Experimental Study on the Characteristics of Pressure Variation of KTX Passing Through Tunnel

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Abstract

Experimental study has been conducted to clarify the internal and external pressure variation characteristics for KTX(Korea Train eXpress) passing through tunnel. Abrupt pressure variation gives rise to the ear-discomfort for passenger and fatigue for car body. In this study, the internal and external pressure variation are measured by using KTX real train experiment and on-board portable data acquisition system in Gyeongbu high speed commercial line. The tunnels from 200 m to 4000 m in length are chosen for the investigation of tunnel length effects. From the results of experiment, the internal pressure variation rate for all the test tunnels is lower than the standard criteria of 200 Pa/s. And, the critical tunnel lengths for pressure wave pattern are classified into 7 groups by using the theoretical L-t diagram analysis.

Keywords : Pressure variation, Ear-discomfort, High speed train, Critical tunnel length

1. Introduction

In order to operate high speed train which runs with the maximum speed of 300km/h, there are many unexpected aerodynamical issues which are not experienced in conventional lines. For the safety and comfort, many researches have been conducted to clarify aerodynamical issues.

For examples, aero-acoustic noise which is proportional to the train speed to the fifth or sixth power, the contact loss of pantograph due to lift force, the increase of drag force, ear-discomfort of passenger and fatigue of car body due to pressure variation and train wind effects in wayside or platform are induced in operation of high speed train.

Ear-discomfort due to pressure variation directly affects to the ride-comfort of passengers who are riding high speed train.

When a train is passing through tunnels, there is a steep pressure gradient. The abrupt pressure difference penetrate into the cabin of rolling stock and cause ear-discomfort. Many countries have been conducted speed-up projects in high speed train as well as conventional one. In some cases, pressure variation in single tunnel of conventional line is almost same to that in high speed train. These pressure variation in outside penetrate into HVAC equipment or non-sealed parts of car body and result in internal

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In this study, experimental study by using KTX train set has been conducted to measure pressure variation in tunnels in Kyungbu high speed line between Seoul and Daejeon.

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nels in Kyungbu high speed line between Seoul and Dae-jeon.

And, We also investigate the internal and external pressure characteristics qualitatively and quantitatively. Obtained results are compared to that of Japanese one.

2. The Details of Experiment

Fig. 1 shows the schematic sketch of experimental train set to measure internal and external pressure variation.

Pressure sensors are installed on bogie, gangway and seat in passenger compartment and measured data are transferred and saved in a portable computer in real time.

Pressure sensors can be used to measure atmospheric pressure. Maximum and minimum limit of pressure values are +10 kPa and -10 kPa respectively. The sampling rate of data is 100 kS/s and 16 bits 16 channel AD converter is used to treat graphic view. Real tests with KTX train set have been conducted to measure external and internal pressure variation.

The test line is a section between Seoul and Daejeon. Experiments were conducted in all the tunnels in this line and maximum velocity of experiment train set was 300 km/h. The train set which is composed of 2 power cars and 18 trailer cars was used and experimental instruments were installed in 18th car.

3. Results and Review

Passengers in a train generally feel ear-discomfort due to pressure variation rate per second. Such phenomena also happen in a elevator or airplane.

Because pressure variation is approximately proportional to the velocity of train squared, passengers in a non sealed train with high speed often feel ear-discomfort. These problems firstly issued with the opening to traffic of Shinkansen in 1964. At that time, the sealing technology of car body applied to Shinkansen, but that is not general cases in other countries.

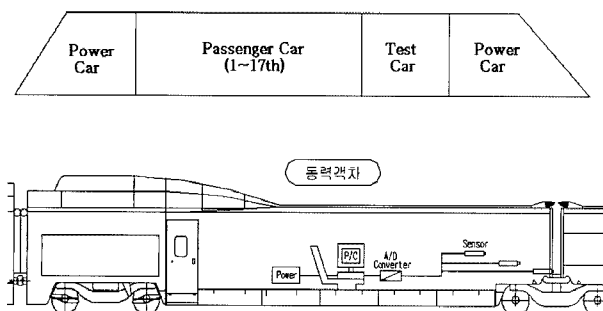In Europe, ear-discomfort problems have been issued

Fig. 1 Schematic Sketch of Test Car

Table 1. Criteria of Pressure Variation(BR) [7]

Train & Track type	Criteria for Pressure Variation	
	Extreme	Normal
Non sealed car Tunnel ratio ≤ 10%	4.0 kPa/4s	2.5 kPa/4s
Non sealed car Tunnel ratio ≥ 25%	3.0 kPa/4s	2.0 kPa/4s
Sealed car Tunnel ratio ≥ 25%	1.25 kPa/4s	0.8 kPa/4s
Sealed car Tunnel ratio ≥ 50%	1.0 kPa/4s	0.7 kPa/4s

according to the speed-up of non sealed train. British researchers have conducted air tightness experiment and running tests with train set and obtained a series of guideline of pressure variation for ear discomfort as follows;

① Although the pressure variation is same, ear discomfort is strongly dependent to the individual state of health, feeling and the situation of estimation.

② According to the results of air tightness experiment, passengers feel ear discomfort in case of pressure increase. But, when a train passes through tunnel with high speed, there are repeatedly pressure increase and decrease in a short time, and cause ear discomfort.

③ If pressure varies very slowly, active and passive responses of ear adapt to the pressure variation rate. In case of railway tunnels, pressure difference compared to original state play a role of ear discomfort.

④ In the railroad line with lots of tunnels, the estimation standard for criteria of pressure variation will be more strict one.

Summarized results which were conducted by British researches are shown in Table 1 for the cases of train and line type.

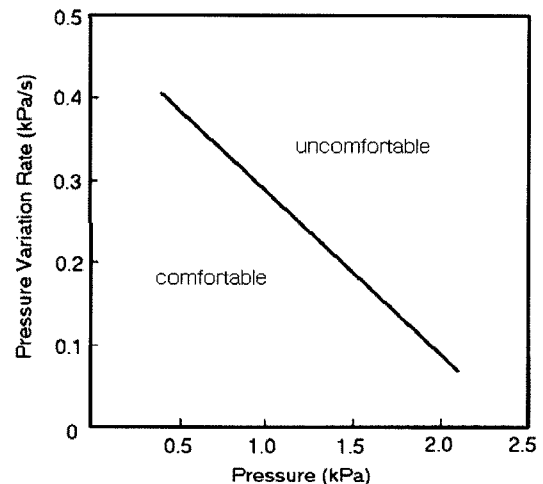On the other hand, Japanese researchers also have con-

Fig. 2 Criteria of Pressure Variation(JR) [7]

ducted lots of experiments and laboratory tests to set a guideline of ear discomfort to peak pressure and pressure variation rate as like Fig. 2.

Korean high speed train system originated from French TGV adopts the standard of SNCF, which is for the pressure variation of interior and for the pressure variation rate.

Pressure load induced by a train running with high speed results in ear discomfort for passengers and fatigue load for car body and tunnel lining. Sometimes these loads induce troubles as like the broken windows and separation of concrete in tunnel. It is well known that these pressure loads result from compression wave and expansion one in tunnel. Pressure increase by a train entrance to tunnel can be calculated from the simplified theoretical equation as like [5].
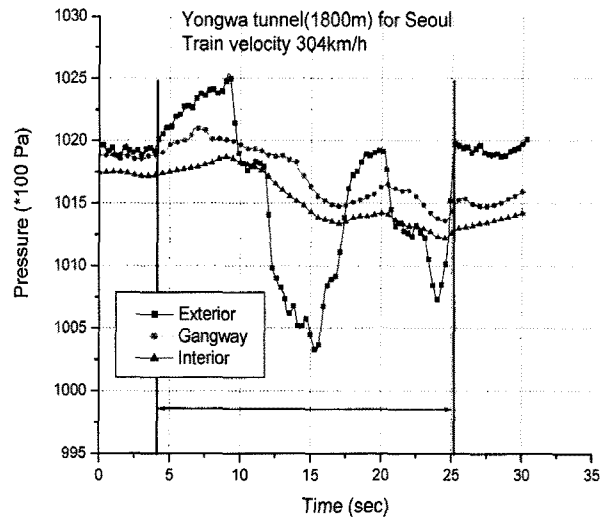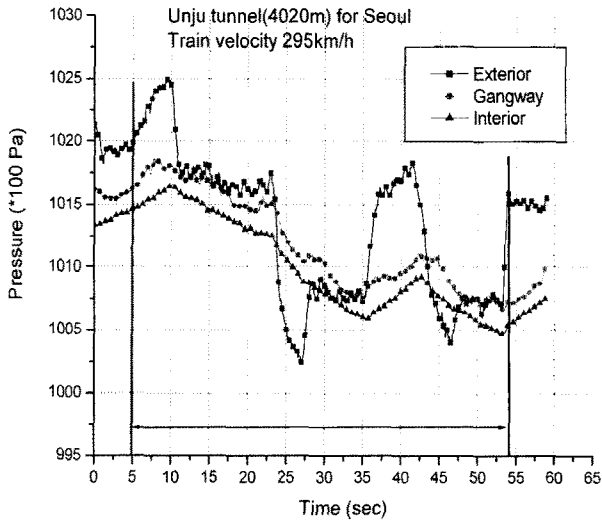

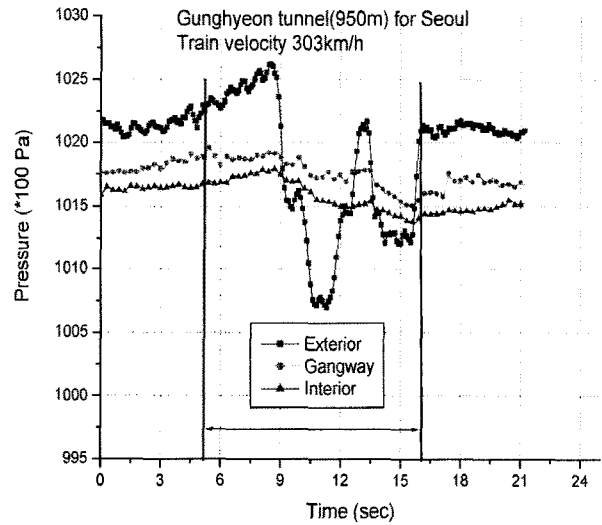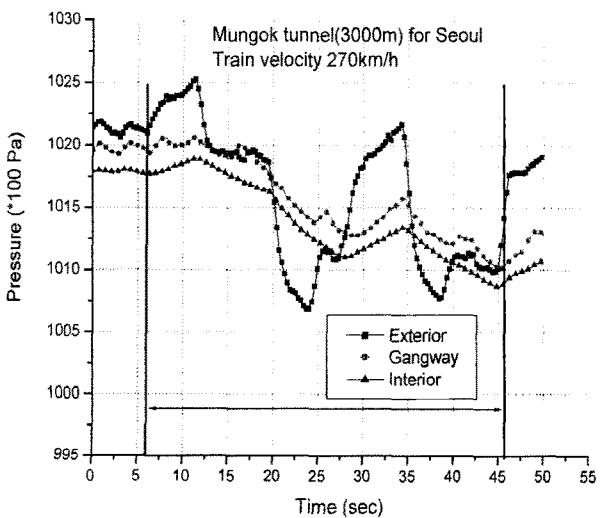Fig. 5 Yongwa Tunnel

Fig. 3 Unju Tunnel

Fig. 6 Gunghyeon Tunnel

Fig. 4 Mungok Tunnel
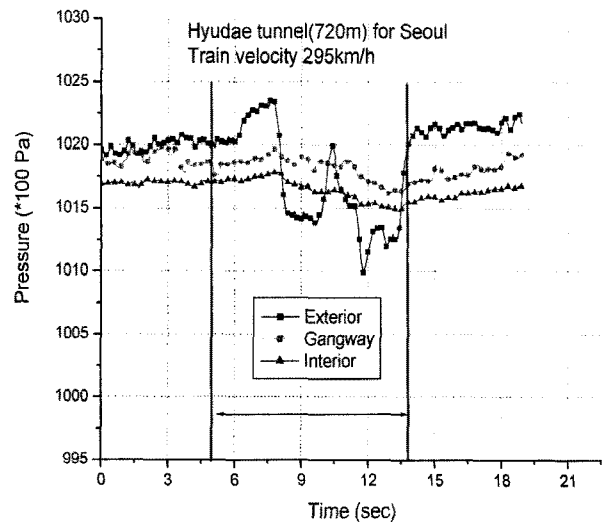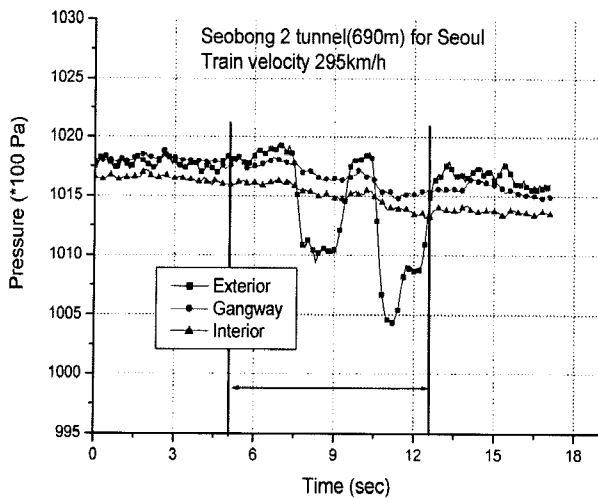

Fig. 7 Hyudae Tunnel

Fig. 8 Seobong 2 Tunnel
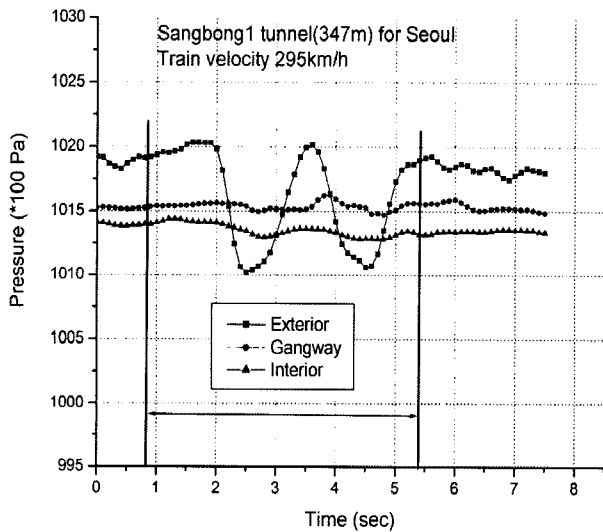

Fig. 9 Sangbong 1 Tunnel

$$\Delta p = \rho V^2 \frac{R(1+R)}{1-M^2} \qquad (1)$$

where, ρ: density (kg/m³)

   V: train velocity (m/s)

   M: Mach number

   R: cross section area ratio of train-tunnel

By using the above equation with train velocity of 300 km/h, pressure increase is 1548 Pa in case of Shinkansen 300 series with the train-tunnel ratio of 0.178 and 768 Pa in KTX with 0.096 respectively. The physical features for KTX are characterized as large tunnel cross section area and small car body.

Experimental results of Internal and external pressure variations of train are shown in Fig. 3~Fig. 9. Pressure variations are measured in Unju tunnel(4020m), Mungok (3000 m),Yongwa(1800 m), Gunghyeon(950 m), Hyudae (720m), Seobong 2(690 m), Sangbong 1(347 m) tunnels,

because these tunnels are representative ones in Kyungbu high speed line between Seoul and Daejeon.

Average velocity range is between 270 km/h~300 km/h. There are some deviations in test velocity because train velocity is already determined by the characteristics grade and curvature of line.

As we can see from the figures, the patterns of pressure variation are classified into four groups according to the length of tunnel and each pattern has a particular pressure characteristics.

In case of Unju tunnel that is the longest one, the pattern of pressure wave which are composed of compression wave generated by the nose of train and expansion one by the tail is similar to that of Shinkansen. Though the shape of train and train-tunnel ratio is different, qualitative results resemble each other.

The train in tunnel collides with the rear expansion, front expansion, rear compression, front compression, front expansion, rear expansion and front compression waves one by one.

During the process, there are pressure increase in case of collision with compression wave and pressure decrease in case of expansion one respectively.

When a train enters into tunnel with high speed, pressure variations are induced by three factors as follows; first one is compression wave by the train nose, second one is expansion wave by the train tail and third one is pressure increase by the change of train-tunnel cross sectional area.

Physical mechanisms are as follows;

When a train runs into tunnel, compression wave is generated by the abrupt decrease of train-tunnel cross sectional area.

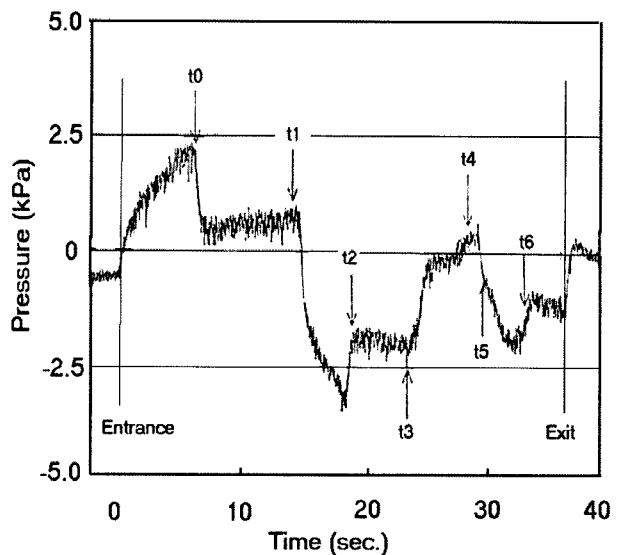This wave propagates toward the other side of tunnel

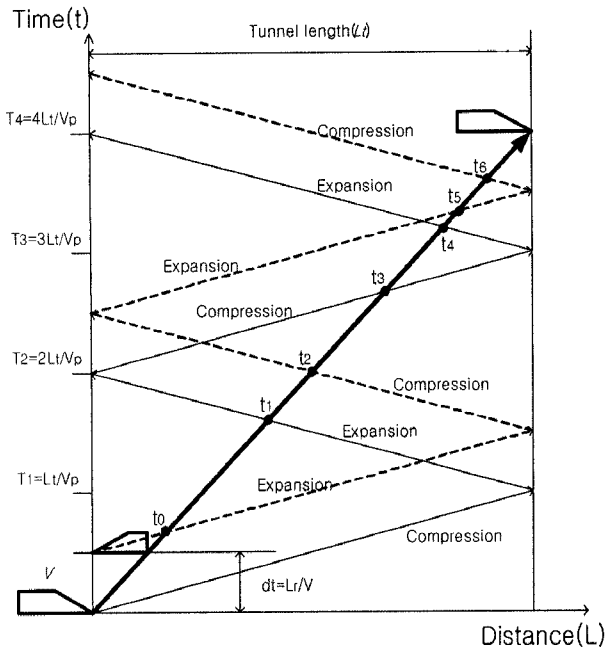**Fig. 10** Pressure variation of shinkansen

Fig. 11 Pressure Wave Pattern

and emits pulse wave, so called micro pressure wave.

At the same time, expansion wave is reflected toward the entrance side of tunnel and then propagated. Alternatively the reflected expansion wave generates compression wave and propagates toward the exit side of tunnel.

When the tail of train runs into tunnel, expansion wave is generated by the abrupt increase of train-tunnel cross section area. This expansion wave also propagates toward the exit side of tunnel and reflects compression wave like the process mentioned above. On the other hand, pressure increase at the stagnation point of train nose compensates with the expansion wave induced by the train tail.

From the Fig. 10 and Fig. 11, the pressure in tunnel increase during the elapsed time which is the time required for train to meet the first expansion wave. And pressure decreases at the point, t_0.

After that, pressure variation is relatively small, but pressure decrease occurs at the time t_1. In case of compression wave, the pressure in tunnel increases and conversely decreases in case of expansion wave.

If we know the specification of train, velocity, tunnel size in advance, the pressure variation patterns in tunnel can be estimated by using L-t diagram analysis and calculate the critical tunnel length [6].

The elapsed time for the entrance of train tail can be calculated theoretically by the train length(L_r) divided by train velocity(V), that is, $dt=L_r/V$. The time, t_r, that is elapsed for train to pass through tunnel equals to the tunnel length divided by train velocity, $t_r=L_t/V$.

The next parameter is the elapsed time that expansion wave reflected at the tunnel exit encounters with the train

velocity line, that is, $t_b=3Lt/V_p+dt$.

Therefore, the critical tunnel length is calculated by the above two equations. The result is represented as follow,

$L_t=L_rV_p/(V_p-3V)$.

By using the constants, the length of train, the speed of sound and train velocity, which are 387 m, 340 m/s and 83.3 m, respectively, the critical tunnel length is calculated as 1462 m.

From the results of experiments, we know that the pattern of pressure variation in the short tunnels such as Hyudae, Sangbong and Seobong tunnel are different to that of critical tunnel length.

But, it is impossible to apply the integrated one equation to all the tunnels.

In this study, we conclude that the patterns of pressure variation are different according to the tunnel and train length and train velocity. And, we can classify the patterns following the elapsed time of the entrance of train tail and the propagation of pressure waves as follows [6]

$$\text{Pattern 1} : L_t = \frac{L_rV_p(V_p+V)}{2V(V_p-3V)} \tag{2}$$

$$\text{Pattern 2} : L_t = \frac{L_rV_p}{(V_p-3V)} \tag{3}$$

$$\text{Pattern 3} : L_t = \frac{L_rV_p(V_p+V)}{2V(V_p-V)} \tag{4}$$

$$\text{Pattern 4} : L_t = \frac{L_rV_p(V_p+V)}{4V^2} \tag{5}$$

$$\text{Pattern 5} : L_t = \frac{L_rV_p(V_p+V)}{3V(V_p-V)} \tag{6}$$

$$\text{Pattern 6} : L_t = \frac{L_rV_p(V_p+V)}{4V(V_p-V)} \tag{7}$$

$$\text{Pattern 7} : L_t = \frac{L_rV_p}{(V_p-3V)} \tag{8}$$

Therefore, the critical tunnel length for each patterns are 3713 m, 1462 m, 1302 m, 1217 m, 868 m, 651 m and 513 m, respectively.

The pressure wave characteristics of pattern 1 is in order of expansion, expansion, compression, compression, expansion, expansion and compression. That of pattern 2 is expansion, expansion, compression, compression, expansion and expansion. That of pattern 3 is expansion, expansion, compression, compression and expansion. That of pattern 4 is expansion, expansion, compression, compression and expansion. That of pattern 5 is expansion, expan-

Table 2. Pressure Variation of KTX

Tunnel	Length (m)	Pressure variation rate (Pa)		Pressure difference (Pa)
		Internal	External	
Unju	4020	55	386	2300
Mungok	3000	48	344	1854
Yongwa	1800	70	423	2194
Gunghyeon	950	75	895	1862
Hyudae	720	79	1450	1380
Seobong 2	690	87	1660	1400
Sangbong 1	347	100	1683	1007
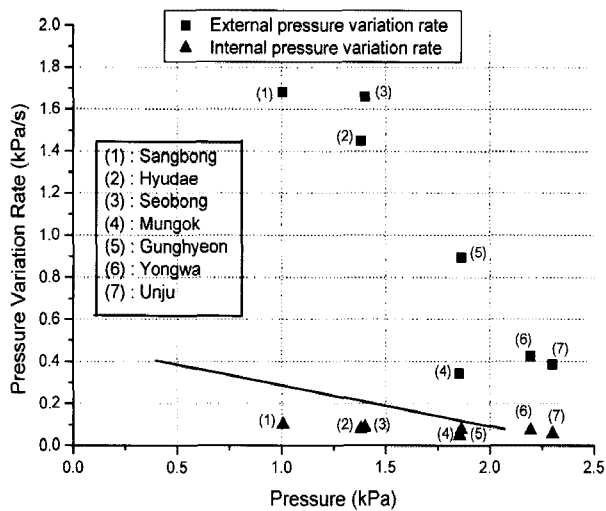
Fig. 12 Pressure Variation Rate of KTX

sion, compression, compression and expansion. That of pattern 6 is expansion, compression, expansion and expansion. That of pattern 7 is expansion, compression and expansion.

Test tunnels in the line are classified as follows;

Unju tunnel is a kind of the pattern 1, Yongwa and Mungok tunnels are the pattern 2, Gunghyeon is pattern 5, Hyudae and Seobong are pattern 6, Sangbong is pattern 7.

Because atmospheric pressure at steady state varies about 1.0 kPa per 100 m in altitude, there are atmospheric pressure difference between the entrance and exit of Unju tunnel due to the altitude. The maximum pressure difference and pressure variation rates for each tunnel are summarized in Table 2.

The maximum pressure difference equals the maximum value minus minimum one and pressure variation rate is calculated by the steepest pressure change slope per second.

Pressure difference is proportional to the length of tunnel, but pressure variation rate is inversely proportional to that.

In case of Sangbong tunnel, pressure variation rate is the most severe one due to the short tunnel length. So, pressure waves rapidly propagated and reflected compared with other tunnels.

The external and internal pressure variation rates are shown in Fig. 12.

Internal pressure variation rate of KTX for all the test tunnels is lower than the critical value of British standard 200 Pa/s.

If the speed-up project is conducted in the future, we have to prepare an air tightness technology to seal the car-body by using high technology, for example, continuous ventilation system etc, because the condition of pressure variation will be more severe state.

4. Conclusions

Experimental study has been conducted to measure the external and internal pressure variation of train in tunnel by using KTX which is operated with maximum speed in commercial line.

Obtained results are summarized as follows;

(1) The external and internal pressure variation of KTX in tunnels of Kyungbu high speed line are measured and analyzed qualitatively and quantitatively

(2) The critical tunnel lengths for pressure wave patterns are classified into 7 groups according to the theoretical review by using L-t diagram analysis.

(3) Internal pressure variation rate of KTX for all the test tunnels is lower than the standard criteria of 200 Pa/s.

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