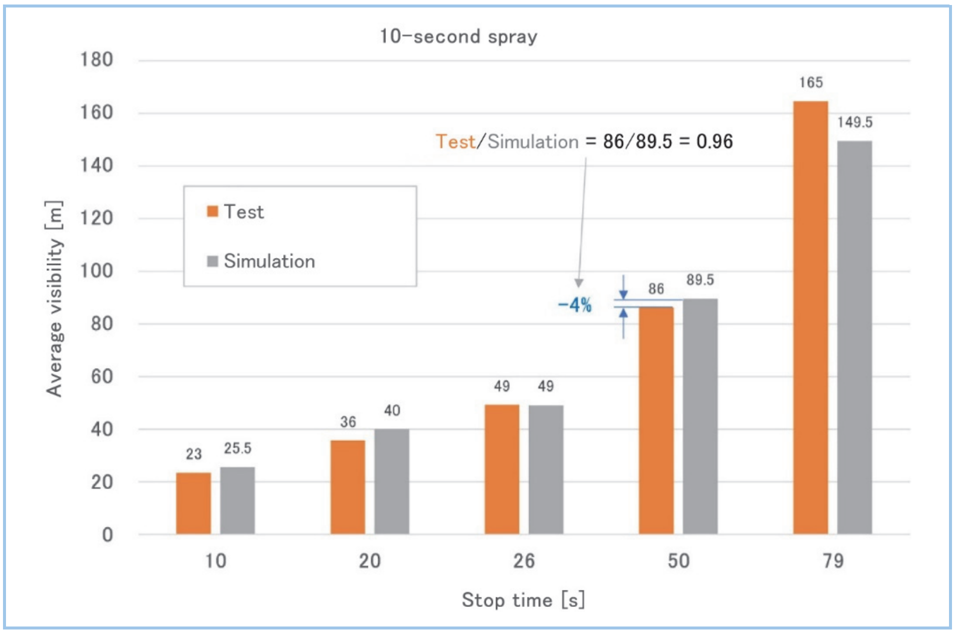

Figure 5 Comparison of spray stop time and time-averaged visibility
Verification results of fog visibility control in vinyl tent

4.2 Verification in large space

To evaluate the effectiveness of the developed control method in a large space, verification was conducted using a demonstration test facility (**Figure 6**). This facility has a test area with a width of 7.5 m, a height of 7 m, and a length of 48 m (the fog test area is 35 m), which has a volume 200 times larger than that of the aforementioned tent.

Figure 7 shows a testing situation in which multiple nozzles arranged on the ceiling of the fog area are spraying. In this facility, by knowing the outdoor temperature, humidity, and leakage amount in advance, it is possible to emulate a fog environment in a large space (approximately 1,800 m^3) without operating boilers or cooling equipment for humidified air. Furthermore, the water volume per nozzle is approximately 1.5 L/h; even with all nozzles spraying continuously, the water consumption per hour would only be about 45 L/h.

Figure 8 shows the results of intermittent spraying corresponding to target visibilities of 185 m, 75 m, and 40 m. The table in the center of the figure shows the average values for 10 minutes after reaching a steady state at a total of nine locations: three horizontal positions (the left side (★), the center (●), and near the wall (▲) of the area) and three vertical positions (upper: 5.5 m, middle: 3.5 m, lower: 1.5 m). For example, for the target visibility of 185 m, the spatial average of the nine points is 189 m, with a standard deviation of 27 m. The graphs on the right side of the figure show the changes in visibility over time; the red line represents the simulation results using the developed control method, and the green line represents the average visibility of the nine points at each moment. Since the simulation shown by the red line approximates the interior as a single point, the visibility drops immediately after spraying starts and gradually rises during the stop time due to leakage to the outside. The shorter the target visibility, the shorter the stop time, resulting in smaller steps in the graph. Meanwhile, the measured average values shown by the green line experience a delay in the visibility drop compared to the red line by the time required for fog advection, as the nozzles and measurement positions are separated. Additionally, a temporary rise in visibility is observed until stabilization (up to 10 minutes) due to airflow. After stabilization (from 20 minutes onwards), despite the wide range of target visibilities (40, 75, and 185 m), both the simulation and actual measurements remain within the set target values and show no fluctuations.

As a result of verifying spray patterns for other visibilities, it was confirmed that this facility can emulate any given visibility from 10 to 200 m with an accuracy of ±10-15% within approximately 20 minutes from the start of the test and maintain it.

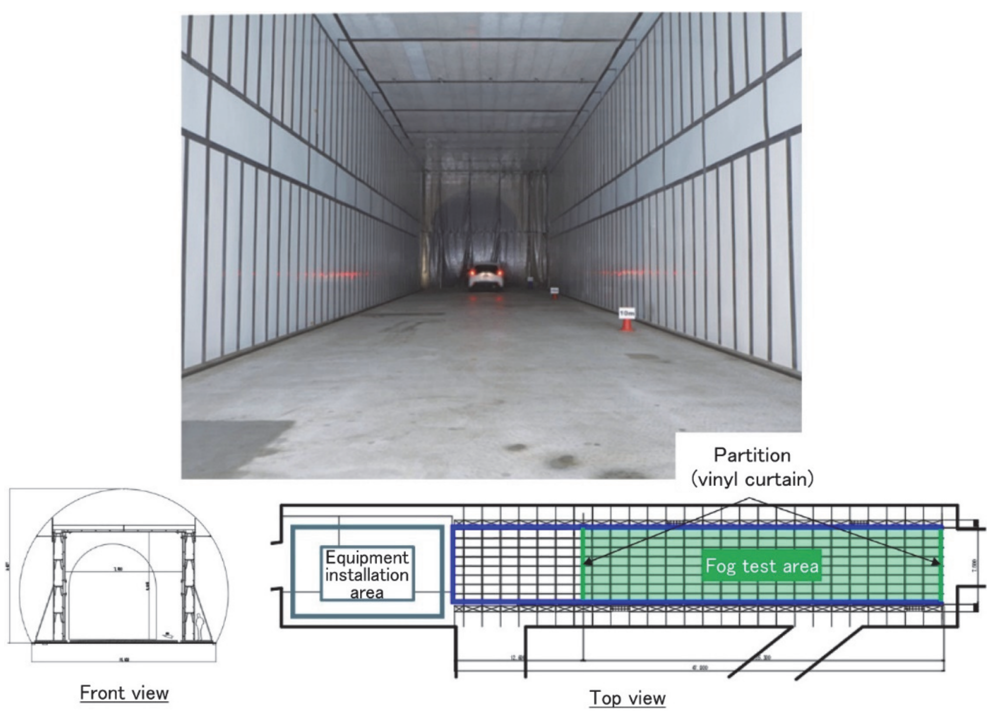

Figure 6 Demonstration test facility (Top: External photo, Bottom: Schematic diagram)
Demonstration test facility used to verify developed control method

Figure 7　Fog emulation in demonstration test facility
Testing situation in which fog is generated within demonstration test facility

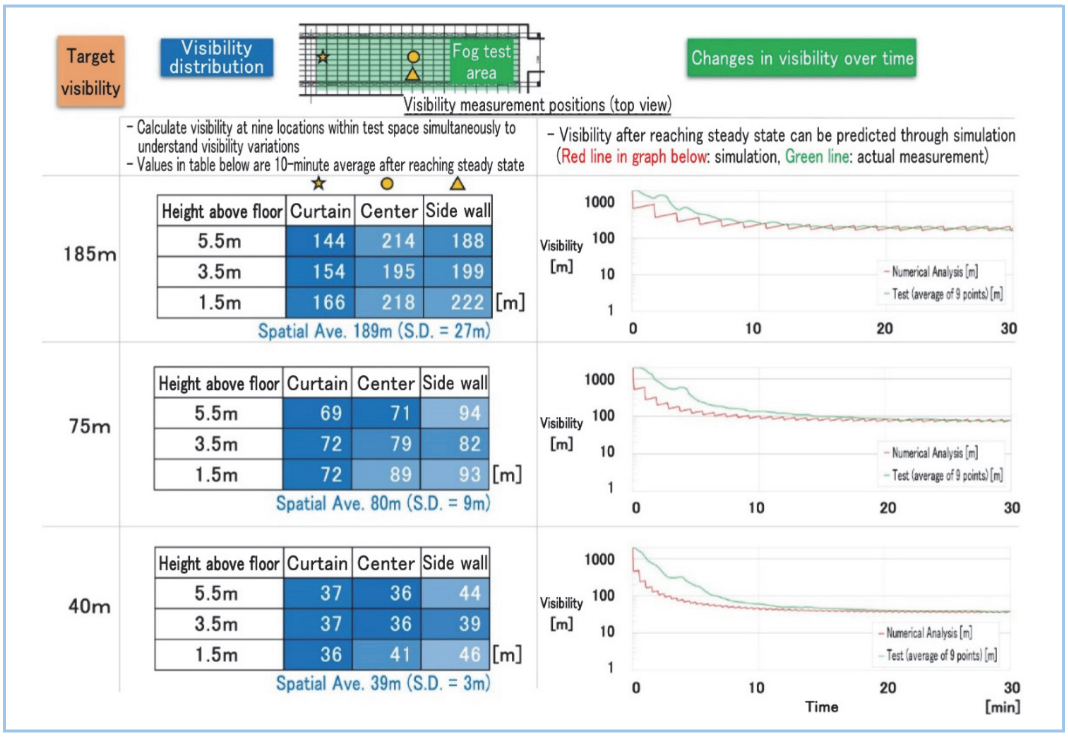

Figure 8　Spatial distribution of visibility (left) and changes over time (right)
Verification results of fog visibility control in demonstration test facility

5. Conclusion

Among environmental emulations, fog emulation requires a significant amount of time to reach specified conditions, and for that emulation, achieving and maintaining a uniform environment is highly challenging. This report described a control system and method capable of generating and maintaining fog through a simple approach that does not require boilers or cooling equipment for humidified air. Since indoor vehicle driving tests require large spaces, the developed control method, being a simple approach, is particularly effective. However, because the demonstration test facility has a temporary simple structure using vinyl curtains at the boundaries in the longitudinal direction, it was sometimes difficult to control visibility between 50 and 200 m under conditions where the effects of outdoor temperature, humidity, and wind were significant. Therefore, to cope with large disturbances, it is necessary to consider the building structure (hardware) in addition to the developed control method (software).

Adverse Weather Automated-driving Research Environment using the developed control method is primarily intended for safety and reliability evaluation tests of autonomous driving systems. However, the various sensors used in autonomous driving (LiDAR, cameras, radar, etc.) are also widely used in other industries. Therefore, it is believed that the developed technology can also be broadly applied to the evaluation tests of perception functions for various products, including other types of autonomous mobility that utilize these sensors.

References

(1) K Inoue, Meteorological properties of Sea Fog Induced by Yamase, Journal of The Meteorological Society of Japan "TENKI", Vol.39, No.8 (1992) (in Japanese)