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Research on sound absorption properties of laminated mixture sound absorbing materials

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Abstract. In this paper, the mixing design test method is introduced into the research of sound absorbing material, and the method of laminated mixture sound absorbing material are put forward. A statistical energy model is established to calculate the sound absorption coefficient of sound absorbing materials, and the sound absorption characteristics of three kinds of sound absorbing materials, such as superfine glass fiber, hemp wool and polyurethane, are studied by simulation, and the accuracy and validity of simulation results are verified by impedance tube experiment. In addition, the method of laminated design of sound absorbing material is discussed, and the regression equation of sound absorption coefficient under each frequency band is obtained. In order to achieve the sound absorbing effect of the absorption coefficient of the target, the optimization of the proportion of three kinds of ingredients is carried out by using the mixture design method, so that the attention frequency band's sound absorption effect is precisely controlled, which provides a new way to improve the noise control of the sound absorbing material.

1. Introduction

The mixture design is a kind of experimental design method of formula proportion, which is often used in industrial and agricultural production and scientific experiments[1]. The application field of mixture design is wide and practical. For example, the effect of mixing formula of malt dextrin health-care compound table sugar on human senses can be formulated by blending design[2]. In the same way, the compound formulation design of emulsifier is also widely used in the principle of mixture design, and the regression equation is obtained through regression analysis, and the stability of ultra-high temperature sterilization milk is evaluated by variance analysis and verification test results[3].In addition to the research on the formula proportion of scientific experiments, in the industrial production, especially in the coal blending design, three different characteristics of coal as three factors for the extreme vertex method of coal blending design, set up a multiple index response optimization model, to obtain the best proportion of three factors[4]. From the present published literature, the Research of sound absorbing materials is mainly based on acoustic impedance method and the transfer matrix method. It has not been seen that the design method of mixture is applied to the optimal design of sound absorption and noise reduction. According to the application examples of the mixture optimization design in other fields, it can be concluded that the mixture design has broad application foreground in the optimum design of the sound absorbing material[5].

2. Simulation calculation and experimental verification

Considering that the optimization of laminated mixture design is a design based on the non-physical Test scheme, in order to ensure the authenticity and practicability of the mixture design results, the sound absorption characteristics of three kinds of sound absorbing materials used in the mixture are tested[6]. In this paper, superfine glass fiber, hemp wool and polyurethane are used as the ingredients for the test design of laminated mixture. The sound absorbing material is simulated by using the special Noise control processing module of VA One software, as showed in Figure 1[7]. Among them, the thickness of a thin aluminum plate (1mm) can be set to reduce the effect of sound insulation on the simulation accuracy. The sound absorbing material is covered on the right side of the median plate of the two cavities, and the thickness of three kinds of sound absorbing materials is set to 20mm and 40mm respectively. The constant external excitation is applied to the left cavity of the simulation model, and the sound pressure level of the right cavity is used as the response value. The response characteristics of three kinds of sound absorbing materials in the frequency range of 200Hz-6300Hz 1/3 time Octave are shown in Figure 2.

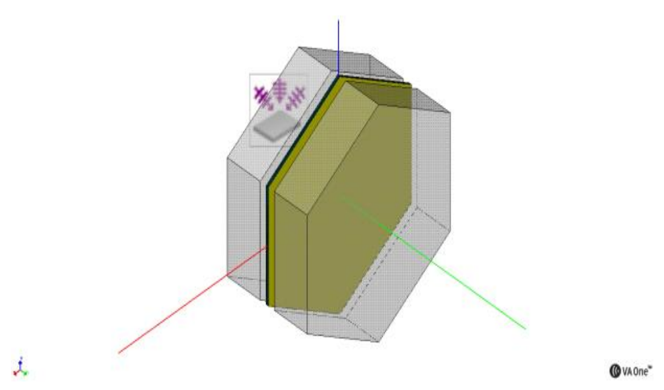

Figure 1. Experimental simulation model of sound absorption charact-eristics.

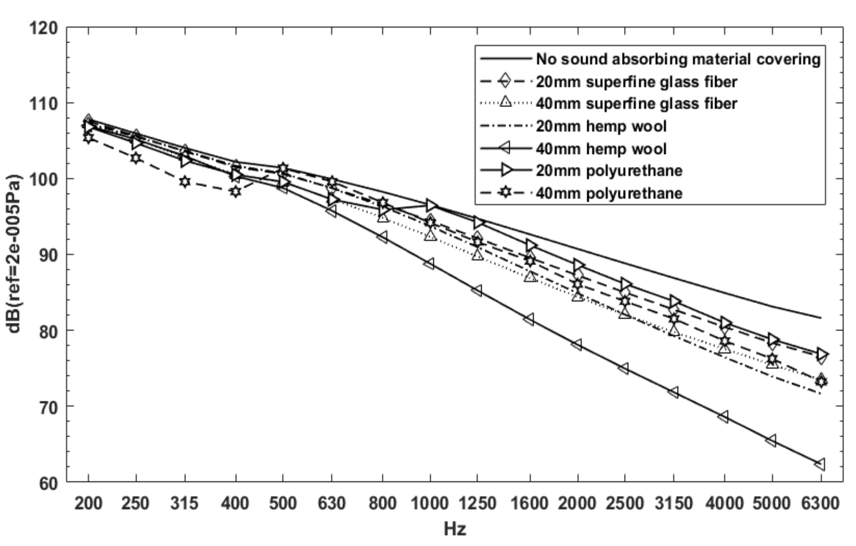

Figure 2. Response sound pressure level results of simulation calculation of sound absorption characteristics

The setting of the characteristic parameters of the sound absorbing material is very important to the simulation result, the density, flow resistivity, porosity, tortuosity, viscous c.l. and thermal c.l. determine the sound absorption coefficient of the sound absorbing material in the frequency band, and the characteristic parameters of three kinds of materials are shown in table 1.

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Table 1. Characteristic parameters of sound absorbing materials.

Properties	superfine glass fiber	hemp wool	polyurethane
Density(kg/ m^3)	16	50	22
Flow resistivity(N.s/ m^4)	9000	4.5e+004	5000
Porosity	0.99	0.92	0.96
Tortuosity	1	1.5	1.24
Viscous c.l. (m)	0.000192	5.6e-005	0.000105
Thermal c.l.(m)	0.000384	0.000122	0.00034

Based on the extension of the Biot theory of porous media, both longitudinal and transverse waves should be considered at the same time in the planar propagation model of sound absorbing materials established in the Noise control processing module[8]. The sound pressure level result obtained by the simulation calculation is converted into the corresponding sound absorption coefficient by formula 1, and the sound absorption coefficient of three kinds of sound absorption materials is shown in Figure 3.

$$\alpha = \frac{10^{L_{Pj}/10} - 10^{L_{Po}/10}}{10^{L_{Pj}/10}} \tag{1}$$

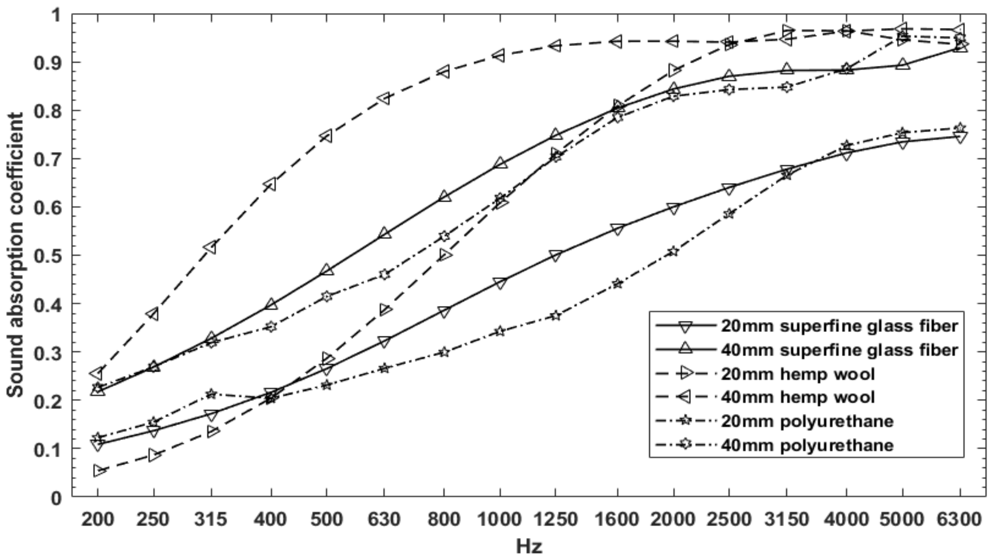

Figure 3. simulation results of sound absorption coefficient of sound absorbing material.

After the simulation results are obtained, the B&K PULSE 7758 impedance tube, b&k4187 microphone and its amplifier are used, and the input module of the B&K3560C data acquisition system is used to calculate the sound absorption coefficient of the experimental measurement by measuring the incident and reflection sound pressure of the white noise emitted by the sound source in the impedance tube[9]. The impedance tube is divided into a large tube and a small tube. The test frequency range of the small tube is 500-6400Hz and the large tube is 50-1600Hz[10]. The test system is illustrated in figure 4. According to the requirements of the impedance tube test, the material to be measured need to be cut to 30mm and 100mm cylindrical samples. Ultra-fine glass fiber, polyurethane, cashmere thickness of 20mm and 40mm, the thickness of the materials and components as showed in Figure 5.

Figure 4. Test system.

Figure 5. Test sample.

The continuous spectra of the three sound absorbing materials with 20mm and 40mm thickness respectively are shown in Figure 6.

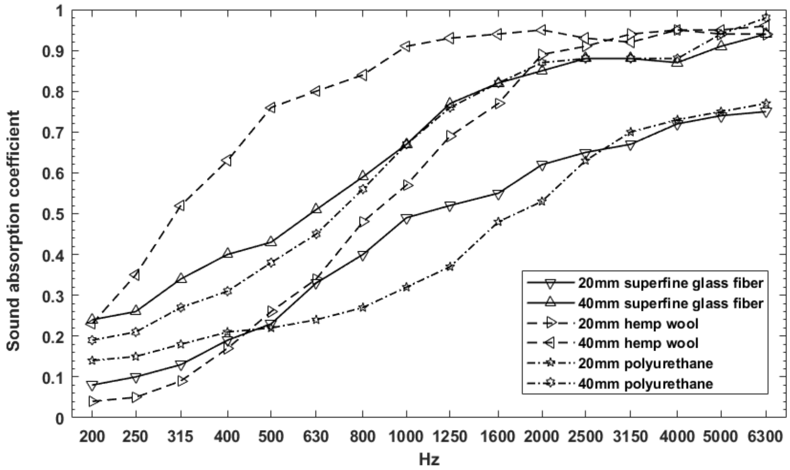

Figure 6. Experimental results of sound absorption coefficient of sound absorbing materials.

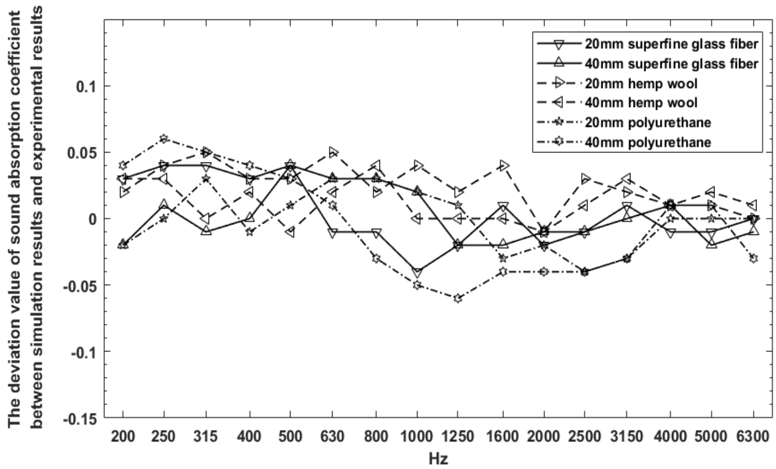

Figure 7. The deviation value between the simulation result and the experimental result.

The simulation results from Figure 3 and the experimental results of figs. 6 shows that with the increase of the thickness of three kinds of materials, the sound absorption coefficient increases, the sound absorption peak moves to the low frequency, and the low frequency sound absorption performance increases. When the thickness of the cashmere reaches 40mm, it shows a good sound absorption effect in low frequency. On the other hand, Figure 7 shows that the deviation of the simulation results of sound absorption coefficient and experimental results is basically less than 0.1, we can think that the simulation calculation is accurate. On the premise of guaranteeing the accuracy of simulation calculation, the optimization process of mixture design can be effectively saved by simulation calculation and the research efficiency is improved.

3. Laminated mixture design

The mixing design of laminated sound absorbing material is aimed at controlling the sound absorption effect in the frequency band. In Practical engineering application, if we want to develop high performance wide band sound absorbing material, even can realize the active control to the sound absorption coefficient in any one band, this makes the laminated mixture design with the sound absorption coefficient as the target have practical significance[11,12,13].

Set 10mm-60mm thickness of ultra-fine glass fiber, hemp wool and polyurethane sound absorption material as a mixture of ingredients, using the simplex centroid design, and through the shaft point to enhance the design, without requiring that any component must exist in the mixture or the mixture contains a component can not exceed the specified ratio, The upper and lower bounds of the three components are set to 0 to 1. The design of the simplex centroid is shown in Figure 8, and Table 2 is a simplex design table.

Table 2. simplex Design table and response results.

No	SGF	HW	P	200Hz	250Hz	315Hz	400Hz	500Hz	630Hz	800Hz	1000 Hz	1250 Hz
1	40	10	10	0.40	0.50	0.60	0.71	0.79	0.86	0.92	0.95	0.97
2	10	40	10	0.47	0.60	0.71	0.79	0.85	0.88	0.91	0.92	0.93
3	10	10	40	0.31	0.38	0.45	0.54	0.64	0.74	0.83	0.89	0.93
4	30	30	0	0.56	0.68	0.76	0.82	0.86	0.89	0.90	0.91	0.91
5	20	20	20	0.37	0.47	0.58	0.69	0.78	0.85	0.91	0.94	0.96
6	0	0	60	0.32	0.37	0.43	0.50	0.58	0.67	0.76	0.83	0.88
7	0	30	30	0.30	0.40	0.51	0.63	0.73	0.83	0.90	0.94	0.97
8	30	0	30	0.32	0.38	0.45	0.54	0.62	0.71	0.80	0.87	0.91
9	0	60	0	0.60	0.73	0.80	0.84	0.86	0.87	0.88	0.89	0.90
10	60	0	0	0.34	0.41	0.49	0.57	0.65	0.73	0.80	0.85	0.89

No	SGF	HW	P	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz	6300 Hz	8000 Hz
1	40	10	10	0.97	0.96	0.94	0.94	0.97	0.97	0.98	0.98
2	10	40	10	0.94	0.95	0.96	0.97	0.98	0.98	0.98	0.99
3	10	10	40	0.94	0.95	0.96	0.99	0.98	0.98	0.98	0.98
4	30	30	0	0.92	0.92	0.93	0.96	0.97	0.96	0.97	0.97
5	20	20	20	0.96	0.97	0.97	0.98	0.98	0.97	0.98	0.98
6	0	0	60	0.89	0.89	0.91	0.96	0.96	0.95	0.99	0.98
7	0	30	30	0.98	0.98	0.98	0.98	0.97	0.98	0.98	0.99
8	30	0	30	0.92	0.91	0.90	0.93	0.98	0.96	0.97	0.97
9	0	60	0	0.92	0.93	0.95	0.96	0.96	0.97	0.97	0.97
10	60	0	0	0.92	0.93	0.94	0.94	0.96	0.97	0.97	0.98

From Figure 9 We can know that the relationship between the ratio of proportioning of each ingredient in different frequency bands and the size of sound absorption coefficient is more intuitively reflected by using response tracking chart.

Mixed Isoline graph and response surface graph show the proportional area range of expected target values in different frequency bands as showed in Figure 10.

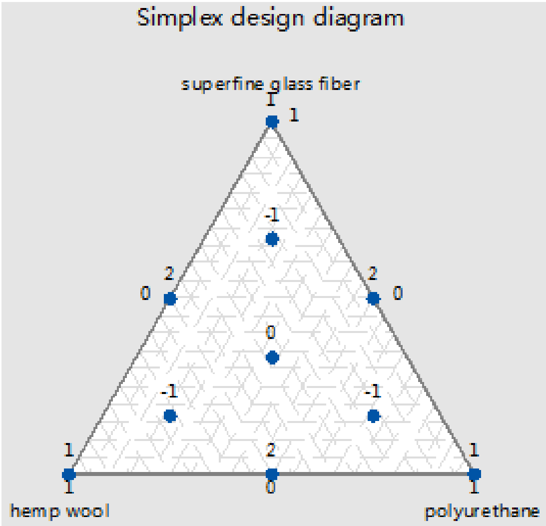

Figure 8. Simplex design diagram.

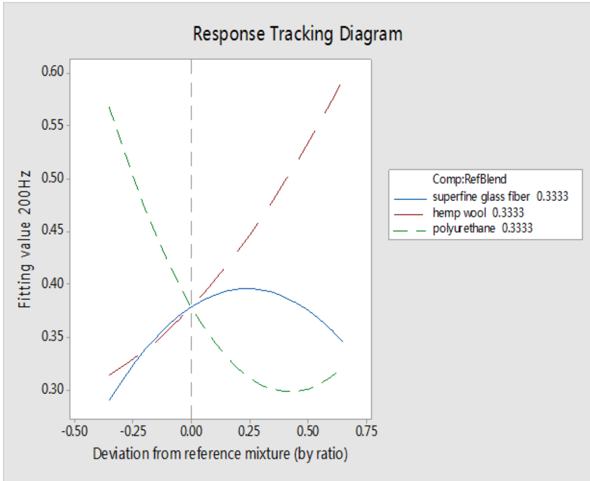

Figure 9. 200Hz Response tracking diagram.

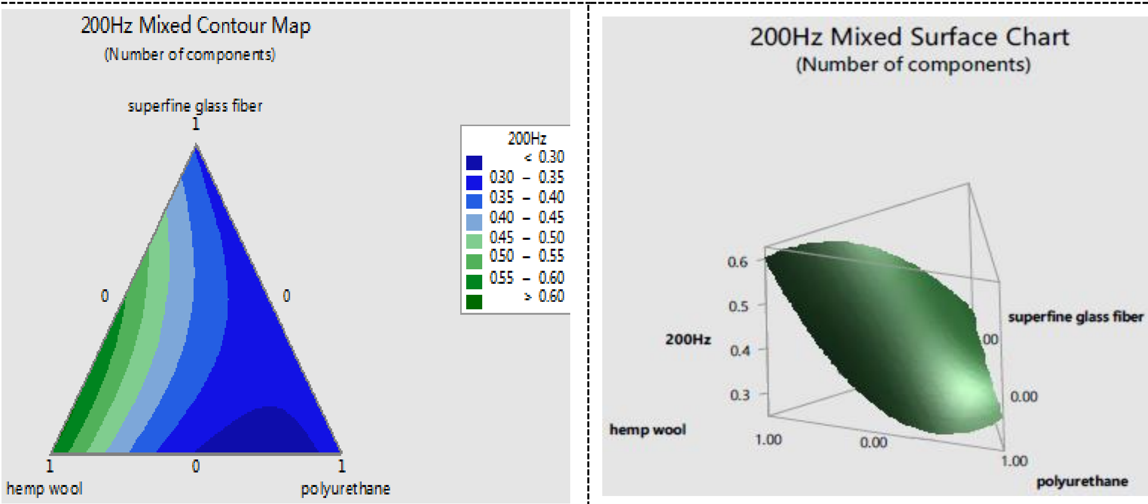

Figure 10. 200Hz mixed Contour graph and response surface graph.

The estimated regression coefficient (component ratio) and variance analysis Table of the response sound absorption coefficient are shown in table 3 and table 4 for the mixture regression analysis of frequency 200Hz.

Table 3. Estimated regression coefficient of 200Hz (component ratio).

Item	Coefficient	Coefficient standard error	T	P	Variance expansion Factor
superfine glass fiber	0.3409	0.006362	*	*	1.964
hemp wool	0.6023	0.006362	*	*	1.964
polyurethane	0.3257	0.006362	*	*	1.964
superfine glass fiber*hemp wool	0.3412	0.029320	11.64	0.000	1.982
superfine glass fiber*polyurethane	-0.0668	0.029320	-2.28	0.085	1.982
hemp wool*polyurethane	-0.6697	0.029320	-22.84	0.000	1.982

S = 0.00659627 PRESS = 0.00289679
Sq = 99.84% R-Sq (Forecast) = 97.32% R-Sq (Adjustment) = 99.64%

Table 4. Variance analysis of the sound absorption coefficient of 200Hz response.

Source	Freedom	Seq SS	Adj SS	Adj MS	F	P
Regression	5	0.107792	0.107792	0.021558	495.47	0.000
Linear	2	0.078843	0.053196	0.026598	611.30	0.000
Two quadratic	3	0.028949	0.028949	0.009650	221.78	0.000
sgf*hw	1	0.006049	0.005893	0.005893	135.43	0.000
sgf*p	1	0.000199	0.000226	0.000226	5.19	0.085
Hw*P	1	0.022701	0.022701	0.022701	521.73	0.000
Residual error	4	0.000174	0.000174	0.000044		
Total	9	0.107966				

From the above table data analysis that:

- Superfine glass fiber, hemp velvet, polyurethane, superfine glass fiber * hemp velvet and hemp velvet*Polyurethane have a significant effect on the response to sound absorption coefficient in the 200Hz frequency band of laminated mixtures, and the P value is less than 0.05 in the analysis of variance, that is, both linear and two regression are significant.
- r-sq = 99.84% indicates that the model is well designed, and when R-SQ is less than 85%, the model design is not good.
- The polynomial regression equation of the 200Hz ternary two Gravity Center is:

$$y_{200Hz} = 0.34x_1 + 0.60x_2 + 0.33x_3 + 0.34x_1x_2 - 0.07x_1x_3 - 0.67x_2x_3 \quad (2)$$

The results of 200Hz-8000Hz band mixture regression analysis are shown in table 5.

Table 5. Coefficient of regression equation.

Frequency band	200Hz	250Hz	315Hz	400Hz	500Hz	630Hz	800Hz	1000Hz	1250Hz
x_1	0.341	0.413	0.494	0.581	0.662	0.739	0.809	0.861	0.900
x_2	0.602	0.729	0.805	0.842	0.858	0.867	0.875	0.884	0.894
x_3	0.326	0.367	0.427	0.490	0.571	0.660	0.756	0.828	0.872
x_1x_2	0.341	0.431	0.510	0.535	0.503	0.421	0.313	0.208	0.114
x_1x_3	-0.067	-0.024	-0.002	0.046	0.070	0.116	-0.150	0.163	0.147
x_2x_3	-0.670	-0.613	-0.432	-0.151	0.075	0.252	0.328	0.333	0.318
Frequency band	1600Hz	2000Hz	2500Hz	3150Hz	4000Hz	5000Hz	6300Hz	8000Hz	
x_1	0.927	0.936	0.933	0.933	0.959	0.972	0.967	0.976	
x_2	0.909	0.925	0.942	0.954	0.962	0.968	0.970	0.973	
x_3	0.883	0.884	0.910	0.966	0.965	0.952	0.985	0.978	
x_1x_2	0.030	-0.014	0.002	0.065	0.029	-0.016	0.026	0.009	
x_1x_3	0.103	0.045	-0.019	-0.033	0.060	0.001	0.004	-0.008	
x_2x_3	0.318	0.321	0.277	0.131	0.045	0.108	0.040	0.050	

From table 5, we know that the proportion of three kinds of sound absorbing materials can be arbitrarily distributed under the condition that the sum of the proportion is 1, and the coefficient of sound absorption of the laminated mixture is obtained by the ternary two quadratic regression equation of each frequency band.

4. Optimization solution

The optimal ratio of sound absorption effect is solved by the regression equation of the sound absorption coefficient in each frequency band. We assume that the target value of the sound absorption coefficient at each frequency is $\hat{y}_i$ $(i = 1,2,..,6)$. The principle of the least squares method is to minimize the square sum of the residuals, i.e. the difference between the simulated test value y_i and the target value $\hat{y}_i$. Set the number of test data sets to M, the residual square sum is as follows:

$$\phi = \sum_{i=1}^{M} (y_i - \hat{y}_i)^2 \tag{3}$$

When the sum of residual squares is estimated under the minimum condition, the equation Group is solved:

$$\frac{\partial \phi}{\partial x_i} = 0, i = 1,2,3 \tag{4}$$

Because of the existence of equality constraint $x_1 + x_2 + x_3 = 1$, the Equality constraint optimization can be transformed into the equivalent minimum problem of Lagrangian function.

$$\min L(\phi, L) = \phi + L(x_1 + x_2 + x_3 - 1) \tag{5}$$

So as to solve the problem of inequality equations:

$$\frac{\partial L(\phi, L)}{\partial x_i} = 0 \tag{6}$$

For a single band of sound absorption coefficient, the largest absorption coefficient of the ingredients is the best. The formula (3)-formula (6) can be used to calculate the overall optimal ratio of multiple-band inner laminated mixture design. For the target of the sound absorption coefficient specified in multiple frequency bands, and the sound absorption coefficient is required by the boundary condition, optimal ratio can be solved by the response optimization solver.

Table 6. Response Optimization Design Table

Response to sound absorption coefficient	lower	Target	maximums	Weight	Importance
200Hz	0.2	0.36	0.5	1	1
500Hz	0.5	0.72	0.8	1	1
1600Hz	0.7	0.95	1.0	1	1

Solution:

Component	Superfine glass fiber	hemp wool	polyurethane	Consensus
Local Solution1	0.525	0.155	0.320	0.993
Local Solution2	0.580	0.123	0.296	0.969
Local Solution3	0.767	0.003	0.231	0.806
Local Solution4	1	0	0	0.838
Global Solution	0.525	0.155	0.320	0.993

The response values of the predicted sound absorption coefficients obtained by the ratio of the whole solution are as follows:

200Hz=0.359795 500Hz=0.719563 1600Hz=0.945856

According to the result of the sound absorption coefficient of the three concerned frequency bands, we can think that using the laminated mixture design method to optimize the ratio. The sound absorbing material can precisely control the absorption coefficient of the frequency band.

5. Conclusions

This study has the following three conclusions:

(1) The sound absorption coefficient measured by the statistical energy model is consistent with that of the impedance Tube experiment, which shows that the simulation calculation of the mixture design using the statistical energy model can ensure the validity of the result.

(2) Laminated mixture design of sound absorbing materials using the simplex centroid design model in the mixture design, the regression coefficients and variance of the response sound absorption coefficients can be used to calculate the coefficients of the frequency bands under any ratio.

(3) The solution of the laminated mixture design of sound absorbing material can be realized by the response Solver optimizer. The optimized direction is based on the demand of the frequency-absorbing coefficient to set the optimization conditions. Through the ratio of the mixture of sound absorption materials, can accurately control the mixing material in a different frequency band of sound absorption characteristics.

Acknowledgements

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