Thermal Transient Analysis of the Railway Brake Disc using the High-Speed Camera

Min-Soo Kim

***Abstract*—**When the friction braking is applied, high temperatures transition can be occurred in the brake disc from inside high thermal to outside in contact with the friction material. The evaluation technology of brake performance and thermal effects in braking has been generally developed with technology of speed improvement of railway vehicles. Particularly brake system of railway vehicles has a crucial role for the safety as well as riding quality of passengers. Brake dynamometer is designed to simulate the brake characteristic of the high speed train, analyze the experimental object, and also is used to develop and test the brake systems including brake parts.

In this paper, we tried to analyze the temperature transition and/or pressure distributions of the brake disc surface during braking using the high-speed brake dynamometer and the high-speed camera with lighting system. Based on information from the acquisition images, we analyzed thermal images in a moment at the same position hourly. The highlight region in thermal image of the disc surface indicates the high temperature. Therefore we could find temperature transition or thermal characteristic of the disc surface. That is, the scattered distribution of thermal moves gradually to a point and be destroyed after that. The results also indicated that the formation and extinction area of hot spot of the disc surface was same region. And these research results will be introduced by means of a braking performance test evaluation technology as well as brake parts development on braking system of the railway vehicles.

***Keywords*—**High-Speed Camera, Thermal Transition Analysis, Brake Dynamometer, Railway Vehicle, Brake Disc

I. Introduction

BRAKE system of railway vehicles has a crucial role for the safety as well as riding quality of passengers[1]-[3]. And the technology of braking performance evaluation and surface temperature dissipation has been generally developed with technology of speed improvement of railway vehicle. Nowadays, technology of the test and evaluation from single braking parts to running testing of integration performance is systematically established[4]-[21].

The brake test evaluation techniques have accumulated with full scaled dynamometer that its level is below 200[km/h] in the performance testing fields of friction materials, KRS (Korean Railway Standards) presents about instantaneous and/or average coefficient of friction, amount of wear, and so on.

Dynamometer is a device for measuring the braking torque, the contact force, or power available from a rotating shaft. The shaft speed is measured with a tachometer, while the instantaneous tangential force based on the wheel radius is measured with contact or noncontact measurement. Variations of this dynamometer are still in use today. Brake dynamometer is designed to simulate the brake characteristic of the high speed train, and has a function of record the data which can be reproduced and help to analyze and compare the experimental object, and also is used to develop and test the brake system.

Recently, high-speed braking performance tester, which is top speed 400 [km/h]-grade is introduced. And then it became able to perform the test of developed braking parts in KRRI (Korea Railroad Research Institute). Therefore we tried to test braking friction materials (disc brake and block brake) for the high speed rotation which is in a current use commercially, and its results will be introduced by means of arranging of a braking performance test evaluation technology on braking friction materials of railway vehicle using the high speed dynamometer (400(km/h)-grade).

In this paper, we tried to analyze the thermal transit characteristic of the brake disc using the high-speed camera for the high speed rotation which is in a current use commercially, and its results will be introduced by means of a braking performance test evaluation technology including thermal effects analysis on the brake system of the railway vehicles using the high-speed camera.

This paper is organized as follows. Section 2 overviews a brake dynamometer and the experiment environment for the disc brake. Section 3 shows the thermal transient experiment results in various braking speed condition when the disc brake is applied using the high-speed camera. The main conclusions are then summarized in section 4.

II. Overviews of the Brake Performance Tester

A. Brake dynamometer

A dynamometer consists of the drive-train parts and the test bed part as follows:

-The drive-train consists of the following elements: drive motor, interchangeable flywheels and brake disc. The flywheels and brake disc is matched to the parts number to be tested.

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-The test bed consist of the following elements: caliper & adapter, power transfer axle, load bearing arm and load cell to calculate the breaking force.

In general, brake dynamometer is designed to simulate the brake characteristic of the high speed train, and has a function of record the data which can be reproduced and help to analyze and compare the experimental object, and also is used to test the brake system.

The expected effects and practical scheme of the brake dynamometer are as follows:

-Development of the brake, disc-pad, wheel and brake system of the high-speed & conventional train

-Test and performance evaluation of the brake system of the high-speed & conventional train with the international standard

-Performance and certification test of the brake parts of the manufactured high speed train.

Table I shows the main features of the brake dynamometer.

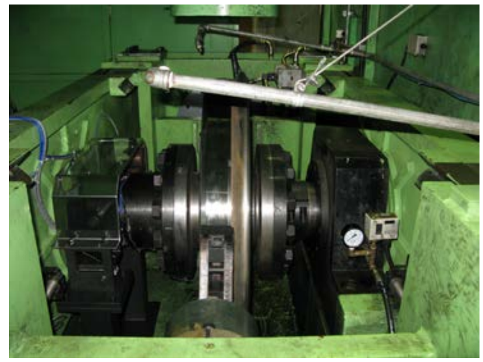
Table I main features of the brake dynamometer

Max. drive power	397(kW), 540(HP)
Max. drive torque	2,527(Nm)
Max. drive speed	2,500(r.p.m), 400(km/h)
Max. brake torque	25,000(Nm)
Pressure Brake	6,000 (N) x 2
Flywheel Inertia	Max./Min. 1900(kg•m²)/400(kg•m²)
Diameter of the test wheel	Φ700~1120(mm)
Acceleration time	[0~1500(r.p.m)] 2 (min.) 30 (sec)

Fig. 1 shows the brake performance dynamometer for the high speed train.

(a) drive motor and inertia parts of the brake dynamometer

(b) disc brake parts of the brake dynamometer



(b) block brake parts of the brake dynamometer

Fig.1 brake performance tester for the high speed train

B. *Disc brake test*

This experiment is as a test for the brake disc pads, refers to a test to assess the safety by verifying the performance of the brake pad tests were conducted with reference to UIC specification (UIC541-3 “Brakes-Disc brakes and their application-General conditions for the approval of brake pads”)[23], braking pad is applied to the current KTX as the pad and the shape of the pad is shown in the Fig. 2.

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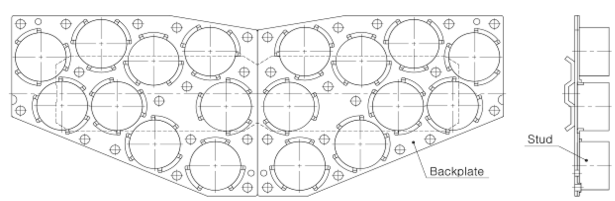


Fig.2 the shape of the brake pad for the disc brake [23]

Material is composed of sintered metal, heat capacity and thermal conductivity is respectively 600 (J kg ℃), 25 (W m ℃).

The test for measuring the friction coefficient was carried out with reference to UIC 541-3 provisions, tests were conducted after obtaining at least 85% contact area of braking pad through adequate pre-test (bedding) prior to the main test. The test was performed in braking initial temperature as 60 (°C) [23].

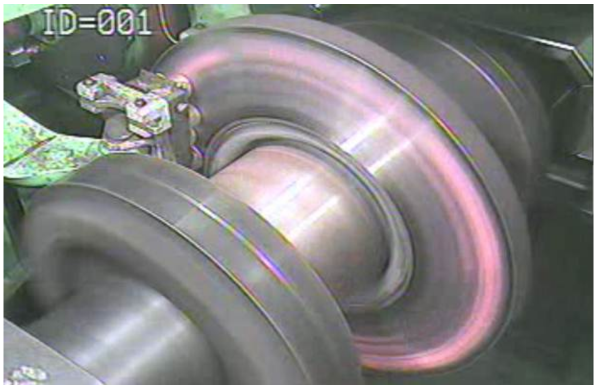


Fig.3 a sample disc surface of high temperature observed when the brake system is applied

We executed the braking test in accordance with an initial speed in 320(km/h) in order to analyze the thermal transition characteristics during the high-speed disc braking. Contact force in 22.5(kN) for the braking cylinder is used during the braking test.

The actual braking tests look like this Fig. 3, thermal band in the disc surface is formed like this figure and the surface morphology of speculated as the formation of hot spots was observed after braking stopping.

III. Experimental Results

A. Experimental Environments

The experiment devices for collecting thermal images using the high-speed camera are shown in the Fig. 4. The device is made up of three parts: the brake disc, the light systems, and the high speed camera systems.

(a) experiment device is made up of three parts: the brake disc, the light systems, and the high speed camera

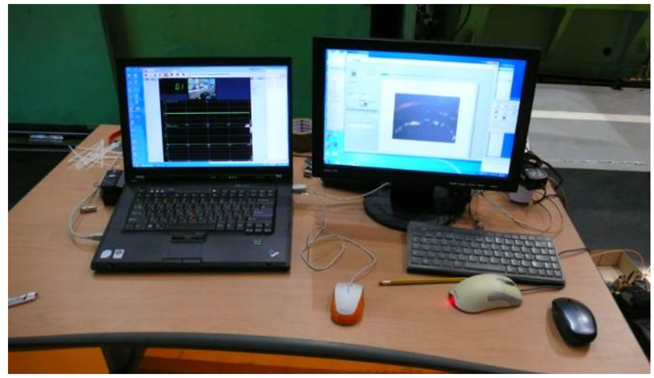

(b) data acquisition and monitoring device
Fig.4 experimental environment for collecting thermal images

Table II shows the main specification of the high-speed camera applied to braking experiment

Table II main features of the brake dynamometer

Model	Basler A504KC
Resolution	1280×1024
Sensor Type	Progressive Scan CMOS (Color)
Pixel Size	12×12(μm)
Frame Rate at Full Resolution	500 (frame/s)
Output Type	Camera Link (Full)
Synchronization	External Trigger or Free Run
Housing Size	41.5×190×190(mm)

Fig. 5 shows the high speed camera for analyzing the temperature transition of the disc surface when it applied the braking stop at initial speed 320[km/h].


Fig.5 the high speed camera for analyzing the temperature transition of the disc surface

B. Disc brake test results

The actual braking test results for issuing the certifications are shown in the Fig. 6. As the velocity curve in Fig. 6 indicates, due to the use of the encoder 1024(pole), speed output at the high-speed rotation region is affected by the vibration noise. It seems the output waveform is distorted by mutually influence. Therefore, in order to remove the effects of noise, the number of encoder's pole should be reduced about 360(pole) and noise shielding devices should be installed.

The process of braking at the initial speed 320(km/h) to stop are shown in Fig. 6. Measured instantaneous coefficient of friction, braking torque at that time, braking force (i.e. 22.5 (kN)), and the temperature of the disc surface are shown in Fig. 6. The results obtained were the maximum surface temperature 451.3(°C) and the average coefficient of friction 0.374.

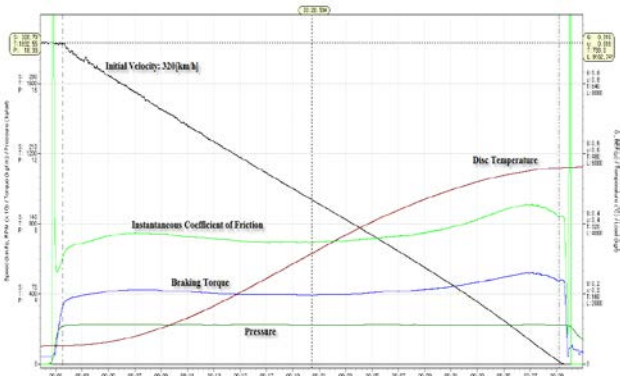


Fig. 6 brake disc test results in initial speed braking 320(km/h) with the contact force 22.5(kN)

The instantaneous coefficient of friction, which μ_a is determined in any instant of the braking by the ratio of total braking force F_t to total contact force F_b, is calculated as

$$\mu_a = \frac{F_t}{F_b} \tag{1}$$

And the average coefficient of friction μ_m, which is determined by integrating the instantaneous coefficient of friction μ_a from reaching 95% of the nominal contact force F_B over the braking distance S_2 [23].

$$\mu_m = \frac{1}{S_2}\int_0^{s_2} \mu_a ds \tag{2}$$

Fig. 7 shows the calculation method of the instantaneous coefficient of friction and the average coefficient of friction during braking time. v_1 means the speed at the beginning of the increase in force of F_b and v_2 denotes the speed at the time at which $F_b = 0.95 \cdot F_B$, where F_B represents the total nominal contact force per disc or per wheel.

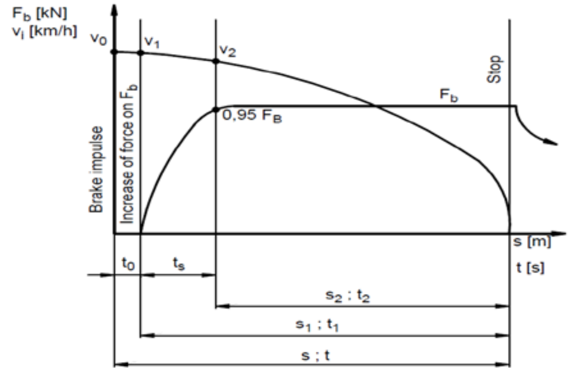
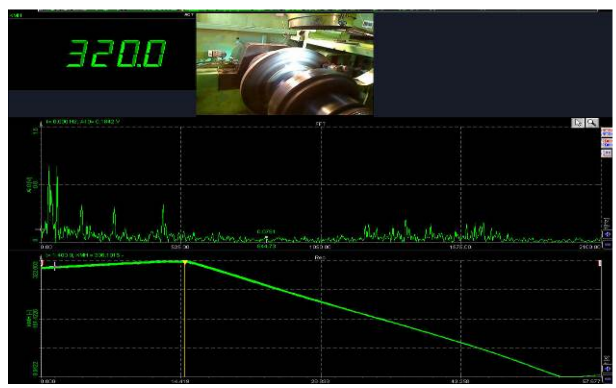
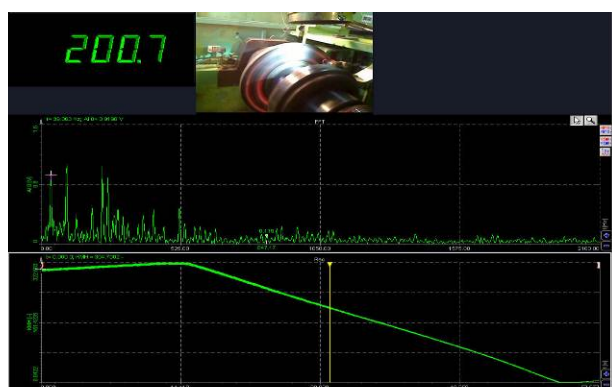


Fig.7 calculation of the instantaneous coefficient of friction and the average coefficient of friction

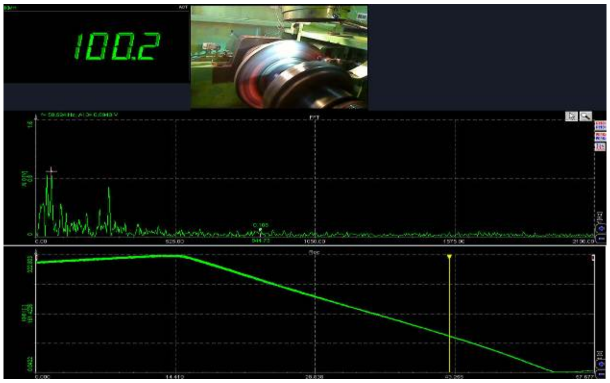
For the thermal transient analysis of this phenomenon during braking in the initial speed in 320(km/h), the following DAQ data which are speed, brake noise, and its frequency analysis are acquired. The signals for analyzing the brake sound of the disc brake using a high performance microphone is measured, and the frequency analysis is performed. Sample data collected from DAQ at the speed point which is 320(km/h), 200(km/h), 100(km/h), and 0(km/h), respectively, is appear in Fig. 8.



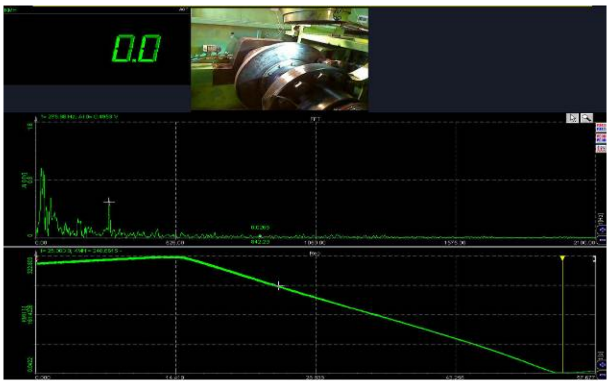
(a) DAQ data in braking velocity 320(km/h)



(b) DAQ data in braking velocity 200(km/h)



(c) DAQ data in braking velocity 100(km/h)



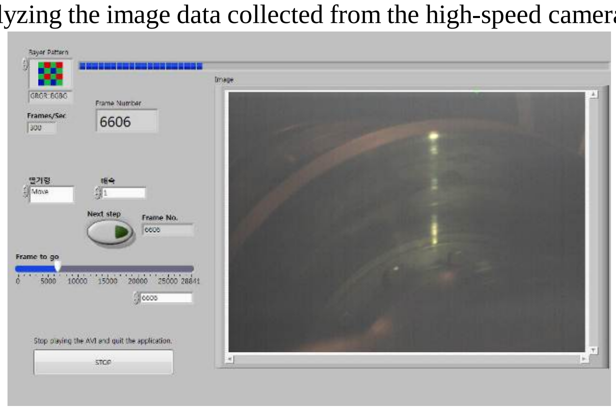
(d) DAQ data in braking velocity 0(km/h)

Fig. 8 DAQ data: speed, braking image, and its frequency analysis

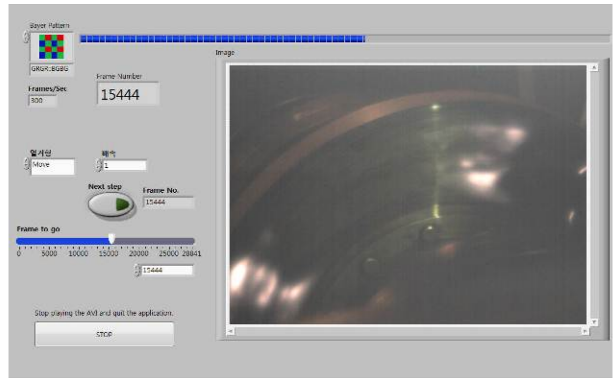
C. Thermal transit analysis of disc braking by using the high-speed camera

Disc brake test was performed at the maximum initial braking speed as 320(km/h). To observe the surface temperature and to analyze the thermal transition of the disc surface during the braking, the following series of the freeze frame represent the still images of disc surface collecting from the high-speed camera. The exposure time of the high-speed camera is setting as 100(μs), the image size is fixed as the 640x480 pixel and the shutter speed is synchronized at 500(frame/s) speed in the high-speed camera system.

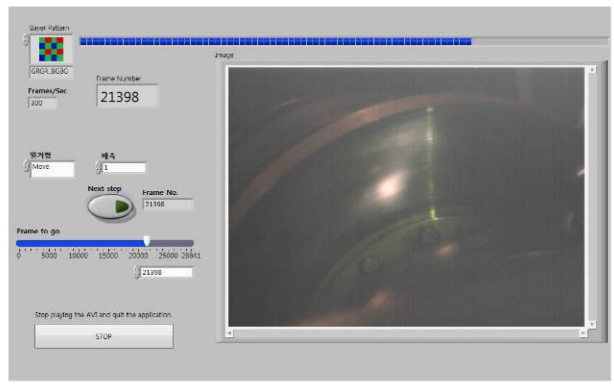
Fig. 9 shows the still image post-processed by high-speed camera on the Labview program which is developed for analyzing the image data collected from the high-speed camera.



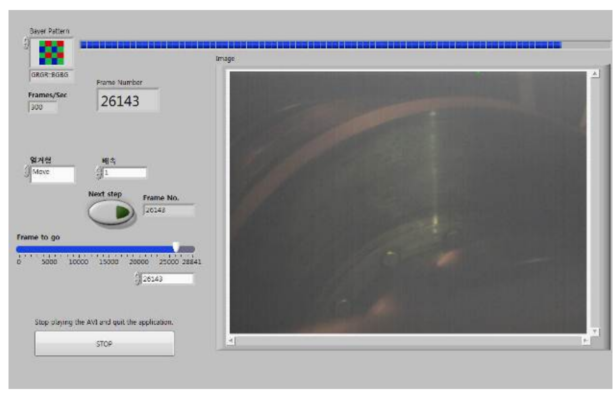
(a) a still image of post-process in braking velocity 320(km/h)



(b) a still image of post-process in braking velocity 200(km/h)



(c) a still image of post-process in braking velocity 100(km/h)

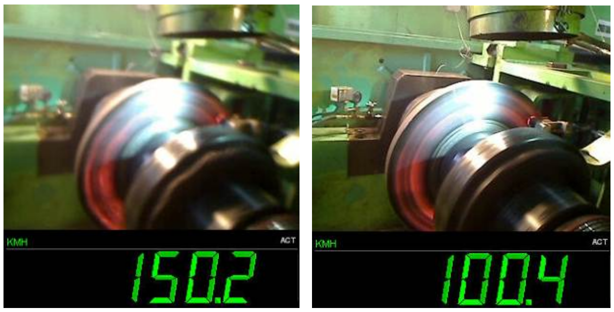


(d) a still image of post-process in braking velocity 0(km/h)

Fig. 9 analysis of the still image by high-speed camera using the Labview program

(a) 320 [km/h] (b) 300[km/h]

(c) 250 [km/h] (d) 200[km/h]



(e) 150 [km/h] (f) 100[km/h]

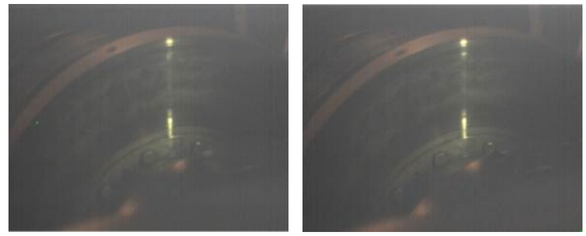
(g) 50 [km/h] (h) 0[km/h]

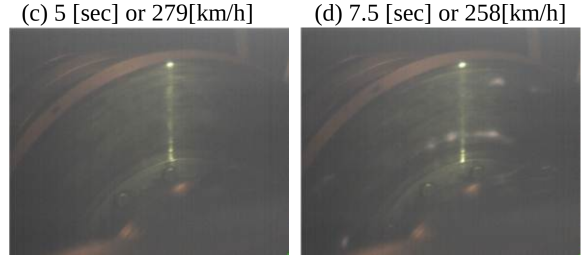
Fig. 10 still images of brake by general camera having a 30 [frame/s]

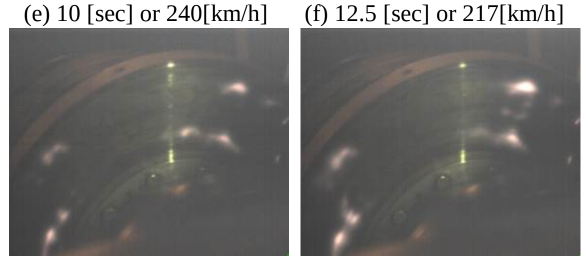
Fig. 10 represents the disc surface image during the braking at several speed points, which have a speed scale 50(km/h), by the general USB camera with 30(frame/s).

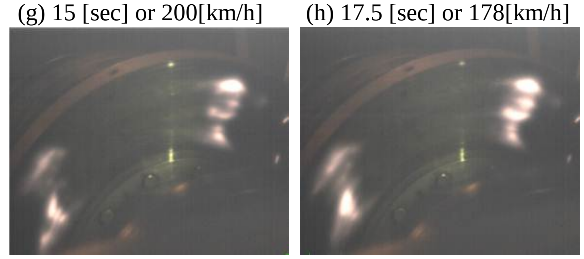
Below 16 figures in Fig. 11 are shown the still images for surface of the disc from initial speed (first measuring point is 320(km/h)) to stop with 2.5(sec) intervals at the same location during entire braking time.

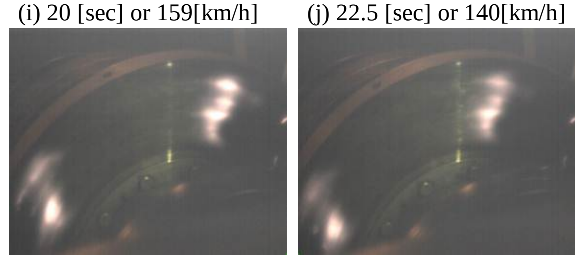

(a) 0 [sec] or 320[km/h] (b) 2.5 [sec] or 302[km/h]

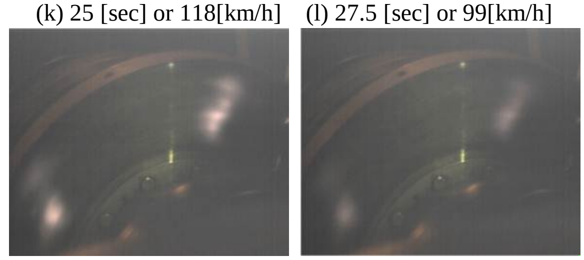

(c) 5 [sec] or 279[km/h] (d) 7.5 [sec] or 258[km/h]


(e) 10 [sec] or 240[km/h] (f) 12.5 [sec] or 217[km/h]


(g) 15 [sec] or 200[km/h] (h) 17.5 [sec] or 178[km/h]


(i) 20 [sec] or 159[km/h] (j) 22.5 [sec] or 140[km/h]


(k) 25 [sec] or 118[km/h] (l) 27.5 [sec] or 99[km/h]


(m) 30 [sec] or 78[km/h] (n) 32.5 [sec] or 57[km/h]

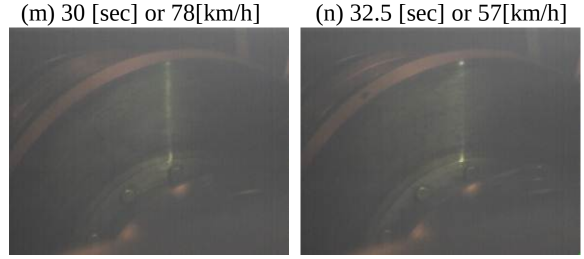

(o) 35 [sec] or 34[km/h] (p) 37.5 [sec] or 7[km/h]

Fig. 11 thermal transit analysis of brake disc by high-speed camera at the same disc location

At the Fig.11 the lightening in thermal image of the disc surface indicates the high temperature. Analyzed its results, 12.5(sec) which means near 217(km/h) speed after braking was applied firstly, the shape of hot spot was observed gradually. Also this was disappeared around 62(km/h). As its results, we can check that formation and extinction area of hot spot was the same position. That is, we could find temperature transition or thermal characteristic of the surface of the disc, which the scattered distribution of thermal moves gradually to a point and be destroyed after that.

IV. Conclusion

In this paper, during the braking test, the DAQ device stored several data which are rotational speed and braking noise in order to analyze its frequency characteristic of the brake sound during initial contact between disc and pad. Further, disc brake testing was performed by using high-speed camera for analyzing the thermal transit characteristic of the surface of the friction material.

With high-speed brake performance tester and the high speed camera system, we analyzed the temperature transit characteristics of the disc surface while disc braking is applied. In experimental environment of the high speed camera system, we used the synchronized lighting system with the same speed of image acquisition. Also, by shortening the exposure time, we could get the clear still images. The disc surface images represented that the lighter region meant the higher temperature. After analyzing the temperature characteristics of disc surface at the same region, we confirmed the process of formation and extinction of the hot spot. That is, the scattered distribution of thermal moves gradually to a point and be destroyed after that. And its results will be improved by means of a braking performance test evaluation technology as well as brake parts development on braking system of the railway vehicles through the matching study with the thermal image camera.

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