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Effects of geometry on the sound field in atria

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Abstract: The atria in commercial buildings are widespread. However, the sound environment has not been given sufficient consideration. Geometry affects the acoustics in the atria. The concept of geometry in this paper includes five parameters, namely, length (*l*), height (*h*), aspect ratio of length to width (*l/w*), skylight form and slope, to provide suggestions for the acoustic environment design in atria. A series of computer models are simulated to analyse the effects of the form parameters on the acoustic environment, such as sound pressure level (SPL) and reverberation time (T_{30} in this paper). The results indicate that with an increase in the length or height, the values of the average SPL decrease, and the trends of the curves are logarithmic. For an increasing length, the T_{30} increases first sharply and then slowly. With the scattering increasing, the increment of the T_{30} is smaller. For an increasing height, the changes of T_{30} are determined by the absorption and scattering. In terms of the aspect ratio of *l/w* increasing for a given volume and area, the average SPL values approximately decrease linearly; furthermore, the T_{30} decreases unless the atrium is extremely high. The T_{30} is the longest for a flat skylight compared to that of other forms, and it is shorter when the skylight has a slope, including either a single or a double-pitch skylight. It can decrease nearly by 40% when the angle of the lean-to skylight is 7°. The T_{30} is lower and the amount of decrease is considerably smaller for an increasing slope. When the absorption is evenly distributed in the atria, the skylight has minimal effect on the average SPL or T_{30} values. Additionally, the classical formula can approximately calculate the SPL distribution unless the atrium is in a form of long space. The Arau-Purchades formula is generally appropriate to predict T_{30} with uneven absorption distributions unless the absorption or scattering coefficient is low.

Key words: Atrium, sound field, geometry, simulation

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1 Introduction

Atria were first used in Roman houses for a large central space, similar to a courtyard (Hung and Chow 2001). With the development of architectural technology, the Atlanta Hotel by John Portman brought the renaissance of classical atrium design forms in the 1960s (Saxon 1986). Thus far, atria have been designed in several types of buildings, such as shopping malls, hotels, office buildings, museums, libraries, residential buildings, etc. There are numerous literatures on daylighting, ventilation, thermal environment, and smoke and fire safety.

An atrium is a typical non-acoustic space (Kang 2007), where the acoustic indexes, discussed in this paper mainly including SPL and reverberation time, influence the sound comfort as important indicators. Chen and Kang (2004) indicated that short reverberation times and low noise levels were important for a large enclosed atrium in a shopping center, in terms of subjective evaluation of acoustic comfort. Furthermore, the reverberation was considered a primary factor that could affect acoustic comfort and speech intelligibility (Dökmeci et al. 2008).

A few studies have been conducted on the sound environment in atriums, which are based on measurements, simulations, comparisons and transformation designs. Jambrošić et al. (2003) obtained the measurements for an old stone atrium used for concerts, and positions of low intelligibility were observed near strong reflective surfaces. Iannace et al. (2015) fabricated a transformation of a canopy with sound-absorbing properties to reduce the drawbacks emerging from live music in a shopping center atrium based on measurements and computer simulations. Using a comparison of measurements, simulations and Sabine RTs, Yap et al. (2007) determined that the Sabine formula was useful for predicting the mean RT for a large atrium if the sound field was diffuse. Moreover, there were other important parameters for predictions, such as volume, shape, dimensions, in addition to absorption. Mahdavi et al. (2007) demonstrated that a large volume led to a long reverberation time as well as a hard material surface, especially glass, using the measurement methods and prediction in five atria. Mei and Kang (2012) revealed the basic sound field characteristics of a typical large atrium through on-site measurements. It was proposed that the sound fields in large atria spaces had several special characteristics due to the large volume, special shape, interactions between the main space and the linked smaller spaces, and boundary conditions.

Generally, the dimensions and forms of the atrium are important factors for architectural design and acoustic indices, similar to those in regularly shaped spaces where classic room acoustical theory was developed. The classic room acoustical theory is based on the assumption of a diffuse sound field (Kuffruff 2009). However, theoretical analyses indicated that the sound field in long or flat rooms, with either geometrical (i.e.

specular) or diffuse reflecting boundaries, was far from diffuse (Kang 1996a). The classic formula is not entirely suitable for all conditions. Kang (1996b, 2002a) analysed the reverberation in rectangular long enclosed spaces with geometrically and diffusely reflecting boundaries, where with an increase in the source-receiver distance, the reverberation time changed continuously. With the same cross-sectional area, the reverberation time was the longest when the section was square for geometrical or diffuse reflecting boundaries. Sumarac-Pavlovic and Mijic (2007) studied the shape and scattering surface of rooms affecting the acoustic response and reverberation. The results indicated that the geometrical properties of the rooms affected their reverberation process with low absorption.

Although the measurements, simulations, comparisons between measurements and simulations or transformations for atria have been obtained in actual spaces, and certain influencing factors on the sound field have been examined in regular and long spaces, they are primarily based on the specific space and receiver positions. Furthermore, minimal research has been conducted on the tendency of the sound field when the space is changing. There is a lack of systematic investigations to illustrate the effects of geometry on the sound field for building atriums.

Therefore, the goal of this paper is to systematically investigate the effects of geometry, such as length, height, ratio of length to width, skylight forms and slope, on the sound pressure level (SPL) and the reverberation time (T_{30} in this paper). The SPL and T_{30} are predicated using computer simulations. Moreover, the results of the theoretical equations are compared with those of the simulation. This paper first introduces the configurations and simulation method and then presents the results and the effects of geometry on the sound distribution and reverberation time in the atrium.

2 Method

A series of parametric studies have been conducted to systematically explore the effects of the atrium geometry on the sound environment of the average SPL and the T_{30}, which includes the length, height, aspect ratio of length to width, skylight forms and slope.

2.1 Configurations

Some typical characteristics of atria were determined through field and web surveys. As shown in Figure 1, the planar schematics of 32 shopping centers in China. It is found that there are many kinds of the atria which vary in shape, and they are rather different from common public spaces, such as very deep and narrow space, or very flat and wide spaces. Moreover, the volumes of the atria are much greater than common public spaces, and the average width of the atria is about 10 m. Furthermore, Figure 2 presents the photographs of the typical elements in the shopping centers. It is illustrated that, in general, the floors are large and slippery with few furniture. The atria are linked with the joining spaces of corridors (i.e. atria in commercial street type) or large spaces (i.e. atria in some shopping malls). The forms of the skylights are flat, arched and or pitched. The architectural characteristics of atria lead to high SPL and long reverberation time. Therefore, the type of atrium was examined in this study, i.e., a basic quadrangular form with 10 m width and an enclosed atrium with skylight.

To investigate the effects of geometry on the sound environment and tendency, five groups of various configurations have been constructed in the simulation, which cover the general dimensions and simplify the forms based on the 32 actual atria, as shown in Table 1. Furthermore, it is noted that in all of the above five groups, there is a consistent reference model, which has a length of 50 m, width of 10 m and height of 24 m with the flat skylight form.

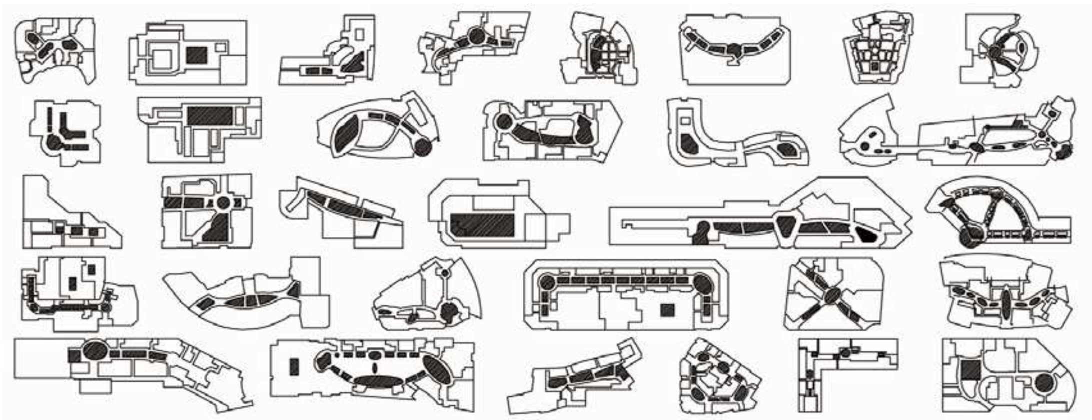


Figure 1. Planar schematics of 32 shopping centers in China

a) Slippery floors of some shopping centers

b) Walls, corridors and large spaces of the adjoining spaces for the atria

c) Flat skylight, the arched skylight and the pitched skylight forms of the atria

Figure 2. Photographs of the typical elements for the atria in the shopping centers

(1) To investigate the effects of length on the sound field, where the first group of configurations have a length of 10 m to 80 m in increments of 10 m, width of 10 m, height of 24 m, and flat skylight form. There are a total of 8 models.

To investigate the general effect of length, another group of models has been added, with a length of 20 m to 80 m in increments of 10 m, width of 30 m, height of 24m, and flat skylight form. There are a total of 7 models.

(2) To investigate the effects of height on the sound field, the second group of configurations have a height of 4 m to 64 m in increments of 4 m, width of 10 m, length of 50 m, and flat skylight form. There are a total of 16 models.

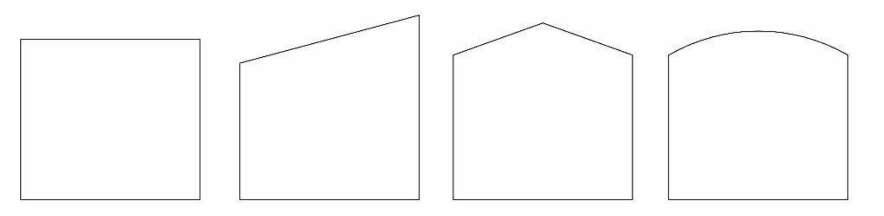
To investigate the general effect of height, another group of models has been added, with a width of 30 m, length of 50m, height of 4 m, 8 m, 16 m, 32 m and 64 m, respectively, and flat skylight form. There are a total of 5 models.

(3) To investigate the effects of the aspect ratio on the sound field, the third group of configurations have an aspect ratio of length to width of 1, 2, 3, 4 and 5, a fixed plan area of 500 m^2, height of 4 m, 8 m, 16 m, 32 m and 64 m, and flat skylight form. There are a total of 25 models.

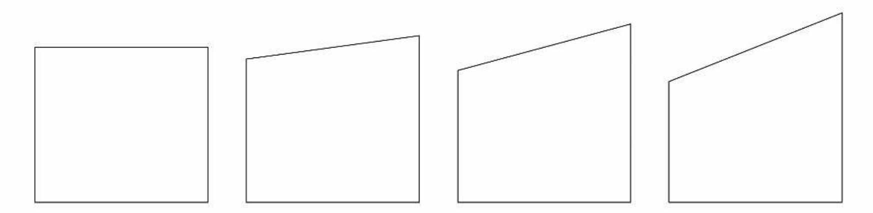
(4) To investigate the effects of the skylight form on the sound field, the fourth group of configurations have a flat (0°), single-pitched, double-pitched and arched skylight form, as illustrated in Figure 3 a). The plan area is 500 m^2, aspect ratios of 1, 3 and 5 are used for the same volume conditions, and the heights are 12 m, 20 m, 28 m and 36 m. There are a total of 48 models.

The definition of the height in this group is based on the height of flat skylight form. To study the effect of skylight form on the sound field, the value of the volume would be the consistent among the models with different skylights. Therefore, under the conditions of fixed volume and length, the values of the cross-sectional area of other models are consistent with that of the flat skylight. This is how the heights in Group 5 are determined.

(5) To investigate the effects of the skylight slope on the sound field, the fifth group of configurations have a single-pitched skylight form of 0°, 7°, 15° and 22°, as illustrated in Figure 3 b). The plan area is 500 m^2, aspect ratios of 1, 3 and 5 occur for the same volume conditions, and the heights are 12 m, 20 m, 28 m and 36 m. There are a total of 48 models.



a) Cross-sectional views of atria with flat, single-pitched, double-pitched, and arched skylight forms



b) Cross-sectional views of atria with skylight slopes of 0°, 7°, 15° and 22°

Figure 3. Cross-sectional views of atria with different skylights with a consistent cross-sectional area

2.2 Boundary conditions

From the investigations as mentioned above, it is found that the configurations of floors and skylights are relatively simple, however, the conditions of adjoining spaces are complicated. The walls boundaries of the adjoining spaces are very different in various buildings.

Table1 Five groups of parameter configurations for atrium simulations

Group	Width (m)	Length (m)	Height (m)	Aspect ratio (*l*/*w*)	Plan area (m^2)	Skylight form	Number of simulations
Group 1.1	10	10-80, step 10	24	—	—	Flat	8
Group 1.2	30	20-80, step 10	24	—	—	Flat	7
Group 2.1	10	50	4-64, step 4	—	500	Flat	16
Group 2.2	30	50	4, 8, 16, 32, 64	—	1500	Flat	5
Group 3	—	—	4, 8, 16, 32, 64	1, 2, 3, 4 and 5	500	Flat	25
Group 4	—	—	12, 20, 28, 36	1, 3 and 5	500	Flat, single-pitched, double-pitched, and arched	48
Group 5	—	—	12, 20, 28, 36	1, 3 and 5	500	Single-pitched 0°, 7°, 15° and 22°	48

To simplify and find out a typical atrium, 5 models with a consistent volume, constituted by the atrium spaces and the adjoining spaces are tested. The different configurations for walls are set as shown in Table 2. Because of the hard materials and low absorption coefficients in most atria from the views of the investigations as mentioned above, the absorption coefficients of the floor with few furniture, the ceiling and the balcony are set as 0.01, 0.01 and 0.03 at 1 kHz for the simulated models, which generally corresponds to the marbles or glazed tiles on the floor and glass on the skylight and the balcony. It is also considered that in actual cases, the distributions of absorption vary considerably. In the first model, the absorption and scattering coefficient of the walls are 0.5 and 0.05, respectively. In the second model, these coefficients are 0.06 and 0.4, namely low absorption and medium scattering. In the third model, the coefficients are 0.06 and 0.05, namely low absorption and scattering, which are related to actual cases of street type in the atrium. In the fourth model, these coefficients are 0.06 and 0.2, namely low absorption and medium scattering. In the fifth model, the coefficients are 0.06 and 0.4, namely low absorption and high scattering in this test.

Table 2. The parameter combinations of the atria and the adjoining spaces

No.	w_1 of atrium (m)	w_2 of adjoining space (m)	Total w (m)	l (m)	h (m)	Positions (Absorption coefficient/Scattering coefficient)			
						Floor	Wall	Ceiling	Balcony
1	20	0	20	50	24	0.01/0.05	0.5/0.05	0.03/0.05	—
2	20	0	20	50	24	0.01/0.05	0.06/0.4	0.03/0.05	—
3	10	10	20	50	24	0.01/0.05	0.06/0.05	0.03/0.05	0.03/0.05
4	10	10	20	50	24	0.01/0.05	0.06/0.2	0.03/0.05	0.03/0.05
5	10	10	20	50	24	0.01/0.05	0.06/0.4	0.03/0.05	0.03/0.05

Figure 4 illustrates the average SPL and T_{30} for each test model. The average SPL of Model l is much lower than that of the others, by about 5 dB, due to its higher absorption. The values of SPL are rather similar among the Model 2, 3, 4 and 5, which illustrated that the scattering and the joining spaces has little effect on SPL.

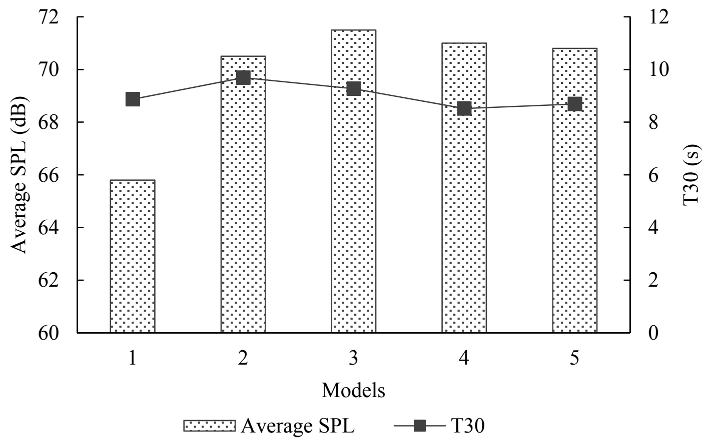


Figure 4. Average SPL and T_{30} of the 5 test models

Corresponding to SPL, the values of T_{30} are 8.87 s, 9.69 s, 9.27 s, 8.52 s and 8.69 s among the Model 1, 2, 3, 4 and 5. Model 1 is better because the T_{30} of Model 1 is at the medium level among all the five test models, although there is no much difference among the five models. In other words, the wall absorption coefficient of 0.5 and the scattering coefficient set as 0.05 in this paper could approximately represent the case with adjoining spaces.

2.3 Simulation method

The ODEON Room Acoustics Program version 9.2 is used to simulate the building atrium (Christensen 2003). The accuracy of the ODEON simulations has been proven in various types of spaces. Christensen (2013) obtained measurements and performed simulations using ODEON in acoustics for a typical auditorium and a large cathedral. The results of the comparison between the measurements and the simulations indicated a reasonable agreement for both rooms. Gade et al. (2005) simulated the Roman theatre of Jerash using ODEON, thus indicating a good agreement with the measurements at middle and high frequencies. Bradley and Wang (2007) conducted a comparison between a coupled volume concert hall and a computer-generated model of the hall. The results demonstrated a high level of accuracy for the high frequency ranges, particularly at 1 kHz. Passero and Zannin (2010) conducted an on-site measurement as well as an ODEON simulation to determine the reverberation time for a classroom. The results indicated that the difference was negligible between the computer simulation data and the measurements at a frequency of 500 Hz and a mean RT at octave-band frequencies of 125–4000 Hz. In an urban sound environment, Paini et al. (2004) simulated the acoustics of public open squares with ODEON and compared it with the measurements, which also indicated a good agreement.

To determine appropriate parameter values in the simulations, the reference model was tested three times using different rays, i.e., 50000, 100000 and 500000. The results of the average SPL were 67.20 dB, 67.21 dB and 67.15 dB, and the T_{30} were 4.54 s, 4.81 s and 4.81 s, thus indicating that the differences were negligible. The 100000-ray parameter was selected. The impulse response lengths were set at 10000 ms for all of models based on pilot simulations used to determine the RT ranges. The transition order (TO) was set at 2 based on previous studies (Paini et al 2004, Wang and Vigeant 2008).

There are many sound sources in atria, such as elevators, air-condition equipment, PA system, and voice. To determine the amount and the position of the sound source in the simulations, the reference model was tested three times. The first one is an omnidirectional source at the center of the floor. The second one is an omnidirectional source at the position of 1 m away from the short wall and 5 m away from the long wall. The third one is two omnidirectional sources at the two positions mentioned above. The sources were all at a height of 1.5m. The resulted SPL attenuation with increasing source-receiver distance is rather similar between the two source positions, with a variation of less than 1 dB, and the average SPL with two sources is 3 dB higher than those of a single source in both positions, as expected. The reverberation times T_{30} were 4.81 s, 4.73 s and 4.78 s, respectively with the three source conditions, which are rather consistent. Therefore, one omnidirectional source is selected and a position of (1, 1) with a height of 1.5 m, where the centerof the floor is (0, 0) in the atrium. The receivers are positioned using a grid of 2 m×2 m evenly distributed on the floor, where 1.2 m corresponds to the height of seated people, as shown in Figure 5.

Two key acoustic indices, the SPL and the reverberation time, are analysed. The former is relevant to communication or noise disturbance while the latter is relevant to acoustic comfort and speech intelligibility for conversation and public address (PA) systems (Mei and Kang 2012).

a) Cross-sectional view b) Plan view

Figure 5. Configuration of the atrium for source and receivers
(using *l* of 50 m and *w* of 10 m as an example)

The results at 1 kHz are represented in this paper as a typical frequency because of the general similarity over the frequency range, which also considers that speech is a primary sound source in atria, mainly at mid- and high frequencies. Moreover, the simulation results, particularly for Group 1 and Group 2, are compared with the results using the classical formula for calculating the SPL (Beranek 1954):

$$SPL = L_w + 10\lg\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right) \quad (1)$$

where

L_w: sound power level of the source, dB

Q: directivity factor of the source, set at 2 in this paper

r: source-receiver distance, m

R: total room constant, $R = (S \times \alpha)/(1 - \alpha)$

S: total area of the boundaries, m^2

α: average random absorption coefficient of the boundaries

The simulated T_{30} are also compared with calculated results using the Arau-Purchades reverberation formula, a formula for rooms with asymmetric distribution of absorption (Araupuchades 1988). In the formula the first portion corresponds to the absorption of the materials located parallel to the x axis, the second parallel to the y axis, and the third parallel to the z axis:

$$\mathrm{RT} = \left[\frac{0.16V}{-S\cdot\ln(1-\alpha_x)+4\mathrm{m}V}\right]^{\frac{S_x}{S}} \cdot \left[\frac{0.16V}{-S\cdot\ln(1-\alpha_y)+4\mathrm{m}V}\right]^{\frac{S_y}{S}} \cdot \left[\frac{0.16V}{-S\cdot\ln(1-\alpha_z)+4\mathrm{m}V}\right]^{\frac{S_z}{S}} \quad (2)$$

where

m: absorption coefficient of air

V: volume, m^3

S: total area of the boundaries, m^2

α_x, α_y, α_z: average absorption coefficient of the surfaces of the floor and ceiling, average absorption coefficients of the surfaces of the parallel side walls, and average absorption coefficients of the surfaces of the front and back walls, respectively

S_x, S_y , S_z: the area of the surfaces, similarly defined as for α_x, α_y, α_z.

3 Results

This section presents a series of acoustic simulations of the atria by investigating the effects of geometry on the sound distribution, which are length, height, aspect ratio of length to width, skylight form and slope.

3.1 Length and scattering

3.1.1 Length

To investigate the effects of length on the acoustic characteristics in the atrium, the simulations are conducted by increasing the length from 10 m to 80 m, with a width of 10 m and 30 m respectively as mentioned in Group 1 in Table 1. Figure 6 depicts the average SPL for each simulation model. As expected, it can be seen that the average SPL has a tendency of attenuating with an increase in the length. It is interesting to note that the attenuation decreases as the length increases. The correlations between the average SPL and the length have been determined and the curves have also been plotted in Figure 6. The equations have been elaborated and the trends of the attenuations are found to be approximately logarithmic, as shown in Eq. (3) and (4), with coefficients of determination R^2 as 0.99. The decreases of average SPL when the length is doubled are approximately consistent.

$$\text{Average SPL} = 81.259 - 3.854\ln(l) \quad \text{with the width of 10 m} \tag{3}$$

$$\text{Average SPL} = 74.963 - 2.791\ln(l) \quad \text{with the width of 30 m} \tag{4}$$

Figure 7 presents a comparison of the SPL for receivers between theoretical calculations and simulations in four models with a width of 10 m and lengths of 20 m, 40 m, 60 m and 80 m. It can be observed that the values of theory and simulation are nearly the same in small spaces, i.e., length of 20 m or 40 m, width of 10 m and height of 24 m, and a difference of approximately 1 dB occurs in relatively large spaces, i.e., lengths of 60 m or 80 m. The theoretical values are approximately 1.2 dB higher than that of the simulation when the receivers are extremely close to the source but become less when the receivers are in the far field, at a maximum of 1.3 dB. Therefore, the basic characteristics of the sound field distribution can be calculated using a classical equation in the configurations similar to the ones studied in Group 1. A similar phenomenon had been observed for the cases of long spaces with geometrically reflective boundaries (Kang 2002a).

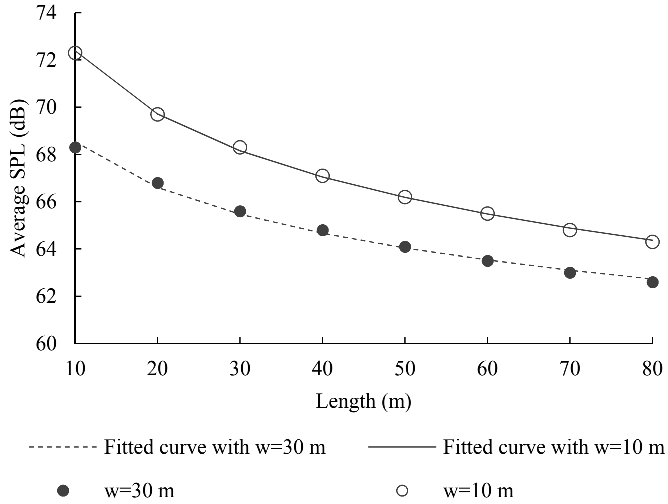


Figure 6. Average SPL in the atria with the length variation

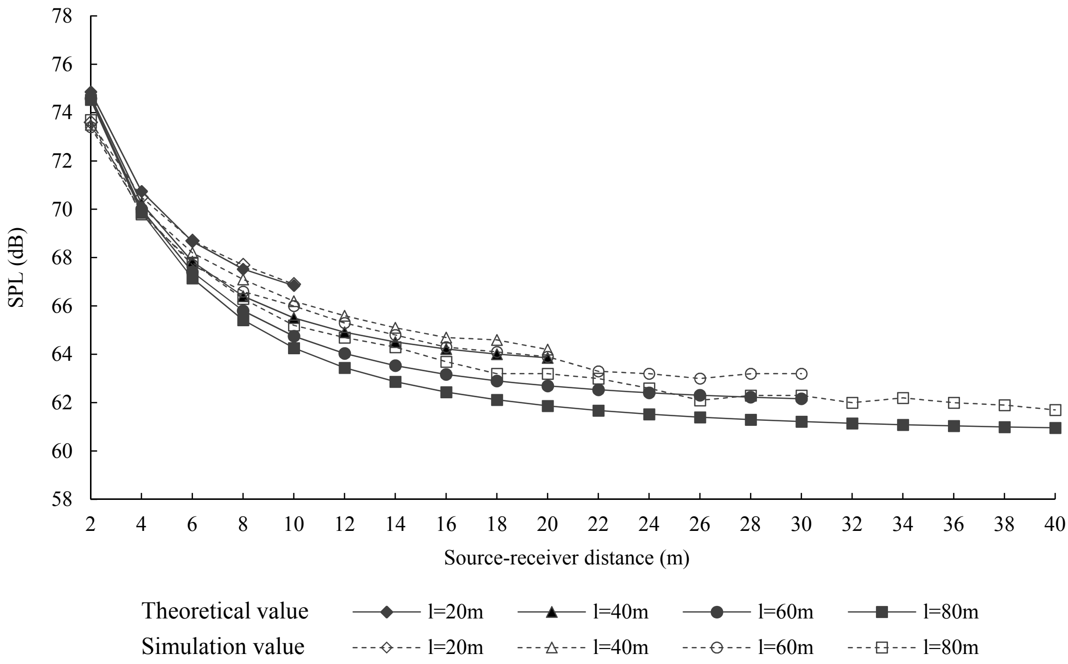


Figure 7. Comparison of SPL between calculations and simulations with the width of 10 m

Corresponding to Figure 6, Figure 8 depicts the average T_{30} in each simulation model with a width of 10 m and 30 m respectively, and the length of the atrium increasing from 10 m to 80 m, as mentioned in Group 1 in Table 1. As expected, the T_{30} is increasing with a longer atrium. With the width of 10 m, the T_{30} increases sharply when the length is from 10 m to 20 m, by 1.35 s. However, when the length is greater, the increment of T_{30} becomes smaller, for example, by 0.73 s from the length of 20 m to 30 m. The increasing of T_{30} is much smaller with further increase of atrium length. The situation with the width of 30 m is similar. Overall, it is illustrated that the T_{30} would increase rapidly with the length and only slightly after a certain length.

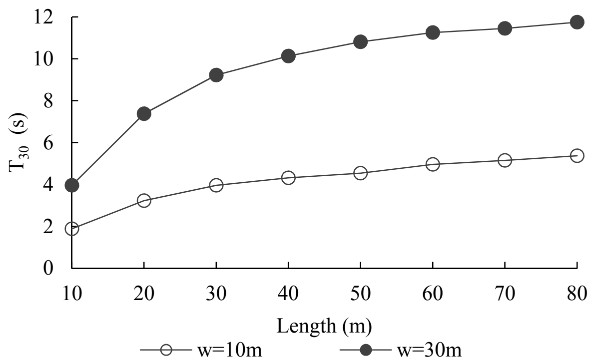


Figure 8. T_{30} in the atria with the length variation

3.1.2 Scattering

To investigate the effects of absorption and scattering on the sound field under the condition of length variation, different models have been simulated, as shown in Table 3. The Models 1-4 represent the walls with medium absorption and increasing scattering, and Model 5 represents the walls with low absorption and medium scattering. The Models 1-5 represent the floors with low absorption and increasing scattering.

Table 3 The models of the different absorption and scattering coefficient for the atrium

No.	Positions (Absorption coefficient/Scattering coefficient)		
	Floor	Wall	Ceiling
1	0.01/0.05	0.5/0.05	0.03/0.05
2	0.01/0.1	0.5/0.1	0.03/0.05
3	0.01/0.2	0.5/0.2	0.03/0.05
4	0.01/0.2	0.5/0.4	0.03/0.05
5	0.03/0.2	0.06/0.4	0.03/0.05

Figure 9 depicts the average SPL for each simulation model with different absorption and scattering coefficients. It is observed that the changes of average SPL in these groups are very similar. The average SPL are decreasing and the decrements are smaller with taller atria. The situation is similar to that in Section 3.1.1. With the increasing scattering, the average SPL is decreasing.

Corresponding to Figure 9, the T_{30} values are presented in Figure 10 for each model. It is illustrated that the T_{30} is increasing with the increasing length. The T_{30} increases rapidly and then slowly, as also mentioned in Section 3.1.1. It can be seen from Models 1-4 that with a greater scattering, the increment of T_{30} is becoming smaller. In Model 5, the values of T_{30} are almost consistent when the length is increasing, in which the absorptions are very low and the scattering is medium.

Figure 10 also presents the calculated results using the Arau-Purchades formula for Models 1-4 and Model 5. The calculated reverberation times of Models 1-4 are very similar to those of Model 4 simulations, possibly because of the medium absorptions and scattering. However, the calculated values for Model 5 are higher than those of simulations, probably because of the low absorptions.

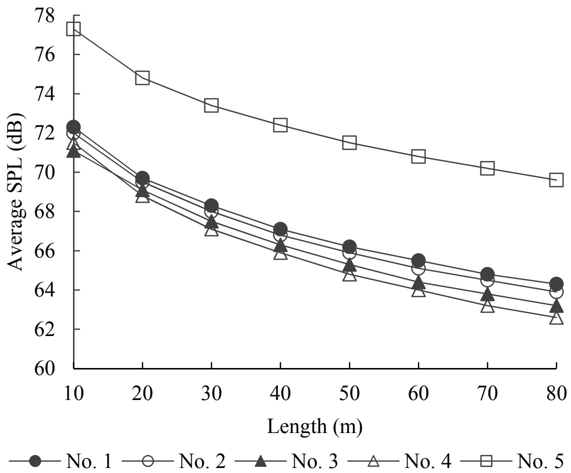


Figure 9. Average SPL of different absorption and scattering coefficients with the length variation

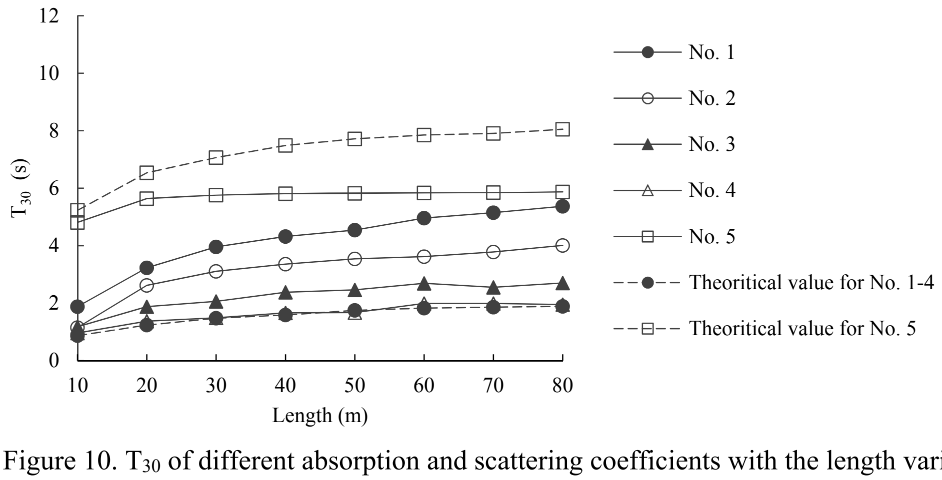


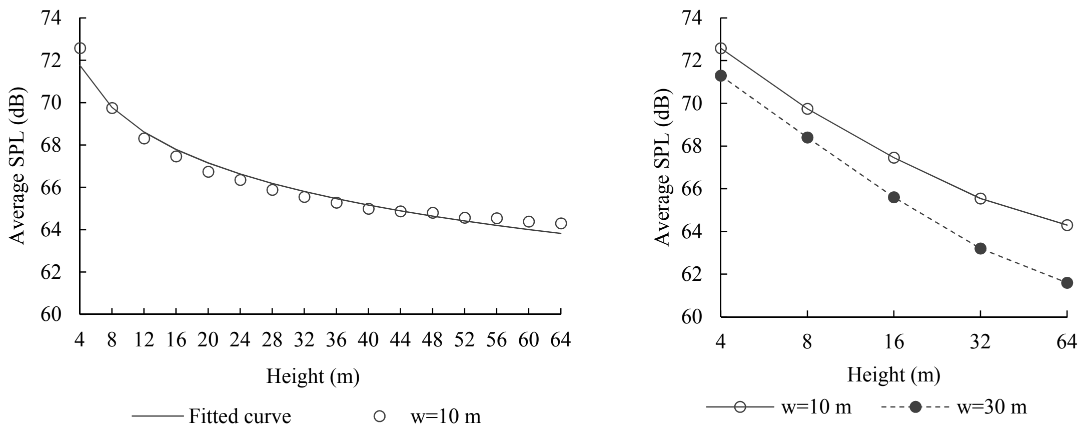
Figure 10. T_{30} of different absorption and scattering coefficients with the length variation

3.2 Height and scattering

3.2.1 Height

To examine the effects of the height on the sound field in the atrium, Figure 11 illustrates the average SPL in each simulation model for an increase in height, as seen in Table 1 (Group 2). It can be seen that with a width of 10 m, the average SPL decreases 3 dB at a height of 8 m with reference to the average SPL of 4 m. With the increasing height, the average SPL is decreasing, and the attenuations are also decreasing. The correlation between the average SPL and the height has been determined in Eq (5) and the curve has been plotted in Figure 11a). The equation has been derived and the trend of the attenuation is found to be approximately logarithmic, with a coefficient of determination R^2 as 0.98. The situation with the width of 30 m is similar, as illustrated in Figure 11b).

$$\text{Average SPL} = 75.727 - 2.863\ln(l) \quad \text{with width of 10 m} \qquad (5)$$



a) Average SPL with the height variation b) Comparison of average SPL

Figure 11. Average SPL in the atrium with the height variation

The simulation results of the SPL at the receivers are illustrated in Figure 12 for 4 m, 8 m, 16 m, 32 m and 64 m of atrium height, with a width of 10 m. Similar to the results of Section 3.1.1, the SPL attenuations are relatively large in the near field, and as the distances between the sources and the receivers increase, the attenuation decreases. This tendency also varies with different heights. For a height of 4 m or 8 m, the SPL continuously decreases slightly along with the length. For a height of 16 m, 32 m or 64 m, the SPL values decrease sharply in the near field, decrease slightly along the length and gradually become stable.

At a given receivers position, with an increasing height, the decrease in the SPL caused by the height increase becomes smaller, especially in the near field. When the height doubles, the SPL of the receivers decreases 2-3 dB in the far field, which is similar to that caused by the increasing length (see Figure 7).

Moreover, the theoretical values compared with the simulation results are depicted in Figure 12. For example, for a height of 4 m, using the theory calculation, the SPL becomes stable when the receivers are more than 7 m away from the source whereas the simulation result indicates that the SPL continuously decreases beyond 7 m. The SPL values for theory and simulation become closer when the height is greater than 16 m. This result possibly occurs because when the height is smaller, the space is more similar to a long space, and the sound field is less diffused (Kang 1996a).

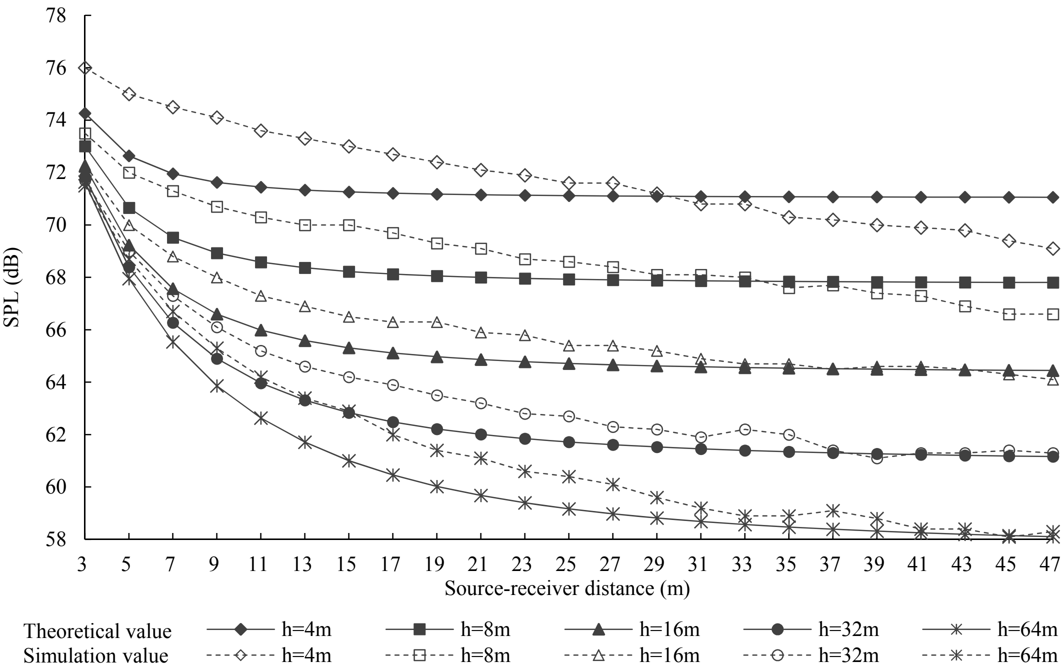


Figure 12. SPL as a function of the length between theoretical and simulation results

Corresponding to Figure 11, Figure 13 depicts the T_{30} with a width of 10 m and 30 m respectively, and a height of 4 m, 8 m, 16 m, 32 m and 64 m, as mentioned in Group 2 in Table 1. With a width of 10 m, the T_{30} increases rapidly by 1.01 s compared with that of the height 4 m to 8 m, increases slightly by 0.7 s from 8 m to 32 m, and decreases slightly by 0.37 s from 32 m to 64 m. With a width of 30 m, the T_{30} first increases gradually with the height from of 4 m to 32 m, by 6.5 s, and then decreases slightly, by 0.81 s. In other words, it is shown that the T_{30} would increase gradually with increasing height and then decrease slightly after a certain height.

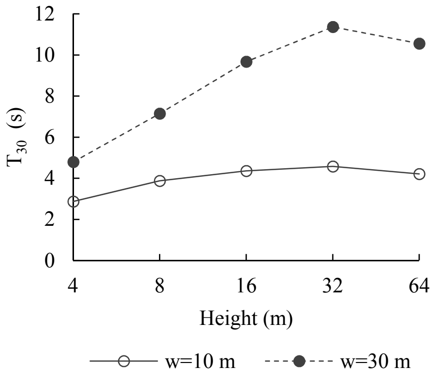


Figure 13. Comparisons of T_{30} with the height variation

3.2.2 Scattering

To investigate the effects of absorption and scattering on the sound field when the height varies, different configurations have been simulated, as shown in Table 3.

The average SPLs for each simulation model with different absorption and scattering coefficients are shown in Figure 14. It is observed that the changes of average SPL are very similar. The average SPL are decreasing and the decrements are smaller with taller atria. This situation is similar to that in Section 3.1.

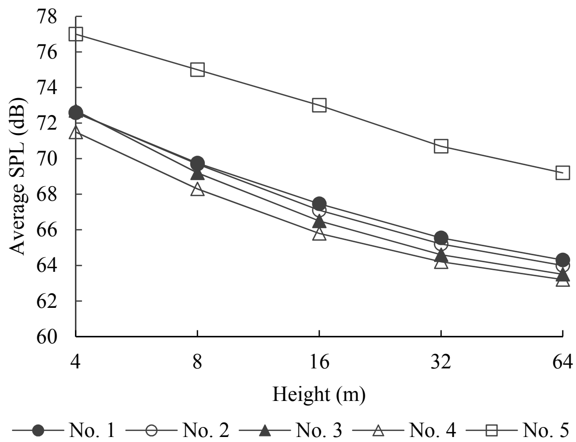


Figure 14. Average SPL of different absorption and scattering coefficients with the height variation

The T_{30} is presented in Figure 15 for models corresponding to Figure 14. It can be seen that the changes of T_{30} are affected considerably by the absorptions and scattering. When the absorption is at the medium level and the scattering is low, i.e. Model 1 and 2, the T_{30} is increasing rapidly first, followed by a slight increase, and then decreasing slowly with the increasing height. When the absorption and scattering are both at the medium level, i.e. Model 3 and 4, the T_{30} is almost consistent. When the absorption is low and the scattering is medium, i.e. Model 5, the T_{30} is increasing gradually and slightly.

The results using Arau-Purchades formula are also presented in Figure 15. The calculated values of Models 1-4 are generally close to the simulation results of Model 3 and 4, because of their medium absorption and scattering. However, for Model 5 the calculations are higher than simulations, probably because of the low absorptions, which is similar to the case in Section 3.1.2.

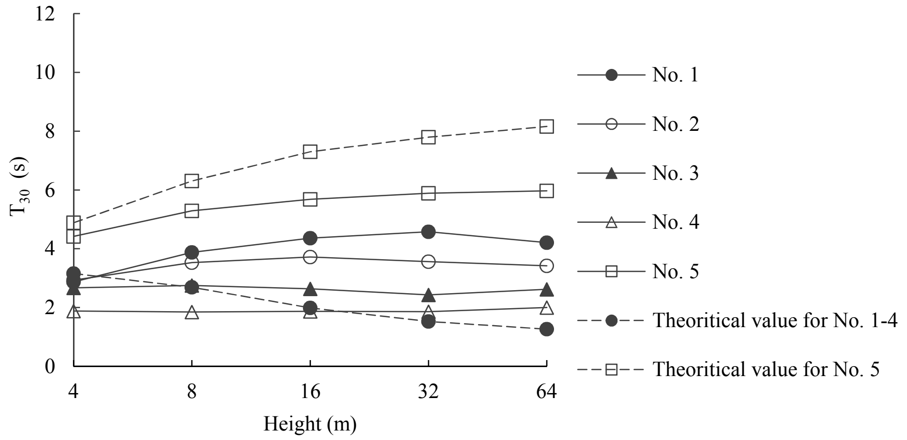


Figure 15. T_{30} of different absorption and scattering coefficients with the height variation

3.3 Length-to-width ratio

To predict the effects of the aspect ratio of length to width, Figure 16 illustrates the average SPL for each atrium model, with floor areas of 500 m^2 and a height of 4 m, 8 m, 16 m, 32 m and 64 m, as seen in Table 1 (Group 3). Using a ratio from 1 to 5, the average SPL decreases 1 dB, and there is a linear trend for a given height. Comparing the different atria heights, the tendencies of the decreased average SPL are consistent. Similar to the results of Section 3.2.1, the attenuations of the average SPL become smaller with a continuous increase in height, e.g., decreases 8.1 dB for an increase in height of 4 m to 64 m at a ratio of 1.

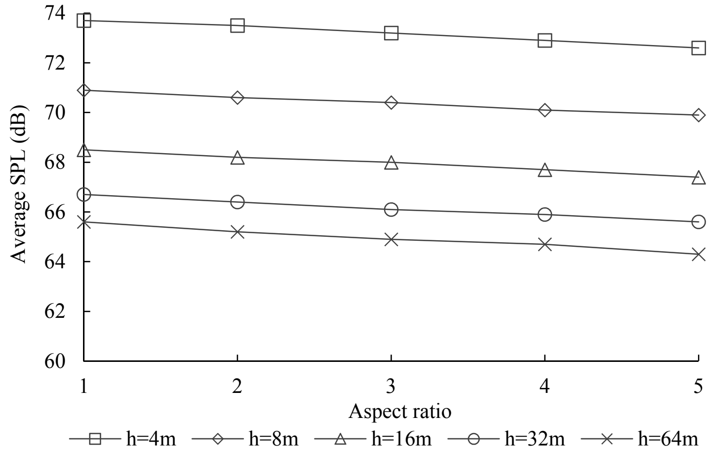


Figure 16. Average SPL in the atrium with a variation in the aspect ratio of length to width

Corresponding to Figure 16, Figure 17 presents the average T_{30} for each atrium model, as indicated in Group 3 in Table 1. It is determined that the T_{30} will decrease with an increasing ratio. For an aspect ratio from 1 to 5, with a height of 4 m, the T_{30} declines from 3.61 s to 2.87 s, and with a height of 8 m, the T_{30} declines from 5.1 s to 3.88 s. When the height of the atrium is 16 m or 32 m, the T_{30} decreases approximately 2 s. This result likely occurs because a considerably larger ratio of length to width signifies a significantly longer perimeter, which results in more wall area for absorption and shorter reverberation times. The longest reverberation time occurs in an atrium with a square plan design. Furthermore, it can be seen that a considerably longer space could result in a shorter reverberation time compared with the same plan area and same height. The result is similar to a dining room (Kang 2002b), where for a greater length/width ratio, the EDT is consistently approximately 10-20% shorter to improve intelligibility. Moreover, it is indicated that the reverberation time increases and then decreases with an increasing height, similar to the results of Section 3.2.1.

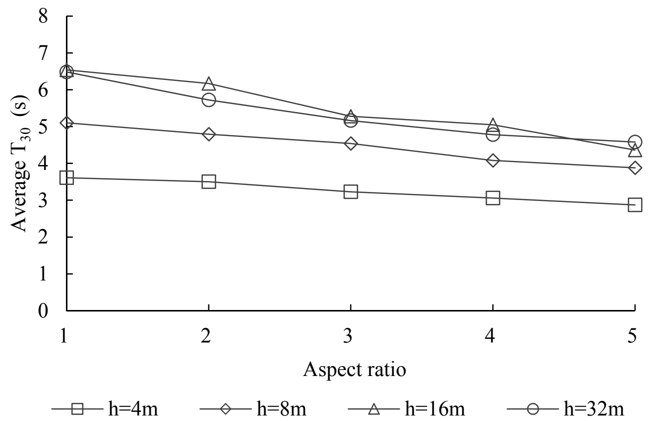


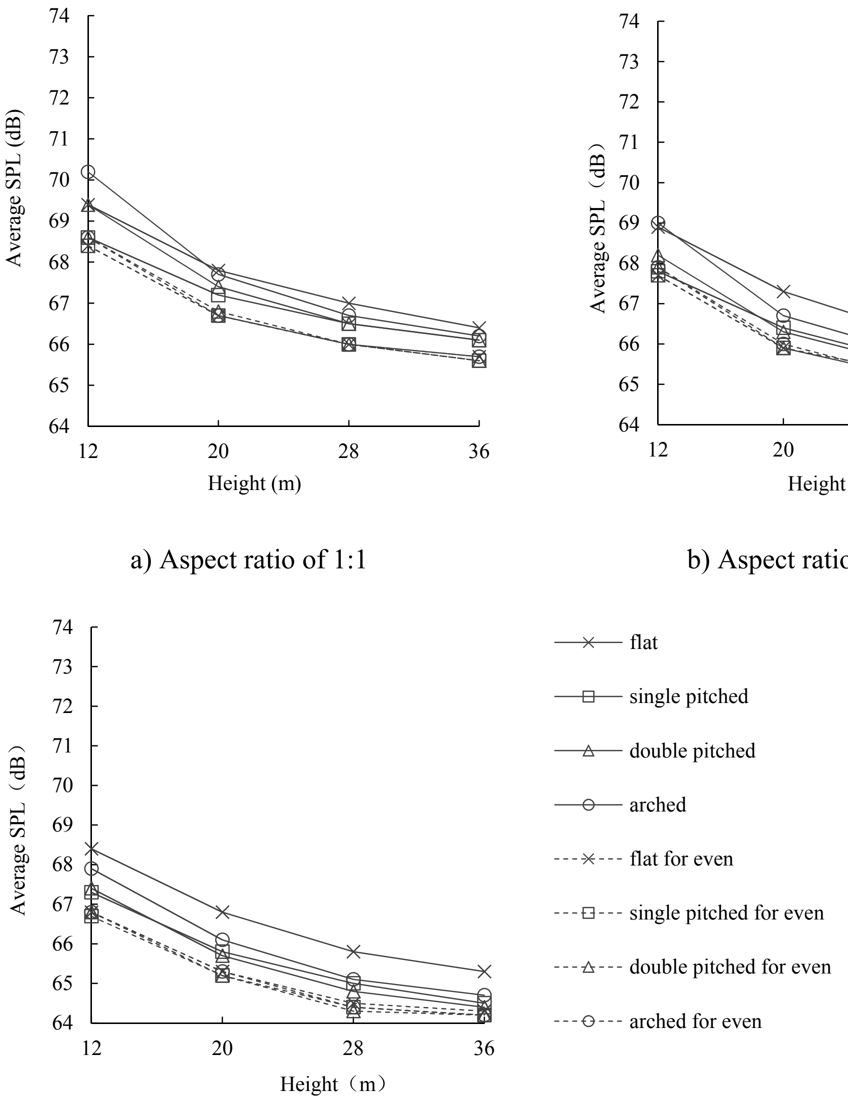
Figure 17. Average T_{30} in the atrium for a variation in the ratio of length to width

Overall, increasing the length-width ratio of the atrium is beneficial for obtaining a lower average sound pressure level and a shorter reverberation time under the same conditions.

3.4 Skylight form

To examine the effects of the skylight form on the sound field characteristics, simulations have been performed for different ceiling forms. Figure 18 illustrates the average SPL for Group 4, as listed in Table 1. It can be seen that for a given volume, the average SPL for flat forms are relatively large compared to that of other forms, including arched and sloping skylights, except for a height of 12 m.

Furthermore, in Figure 18, the average SPL is depicted with sound-absorbing materials uniformly distributed in the atrium, where the average absorption coefficient of all materials is 0.3. In this case, the difference in the average SPL is extremely small among the four skylight forms with a consistent volume. In other words, the ceiling configurations do not contribute significantly to the SPL in the atria when the absorption is evenly distributed.



a) Aspect ratio of 1:1

b) Aspect ratio of 3:1

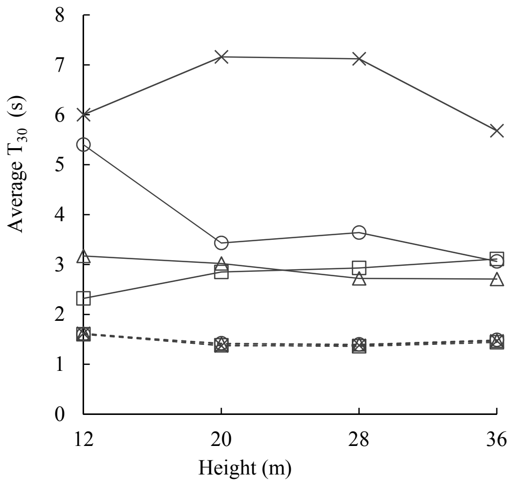
c) Aspect ratio of 5:1

Figure 18. Average SPL in the atrium for different ceiling forms

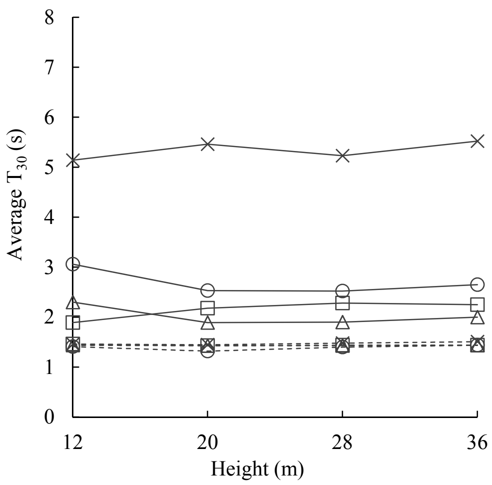
The effects of the ceilings on the average T_{30} are illustrated in Figure 19 and correspond to Figure 18. It can be seen that the average T_{30} for a flat skylight is nearly maximum among all of the cases. With an increase in the aspect ratio, the differences in the T_{30} are small for the other three ceiling forms, except for the flat skylight.

Moreover, based on Figure 18, the average T_{30} is depicted with the sound-absorbing material uniformly distributed in the atrium. The T_{30} is considerably short when the absorption is uniformly distributed. It is determined that there is no effect of the skylight on the average T_{30} when the absorption distribution is uniform.

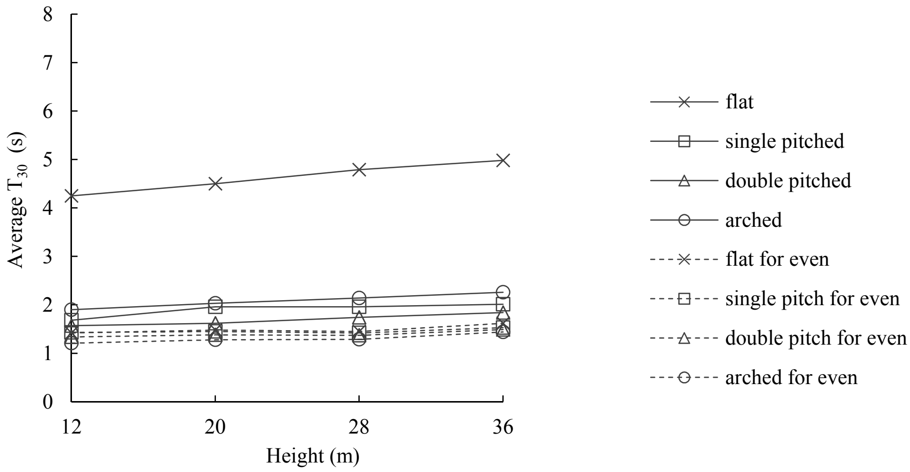
In Figure 18 a), it can be observed that the effect of the arched skylight form on the average SPL is similar to those of other forms. In Figure 18 b) and c), it is seen that the performance of the arched skylight is generally better than that of the flat form and worse than that of the other non-flat forms. The performance is similar among the cases in terms of T_{30}. Based on the above results, the single-pitched skylight form as an example has been chosen to investigate in Group 5.



a) Aspect ratio of 1:1



b) Aspect ratio of 3:1

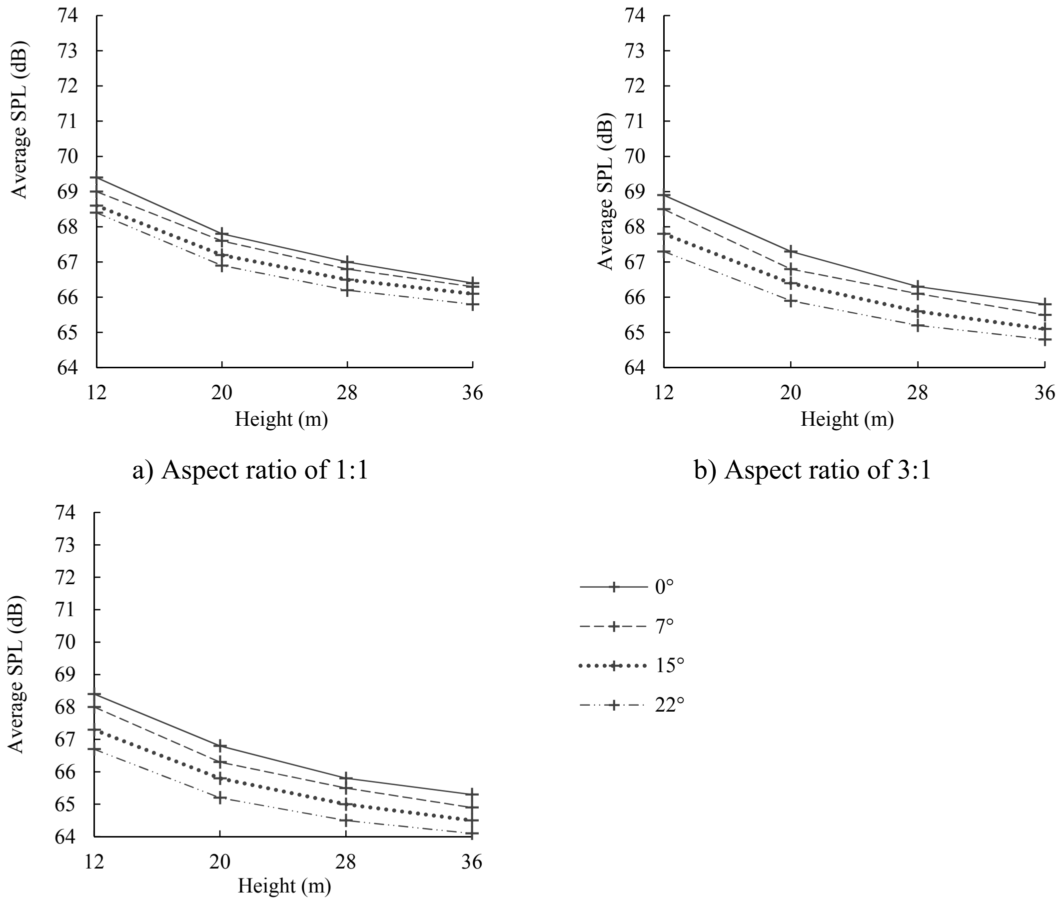


c) Aspect ratio of 5:1

Figure 19. Average T_{30} in the atrium for different ceiling forms

3.5 Ceiling Slope

Figure 20 illustrates the average SPL influenced by an increasing slope of 0°, 7°, 15°, and 22°, as seen in Table 1 (Group 5) for a single pitched skylight. It can be seen that for an increasing slope, the average SPL slightly decreases. The 7° increase in the skylight slope would decrease the SPL by 0.2-0.4 dB for an aspect ratio of 1 and 0.4-0.7 dB for a ratio of 5 with reference to a flat skylight. For a steeper slope, the average SPL is less, which is possible because the effects of the flutter echoes decrease. Furthermore, it can again be noted that for longer spaces, the average SPL is lower.



a) Aspect ratio of 1:1 b) Aspect ratio of 3:1

c) Aspect ratio of 5:1

Figure 20. Average SPL in the atrium for the slope of a single pitched skylight

Figure 21 presents the average T_{30} corresponding to Figure 20 for an aspect ratio of 3. It can be seen that with an increasing slope, the T_{30} gradually decreases, and the decrement is small. The T_{30} values are 5.14 s, 3.14 s, 1.89 s and 1.37 s for a skylight slope of 0°, 7°, 15°, and 22°, respectively, at an atrium height of 12 m, where, for example, with a slope of 7° and a height of 12 m, the reverberation time would reduce approximately 38.9% compared to that of the flat skylight.

The results with the ratio of 1 and 5 are similar to that with the ratio of 3. For example, for a ratio of 1 and a height of 12 m, the T_{30} values are 6 s, 3.44 s, 2.32 s and 1.76 s for a skylight slope of 0°, 7°, 15°, and 22°, respectively. For a slope of 7°, the T_{30} would decrease approximately by 44% compared to that of the flat skylight. It can also be seen that with the atrium becoming longer, the reduction in T_{30} decreases.

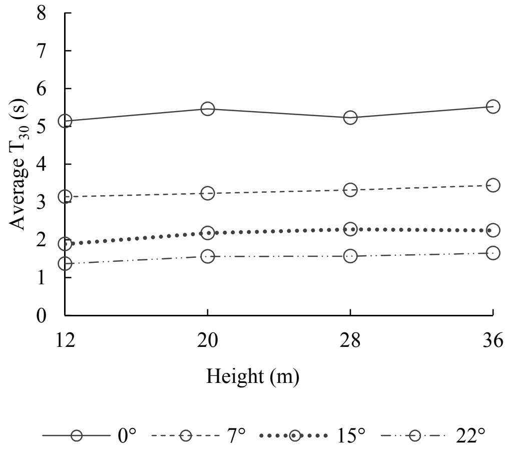
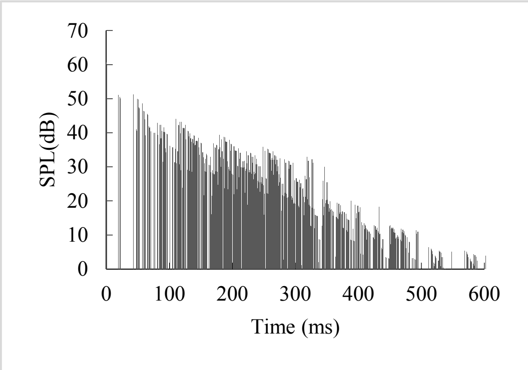


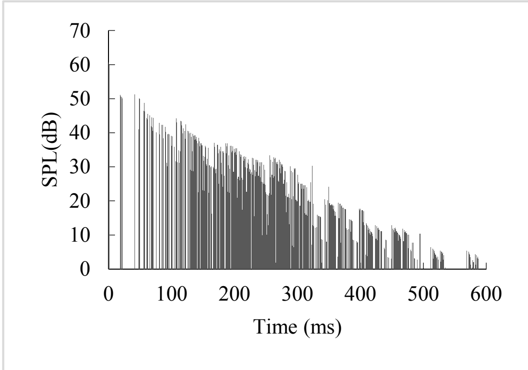
Figure 21. Average T_{30} for a slope of a single pitched skylight with an aspect ratio of 3

A primary reason for the above differences, both for the SPL and the T_{30}, is the flutter echo. Figure 22 depicts the early reflection levels for typical receivers 9 m from the source based on Figure 21. The flutter echo phenomenon can be seen with the flat form. With an increase in the slope, the flutter echo decreases as the reverberation time becomes shorter.

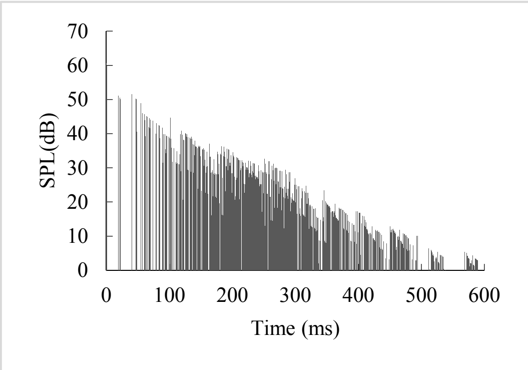
To investigate the effects of scattering with different types of slope ceilings, models with a scattering coefficient of 0.2 for the walls and floors are simulated. For a ratio of 3 and a height of 12 m, the T_{30} values are 3.49 s, 2.5 s, 1.71 s and 1.34 s for a skylight slope of 0°, 7°, 15°, and 22° respectively. It can be seen that for a slope of 7°, the T_{30} would reduce approximately by 28.4% compared to that of the flat skylight. This suggests that with sloped ceiling the scattering also affects the sound field. It is also observed that when the slope is increasing, the reduction of T_{30} due to the added scattering coefficient is decreasing.



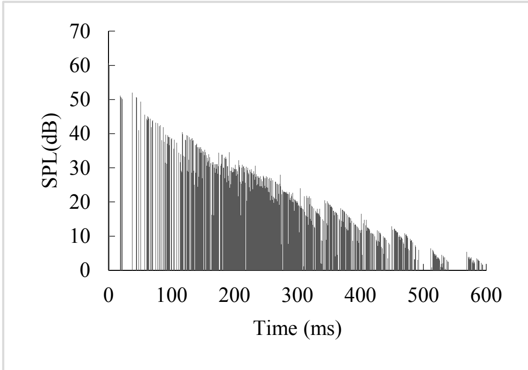
a) Flat skylight



b) Single-pitch roof with 7°



c) Single-pitch roof with 15°



d) Single-pitch roof with 22°

Figure 22. Early reflection levels at a typical receiver

4 Conclusions

The effects of geometry on the acoustic environment in atria have been studied using computer simulation. The results of models using different lengths, heights, aspect ratios, skylight forms and slopes are presented.

With an increase in length, the average SPL decreases, and the tendency of attenuation indicates an appropriate logarithmic curve. This result indicates that for a longer atria, the attenuation is smaller. The attenuations when the length is doubled are consistent. The reverberation time increases sharply in a small space and then slightly increases when the length is more than 20 m. With the increasing scattering, the increment of the T_{30} is smaller.

With an increase in height, the average SPL decreases, and the trend of attenuation is also logarithmic. This result indicates that when the height is greater, the attenuation is smaller. The changes in T_{30} are affected by the absorption and scattering. With increasing height, when the absorption is at a medium level and the scattering is low, T_{30} is increasing gradually, and then decreasing slowly. When the absorption and scattering are at a medium level, T_{30} is almost consistent with the height variation. When the absorption is low and scattering is medium, T_{30} is increasing gradually and slightly, with increasing height.

With an increase in the length, the theoretical values are approximately 1.2 dB more than that of the simulation when the receivers are extremely near; however, the values become less when the receivers are in the far field for a maximum of 1.3 dB. With an increase in the height, the SPL values for theory and simulation become closer for a height greater than 16 m, especially in the far field.

In terms of the length to width ratio, it increases for a given volume and area of the atrium, which signifies that a square atria became rectangular, and the average SPL decreases approximately linearly. The average SPL decrease 1 dB for a ratio from 1 to 5. Furthermore, the T_{30} decreases unless the atrium is extremely deep, which indicates that the longest reverberation time occurs for a square plan form, and a considerably longer space can provide a shorter reverberation time for the conditions of the same plan area and same height in the atrium.

For a flat skylight, the average SPL values are relatively larger than that of the other forms. The T_{30} is the longest when the flat skylight is compared to the other forms, and it is shorter when the skylight has a slope, including a single or double-pitch skylight. For a steeper slope and longer spaces, the attenuations of the average SPL are greater. The T_{30} can decrease nearly by 40% when the angle of a single-pitch skylight is 7°. With an increase in the skylight slope, the T_{30} is shorter, and the amount of attenuation is considerably smaller. The skylight has minimal effect on the average SPL or T_{30} when the absorption is evenly distributed in the atria.

The classical formula can approximately calculate the SPL distribution unless the atrium is in a form of long space. The Arau-Purchades formula is generally appropriate to predict T_{30} with uneven absorption distributions unless the absorption or scattering coefficient is very low.

Acknowledgements

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