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An evaluation of the range-gated-imaging technology under dense aerosol environments

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A B S T R A C T

Range-gated-imaging system, which can be used to eliminate backscatter in strong scattering environments, is based on two high speed technologies. It uses high power, ultra-short pulse laser as the light source. And it opens the optical gate of an ICCD camera with a micro-channel-plate image intensifier in a very short time while the laser pulses reflected by the object is coming back to the ICCD camera. Using this range-gated-imaging technology, the effect of scattered light can be reduced and a clear image is obtained.

In this paper, the test results of the range-gated-imaging system under dense aerosol environments, which simulates environments in the reactor containment building when the severe accident of the nuclear power plant occurred, are described. To evaluate the observation performance of the range-gated-imaging system under such dense fog environment, we made a test facility. Fog particles are sprayed into the test facility until fog concentration is reached to the postulated concentration level of the severe accident of the nuclear power plant. At such dense fog concentration conditions, we compared and evaluated the observation performances of the range-gated-imaging system and the CCD camera.

1. Introduction

When there is a severe accident at a nuclear power plant, such as a LOCA (loss-of-coolant accident) or reactor core meltdown (meltdown of nuclear fuel loaded in the reactor pressure vessel), defined as a design basis accident, the visibility inside the reactor containment building falls sharply due to the mass leaking of a reactor coolant (high temperature/high pressure steam over 250 °C). The fresh water (or sea water) being sprayed from the core spray system to cool the reactor core is vaporized into hot steam when it hits high-temperature (surface temperature of about 250 °C or higher) structures, such as the reactor pressure vessel protecting the reactor core. As the vaporized high-temperature steam is cooling, it generates aerosol, and the visibility inside the reactor containment building becomes bad due to this aerosol (fog). According to test data in cases of severe accidents, the diameters of aerosol particles are in the range of 0.1 μm –5.0 μm (±2 μm on average), aerosol concentration at 300 s elapse after occurrence of the accident is approximately 500 mg/m^3, and the maximum aerosol concentration inside containment vessels is 5 g/m^3 [1–3]. Based on the above mentioned test data, the observation environment inside the reactor containment building in the case of a severe accident of the nuclear power plant is greatly limited by scattering aerosol particles that have an average diameter of about 2.0 μm [4], and the visibility is calculated as 4.0 m – 0.4 m when aerosol concentration is 0.5 g/m^3–5 g/m^3 [5].

In April and October 2015, robots, loaded with LED lamps and colour CCD cameras, investigated the surroundings of the PCV (primary containment vessels) in Unit 1 and Unit 3 reactor buildings of the Fukushima Daiichi Nuclear Power Plant [6,7]. These inspection videos, taken by the robots, demonstrate that it is difficult to observe the surroundings in some areas due to high-temperature steam. At the end of January 2017, the surroundings of the pedestal (supporting structure for the reactor pressure vessel) inside the PCV of Fukushima Daiichi Nuclear Power Plant Unit 2 reactor building were investigated using a guide pipe equipped with LED lamps and pan/tilt camera [8]. In this investigation video, as in the inspection videos of the PCV surroundings in the Unit 1 and Unit 3 reactor buildings, it was similarly difficult to identify the surroundings in some areas due to high-temperature steam. This was because the cooling water, which was poured to prevent re-criticality of the high-temperature fuel debris that presumably reside at the bottom of both the reactor pressure vessel and the PCV and to manage the cold shutdown, which maintains the temperature of the molten

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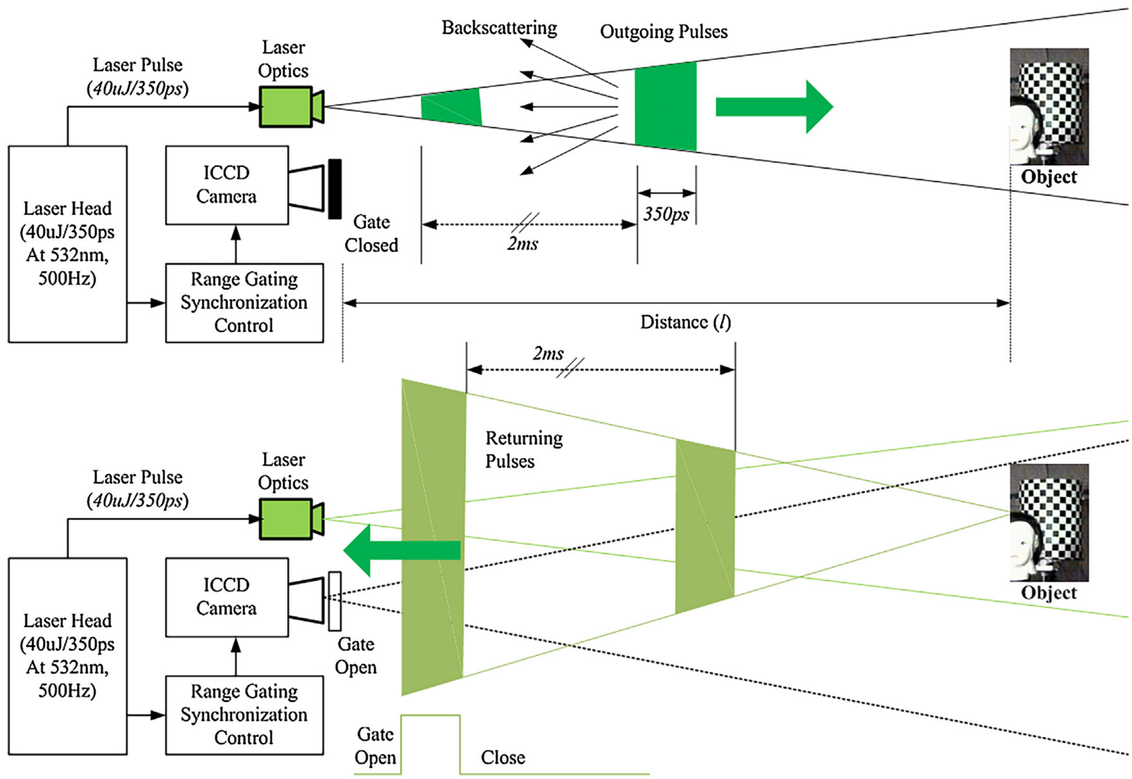

Fig. 1. Operation principle of the range-gated-imaging system.

reactor core below 100 °C, was vaporized into high-temperature steam by colliding with the hot fuel debris in meltdown state, and the steam obstructed the CCD camera's monitoring performance.

We reviewed the range-gated-imaging (RGI) technology as a way to overcome the limit of CCD camera observation performance in the dense aerosol environments generated inside a reactor containment building after a severe accident such as loss-of-coolant accident. In the RGI technology, an ultra-short pulse laser beam is irradiated to the object to be observed, and the images are obtained by opening the gate (shutter) of the ICCD (intensified CCD) camera at the instant the laser beam reflected from the object reaches the camera [9–11]. This allows us to obtain high-resolution observation images because it is influenced very little by scattering and diffuse reflectance caused by aerosol particles (fog or floating matter) in the space between the RGI observation system and the object [12,13].

In this paper, the observation characteristics of the RGI system were evaluated in a dense aerosol environment simulating a severe accident of the nuclear power plant, and the results are described. To simulate the dense aerosol environment due to the generation of aerosols in a severe accident, a test facility with width of 2.5 m, height of 2.5 m, and length of 15 m was set up. After fog particles were sprayed into the test facility, and the observation performances of colour CCD camera and the RGI system were compared and evaluated in the same fog concentration conditions.

2. Range gated imaging

As shown in Fig. 1, the laser module generates an ultra-short high-power laser pulse (40 μJ/350 ps) with a wavelength of 532 nm at a repetition rate of 500 Hz [14]. The ultra-short laser pulse of 350 ps reflects off the object and returns to the ICCD camera that has an electronic circuit for shutter (gate) control. The electronic circuit, which is controlling the shutter of the ICCD camera, opens the shutter synchronizing with the front (rising) part of the width of the laser pulse that is reflected back from the object and closes the shutter synchronizing with the trailing (falling) part of the width of the laser pulse, and the ICCD camera obtains observation images of objects only within the range of the gate on/off pulse width time slot. For example, if the shutter on/off pulse width of the ICCD camera is 200 ps and the velocity of the light transmission is taken into account, the image acquisition range may be calculated as approximately 3 cm.

$$R_{im} = \left(c \times \Delta\tau_g\right)/2 \quad (1)$$

In Eq. (1), R_{im} is the imaging range of the RGI system, c is the velocity of the light in the air, $\Delta\tau_g$ is the gate on/off pulse width of the ICCD camera. Images reflected back from an object located at a farther distance, which is a point after the shutter is closed, and images reflected back from an object located at a closer distance, which is before the shutter is opened, are not visible. As shown in Fig. 1, if the distance between the ICCD camera and the object is l, then the round-trip distance of the laser pulse is $2l$. The travel time of the laser pulse τ_l is expressed as Eq. (2).

$$\tau_l = 2l/c \quad (2)$$

To observe objects located at distance l, the shutter of the ICCD camera in the RGI system needs to be opened after τ_{on} as expressed in (3) and closed after τ_{off} as expressed in (4). The shutter open/close time span $\Delta\tau_g$ of the ICCD camera is variable depending on the volume of the object.

$$\tau_{on} = \tau_l \quad (3)$$

$$\tau_{off} = \tau_l + \Delta\tau_g \quad (4)$$

$$\Delta\tau_g = \left|\tau_{on} - \tau_{off}\right| \quad (5)$$

According to the literatures on the PCV surrounding inspections described in Refs. [6] and [7], the small robot system, which investigated the surroundings of the PCV in units 1 and 3 reactor buildings of the Fukushima Daiichi nuclear power plant, used 4 LED lamps