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Cite this article as:

Ren Xiao-He, Sun Gao-Hui, Wang Lei-Chao, Chen Rong-Rong, Wang Jun, Han Shi-Hui. Facile Adjusting for Cells of Lightweight Isocyanate-based Polyimide Foam and Operable Combination between Different Distinctive Acoustic Foams for Higher Performance[J]. *Chinese J. Polym. Sci.*, 2021, 39(2): 237-248. doi: 10.1007/s10118-020-2482-y

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Facile Adjusting for Cells of Lightweight Isocyanate-based Polyimide Foam and Operable Combination between Different Distinctive Acoustic Foams for Higher Performance

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Abstract New ambient sound absorption material, lightweight isocyanate-based polyimide foam (IBPIF), was fabricated by operable combination between different distinctive acoustic IBPIF. Cellular structure of IBPIF was facilely and obviously adjusted by increased slurry temperature corresponding to change in distinctive acoustic properties. Moreover, density of all IBPIF kept at only 12–17 kg/m³. With increasing slurry temperature from 0 °C to 40 °C, cell size and window opening rate gradually increased from 553 μm to 791 μm and from 6.85% to 58.46%, respectively. In this study, IBPIF generated by slurries at 0 °C (marked as PIF-2) and 40 °C (marked as PIF-6) showed best and distinctive acoustic behavior in 315–800 Hz and 800–6300 Hz regions, respectively. After acoustic behavior study of combined IBPIF prepared by stitching combination between two distinctive acoustic IBPIFs, results showed that only when PIF-6 sheet used as sound receiving surface even though with thickness of only 10 mm could the combined IBPIF possess the best acoustic level in 800–6300 Hz region as PIF-6. Further, acoustic behavior in 315–800 Hz region could be significantly enhanced by increasing thickness of PIF-2 and could reach or close to the best acoustic level.

Keywords Isocyanate-based polyimide foam; Slurry temperature; Cellular structure; Distinctive acoustic; Combination style

Citation: Ren, X. H.; Sun, G. H.; Wang, L. C.; Chen, R. R.; Wang, J.; Han, S. H. Facile adjusting for cells of lightweight isocyanate-based polyimide foam and operable combination between different distinctive acoustic foams for higher performance. *Chinese J. Polym. Sci.* 2021, 39, 237–248.

INTRODUCTION

Noise pollution, mainly including urban noise, industrial noise and traffic noise, which seriously affects people's work, study, physical and mental health, has become one of the three major environmental problems that need to be solved in the world.^[1–5] Porous material is an effective noise reduction material, as sound intensity will be decreased through friction loss, viscous loss, heat conduction and other mechanisms when the sound waves spread into the porous sound-absorbing material.^[6,7] The porous sound-absorbing materials mainly include porous metal materials, porous ceramic materials, and plastic porous materials. Due to their lightweight, easy post-processing, and low cost, plastic porous materials play an important role in the field of sound absorption.^[8–10]

As a new type of high-performance polymeric foamed material, the lightweight isocyanate-based polyimide foam (IBPIF) has more excellent environmental resistance, wider application temperature range, and higher using security compared with traditional polymeric foams.^[11–13] Therefore, it has a wider application field in comparison with other poly-

meric foamed materials. However, up to now, reports on IBPIF mainly focus on preparation technology and modification in flame retardancy, mechanical properties, heat insulation behaviors, and other aspects, with little research on acoustic properties.^[14–16]

Ma *et al.* have reported the acoustic behavior of IBPIF sheets as a non-main section during the systematical and deep study on its mechanical and thermal insulation properties.^[17] It indicates that IBPIF sheets present poor acoustic behavior compared with melamine foam. Although in 500–6300 Hz region, in which the thickness of materials has almost no effect on their acoustic behavior, the sound absorption coefficient (α) of IBPIF is only 0.1–0.5.^[18] In 2018, Yao *et al.* have reported their IBPIF with a better acoustic behavior and density of about 15 kg/m³, the value of sound absorption coefficient (α) maintains around 0.9 from 1850 Hz to 6400 Hz, and slope of α curve keeps at about 0.5/kHz from 200 Hz to 1850 Hz.^[19] The ameliorating in sound absorption performance owes to the change in cellular structure including porosity, size distribution, and so on. Our previous work has reported that IBPIF with a sharp hole structure, density reaching to 129 kg/m³, the average cellular windows size about 84 μm, and 50 mm thickness can ensure the α maintaining around 0.9 from 900 Hz to 6300 Hz and especially the slope of α curve keeping at about 1.0/kHz from 200 Hz to 900 Hz.^[20] However,

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Received May 21, 2020; Accepted July 13, 2020; Published online September 7, 2020

comprehensive influences coming from density about 8 times higher than normal IBPIF, and complex designation and production process vastly increase the consumption and cost of production. It is unfavorable to meet the lightweight requirements of the application carriers and control the construction cost. These disadvantages will induce a negative impact on its wide application. Therefore, on the basis of still ensuring low density, low cost, and simple preparation process of IBPIF, how to greatly regulate cellular structure through a simple route or combination style to achieve the analogous sound absorption performance as previous study has become an urgent demand for IBPIF at present.

Fortunately, the foaming route and mechanism of IBPIF are derived from that of polyurethane foam (PUF) which depends on the free foaming of foaming mixture slurries.^[20–22] Free foaming process all depends on reaction between isocyanate groups and water which can generate carbon dioxide (CO₂). In this reaction, the forming of carbamate is the rate determining step, then carbamate will rapidly decompose and release CO₂.^[23,24] Therefore, the research foundation in PUF can be used to provide designation direction about the effective and simple adjusting technology of IBPIF cellular structure and improvement in acoustic performance. The foaming process includes the steps of bubble nucleation, growth, coalescence, and finally stabilization.^[25–27] The nucleation and growth processes mainly affect the number and size distribution of bubbles, respectively. Meanwhile, the occasional coalescence further controls cellular size distribution. In conclusion, the most important thing is that the foaming process directly affects the final structure of cells and determines the acoustic properties of materials.

For the water free foaming process, temperature plays an extremely important role in determining the foaming process and pore structure in addition to formulation, which runs through the whole process.^[28] According to the experiment and analysis reported by systematic study, when the slurry temperature increases from 10 °C to 30 °C, rate determining step of reaction between isocyanate and water is increased by twice.^[29] Subsequently, the generation rate of CO₂ is logically promoted with increasing slurry temperature. As a result, the nucleation rate is increased and the formation of bubbles is immensely promoted. Then, the generation rate of CO₂ and speed of changing in pressure in bubbles are all promoted. It also results in the change in matching relationship between foaming slurry viscosity and gas diffusion. Then a dramatic change in cellular structure concomitantly occurs. The important influence of temperature on the preparation of PUF has been discussed by related researches. The temperature of slurries increasing from 25 °C to 40 °C results in elevation almost 200% and 700% in opening cell percentage and cellular window area, respectively.^[30] Meanwhile, the cell size gradually increased with the increasing slurry temperature.^[31]

In order to prepare IBPIF with excellent acoustic behavior and lightweight property by effective and direct route, the

method of controlling the temperature of foaming slurry was adopted to prepare a series of IBPIF. The effects of slurry temperature on cellular structure and acoustic properties of IBPIF were investigated in detail. Furthermore, in order to prepare IBPIF with excellent sound absorption properties from 100 Hz to 6300 Hz, the combination of different IBPIF with distinctive acoustic behavior in specific frequency range was designed. Then the combined effect and regular pattern were systematically studied. It is necessary to find the supposed effects of acoustic behavior. In particular, the effects of foaming slurry temperature and furtherly designed combination on the average α of IBPIF in the range of 100–315, 315–800, and 800–6300 Hz were investigated.

EXPERIMENTAL

Materials

3,3',4,4'-Benzophenone tetracarboxylic acid dianhydride (BTDA) was supplied by Beijing Multi Technology Co., Ltd., China. Poly(methylene polyphenylene isocyanate) (PAPI) (trade name PM200), which contains 31.3 wt% free isocyanate group, was obtained from Yantai Wanhua Polyurethanes Co., Ltd., China. Dabco-33 and dibutyltin dilaurate (T12) were employed as catalysts for foaming process, obtained from Tianjin Guangfu Fine Chemical Institute, China. Triethanolamine was purchased from Sinopharm Chemical Reagent Co., Ltd., China. Polyethylene glycol-600 (PEG-600) and polysiloxane-polyether copolymer (AK8805) were supplied by Tianjin Guangfu Fine Chemical Institute, China, and Nanjing Dymatic Shichuang, China, respectively. *N,N*-dimethylformamide (DMF) and methanol were acquired from Sinopharm Chemical Reagent Co., Ltd., China.

Sample Preparation

Synthesis of precursor solution^[32]

BTDA (170 g) was first added into a flask containing DMF (250 g) at room temperature. Then, it was heated to 110 °C and stirred until BTDA dissolved completely and a clear solution with faint yellow was got. Afterwards, the solution was cooled to 60 °C and methanol (35.25 g) was dropped into the solution accompanied by an electromagnetic stirring. After esterification reaction between BTDA and methanol finished, a clarified solution was got and named as the precursor solution.

Preparation of foaming slurry

Foaming slurry A was the mixture of the precursor solution, Dabco-33, T12, triethanolamine, AK8805, PEG-600, and deionized water as listed dosage in Table 1. PM200 (60.0 g) was marked as slurry B. Then slurries were put into the same temperature controlling equipment to adjust temperature and ensure slurry A and B possessing the same temperature.

Preparation of IBPIF

In order to study effects of different slurry temperatures on cellular structure and acoustic performance of IBPIF, IBPIF samples which used slurries at −10, 0, 10, 20, 30 and 40 °C were prepared, and then marked as PIF-1, PIF-2, PIF-3, PIF-4, PIF-5 and

Table 1 Components of slurry A.

Precursor solution (g)	Dabco-33 (g)	T12 (g)	Triethanolamine (g)	AK8805 (g)	PEG-600 (g)	Deionized water (g)
40.0	0.2	0.4	1.0	5.0	5.0	5.3

PIF-6, respectively. The detailed preparation route is shown as following description. When the temperature of two foaming slurries was adjusted to the set value, slurry B was fast poured into slurry A at room temperature followed by a fast and continuous mechanical agitation (1500–2000 r/min) for approximately 20 s. Following this, the homogeneously mixed slurry was poured into a plastic mold that allowed the slurry to foam freely. After foaming and crosslinking processes were completed, the foam precursor was got. Subsequently, foam precursor was transferred to an oven and cured at 180 °C for 2 h to produce the lightweight IBPIF. The whole preparation flow chart could also be found in Fig. 1. The actual pictures of samples cropped and used for sound absorption test is also showed in Fig. 1.

Characterization

The Fourier transform infrared spectra (FTIR) were recorded between 400 and 4000 cm^{-1} with sheets using a PerkinElmer Spectrum 100 spectrophotometer (PerkinElmer, USA). The translucent sheets made of polymer powder and KBr powder at 1:100 were scanned eight times at a resolution of 1.0 cm^{-1} .

The microstructure of the gold-plated IBPIF section parallel to the direction of foam growth was scanned using a scanning electron microscope (SEM), model FEI Quanta 200, at acceleration voltage of 12.5 kV. Image-pro Plus 6.0 software was used to calculate the cell microstructure parameters based on SEM images, including the average cellular window size, opening rate, pore distance, and cell size.

Sound absorption coefficient curves were obtained by using an impedance tube device (SW422 and SW477 impedance tubes, BSWA, China) according to the measurement standard (GB/T18696.2-2002). Cylindrical samples with diameter of 100 and 30 mm were used to test for frequency of 63–1800 and 800–6300 Hz, respectively. Their thicknesses

were all 50 mm. In order to ensure the accuracy, 5 tests were accomplished for every sample. The comprehensive α curve from 63–6300 Hz was got by fitting those from 63–1800 and 800–6300 Hz together. In particular, the one-third octave curve was drawn and discussed in detail.

RESULTS AND DISCUSSION

Chemical Structure and Foaming Process

Fig. 2 shows the FTIR spectra of IBPIF, and the absorption bands exhibit similar relative strength in all curves. The characteristic absorption bands at 1778, 1724, 1373, and 721 cm^{-1} belonged to asymmetric stretching vibration of carbonyl group, symmetric stretching vibration of carbonyl group, —C—N— stretching vibration, and —C—N— bending vibration out of the plane of imide groups, respectively. These revealed generation of imide rings in IBPIF matrix.

In the foaming process of IBPIF, nucleation type was the chemical reaction nucleation, in which nucleation went through the liquid reaction process and the gas was produced in the mixing process. As shown in Fig. 3, the nucleation stage mainly depended on the reaction of isocyanate groups with water and the dissolution of gases in the mixing process. The specific reaction equations is shown in Scheme 1. The step of forming carbamate was a rate determining step of whole reaction. When carbamate was generated, it quickly decomposed to form amine groups and CO_2 with lots of heat releasing. When the CO_2 concentration exceeded the equilibrium saturation concentration, fine bubbles began to form in the mixed liquid. With the continuous releasing of CO_2 , the inner pressure of bubbles was dramatically enhanced and growth stage of cells happened followed by the expansion of the bubbles. Finally, when the phase equilibrium was reach-

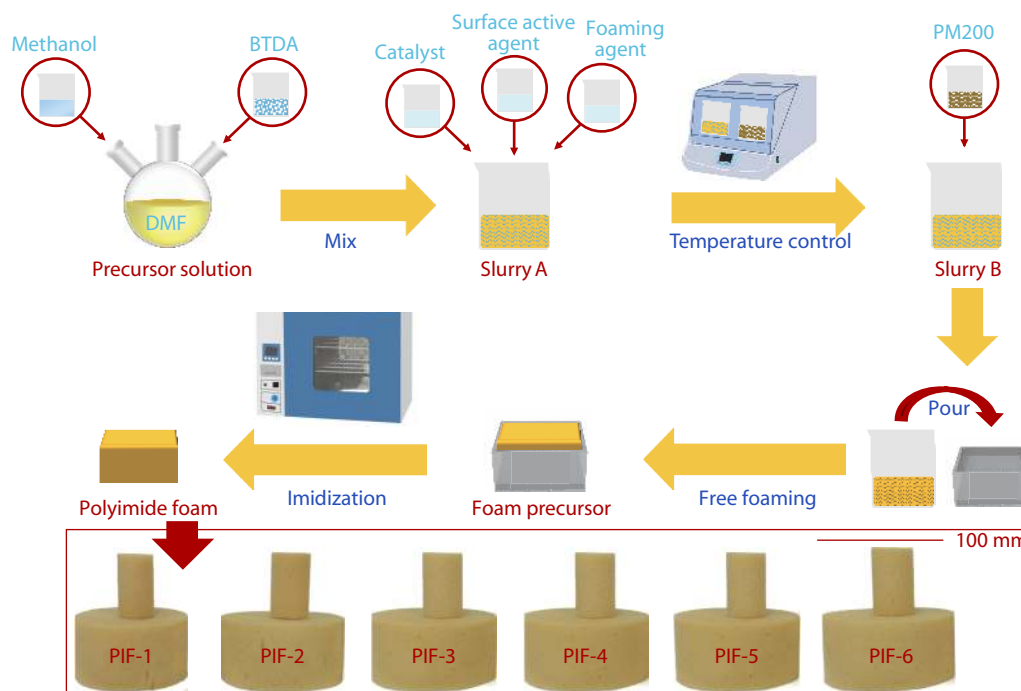


Fig. 1 The preparation flow chart of IBPIF.

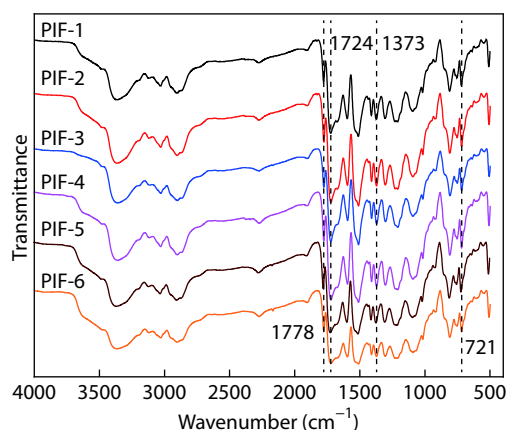


Fig. 2 FTIR spectra of IBPIF.

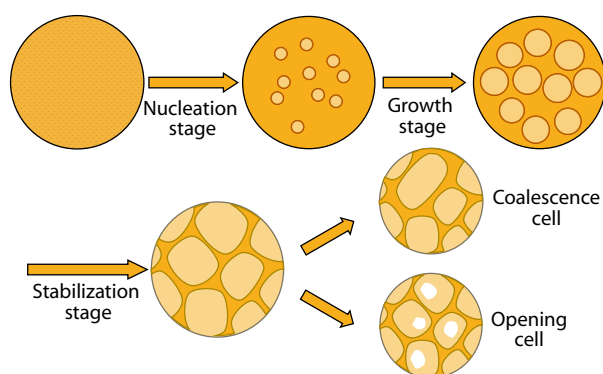
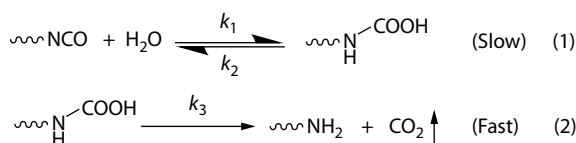


Fig. 3 Schematic diagram of the foaming process.



Scheme 1 The chemical reaction of CO₂ generation.

ed, the bubbles were basically in a stable stage. The surface tension and viscosity of the slurry determined the stability of the bubbles. At this stage, the process of coalescence and membrane rupture might occur in the bubbles. The main reason for this phenomenon was that the matrix strength was not enough to support the bubble hole and manacle CO₂. Meanwhile, liquid foam systems always tend to reduce the interface area and then form coalescence cell or opening cell.^[33]

Cellular Morphological Structures of IBPIF

In Fig. 4, SEM images present the porous structure of the IBPIF. Furthermore, the statistical pore distance, average cellular window size, and cellular window size distribution of IBPIF are shown in Figs. 5 and 6, respectively. The data of cell size, window opening rate, and apparent density are listed in Table 2.

According to the images and data, the shape of the cell was nearly spherical and the cell size tended to gradually increase with increasing slurry temperature. From PIF-1 to PIF-6, the cell size increased from 518 μm to 791 μm corresponding to a promotion by 52.6%. One reason why cell size increased was

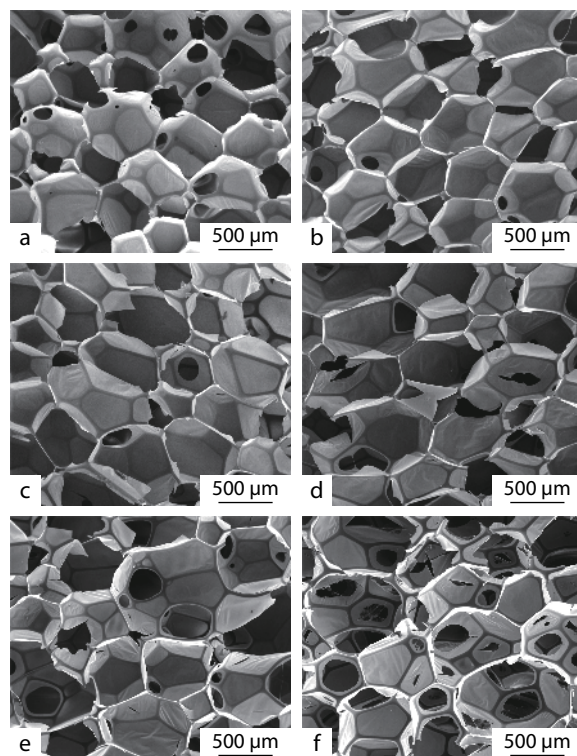


Fig. 4 SEM images of IBPIF: (a) PIF-1; (b) PIF-2; (c) PIF-3; (d) PIF-4; (e) PIF-5; (f) PIF-6.

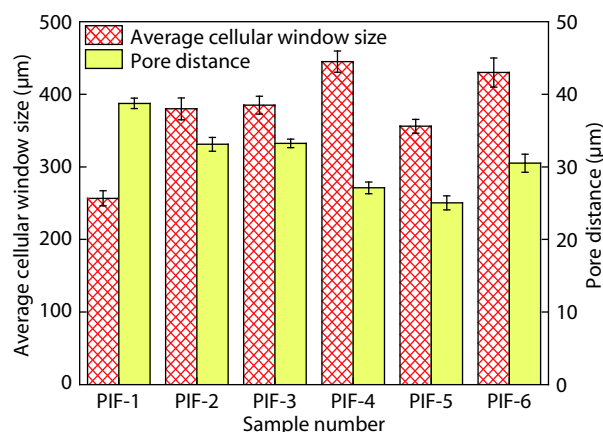


Fig. 5 Average cellular window size and pore distance of IBPIF.

that the higher temperature accelerated the reaction rate of CO₂ production, change in inner pressure of cells, and polymerization process.^[34] It also promoted the movement of molecular chains, and the reduced viscosity promoted the diffusion of CO₂ and the expansion of the gas. The opposite change was true for the pore distance owing to the above-mentioned reasons and the same dosage of slurry used to prepare the foams. At this point, the PIF-5 with larger cell size had the smallest pore distance. The slight rise of the pore distance in the sample PIF-6 might be related to the reflux of slurries to cellular skeleton caused by unstable liquid film. All these factors gave rise to the apparent density decreased by 20.88% as shown in Table 2. The density of PIF-6 was only

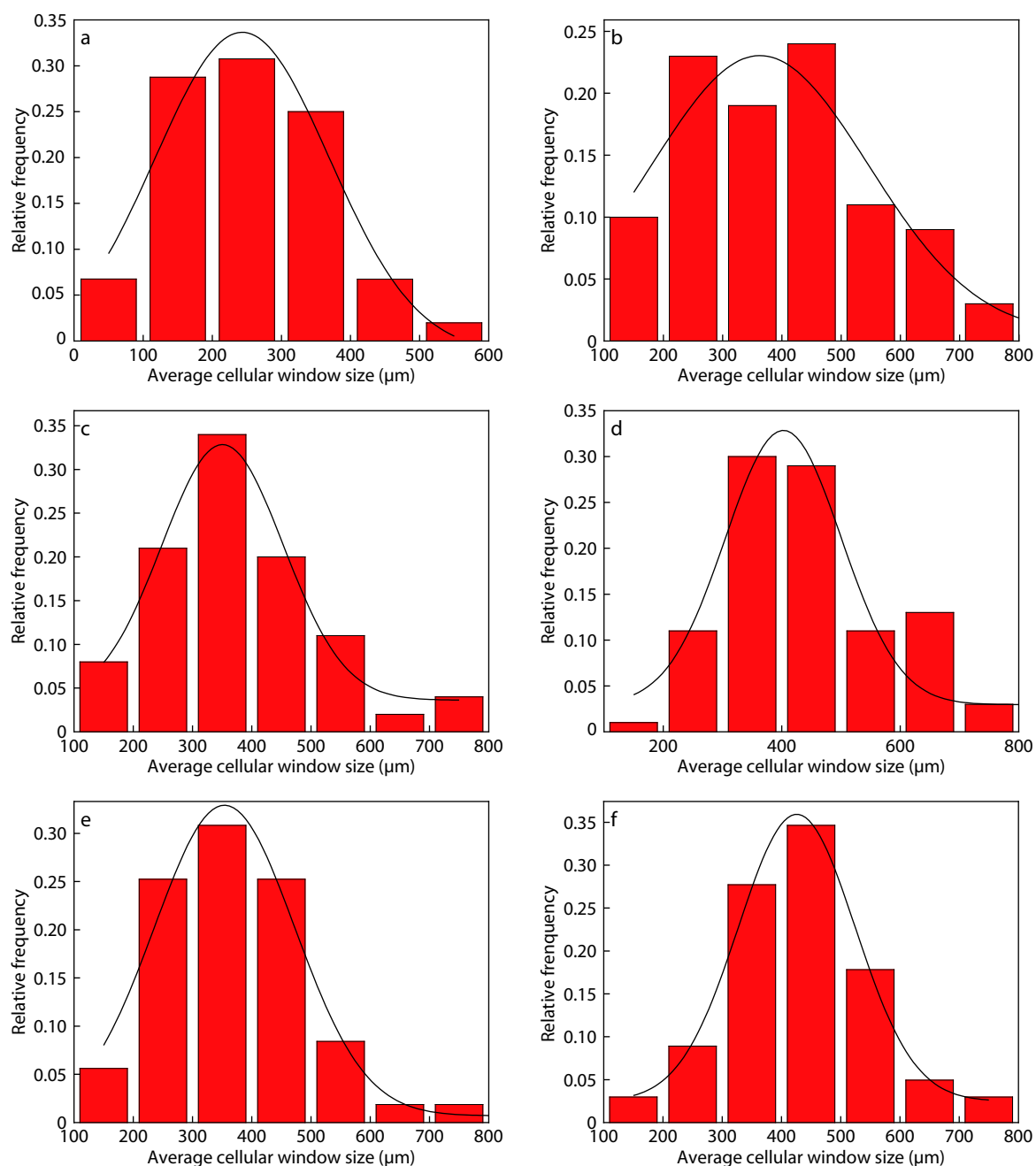


Fig. 6 Cellular window size distribution diagrams of IBPIF: (a) PIF-1; (b) PIF-2; (c) PIF-3; (d) PIF-4; (e) PIF-5; (f) PIF-6.

Table 2 Properties of IBPIF.

Sample number	Cell size (μm)	Window opening rate (%)	Apparent density (kg/m ³)	Average α			
				100–315 Hz	315–800 Hz	800–6300 Hz	100–6300 Hz
PIF-1	518±6	15.79±0.94	17.00±1.26	0.10	0.25	0.44	0.30
PIF-2	553±11	6.85±0.97	16.10±1.37	0.22	0.73	0.77	0.62
PIF-3	605±9	8.20±1.16	14.83±1.18	0.24	0.65	0.80	0.61
PIF-4	662±13	11.29±1.15	13.45±1.06	0.25	0.57	0.76	0.57
PIF-5	782±7	21.43±1.03	12.41±1.22	0.26	0.64	0.83	0.63
PIF-6	791±10	58.46±1.26	11.95±1.51	0.23	0.58	0.88	0.63

about 12 kg/m³ and presented excellent lightweight characteristic.

Under the influence of decrease in substrate viscosity and

increase in CO₂ production rate with increasing slurry temperature, the gradual thinning of cell windows membrane coupled with the effect of gravity drainage resulted in the

rupture of the liquid membrane and the backflow to the strut.^[30,35,36] Eventually, the opening behavior occurred in the cell windows. Therefore, from PIF-2 to PIF-6, when slurry temperature increased from 0 °C to 40 °C, the window opening rate was dramatically enhanced from 6.85% to 58.46% corresponding to a 753% growth. Further, especially from 20 °C to 40 °C, it could be found that the window opening rate was about doubled per 10 °C enhancement in slurry temperature. Meanwhile, the further extension and thinning of the liquid film caused by the decreased surface tension also promoted the opening of windows.^[37] But remarkably, the flow and replenishment of the liquid film were maybe limited by the lower temperature, so that the opening rate of PIF-1 was slightly higher than that of PIF-2. In addition, the reduced surface tension, enhanced CO₂ generation speed and change in inner pressure of cells, and further inflating of cells with increasing slurry temperature also promoted the extension of window surface and area which resulted in the increased cellular window size as shown in Fig. 6. For PIF-6, about 88% of the cellular window size was over 300 μm , which increased by 31.34% compared with that of PIF-2. To sum up, slurry temperature indeed violently affected the cellular structure of IBPIF.

Acoustic Performance of IBPIF

The absorption of sound wave refers to the absorption by the transmission medium, whose essence is the conversion from sound energy to heat.^[38] Sound energy could be firstly dissipated by the vibration of air molecules in cells. As a result of friction and viscous forces, the friction between air molecules and bubble walls limited the movement of nearby air molecules, finally the energy was depleted.^[39] Further, sound waves with higher energy could induce friction, viscous effect, and resonance with cellular skeleton and other structure, then resulted in a larger attenuation in the propagation process.^[40] The sound absorption coefficients (α values) of IBPIF at various one-third octave band central frequencies are shown in Fig. 7.

According to the different characteristics of low and high frequency sound waves, the acoustic property of IBPIF was analyzed and discussed by the full frequency range partition method. Therefore, in order to study the relationship between bubble structure and sound absorption performance in different frequency bands specifically, the whole test region was divided into three parts including 100–315, 315–800, and 800–6300 Hz, marked as band A, band B, and band C, respectively. The average α values of all partly bands and the whole region were calculated and listed in Table 2.

As shown in Fig. 7, α of PIF-1 was obviously worse than those of other foams in the whole region. For samples from PIF-2 to PIF-6, the α presented different distinctive acoustic behaviors in three partly bands. In band A region, the curves were basically coincident, α was increased with increasing frequency, and the slopes of the curves were all around 1.1/kHz owing to the increasing collision and friction between air molecules in cells. The average α of samples in this region was all about 0.24, and α at 315 Hz of all samples reached about 0.4. It indicated that the increasing cell size and window opening rate coming from enhanced slurry temperature made almost no effect on acoustic behavior of IBPIF in 100–315 Hz region.

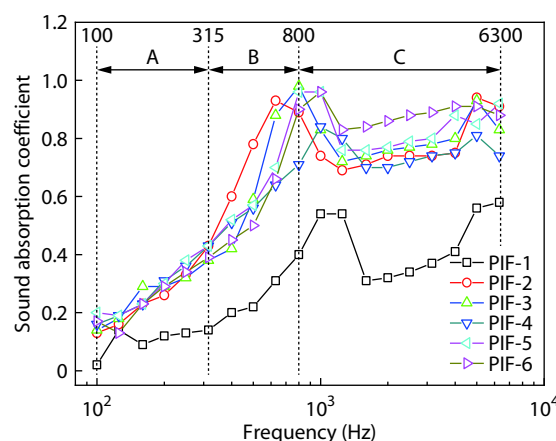


Fig. 7 Sound absorption coefficient of IBPIF at various one-third octave band central frequencies.

It was because the wavelength of sound wave in this region was all more than one meter and with too low vibration frequency and energy, then it would result in the air molecules in cells getting a slow vibration, collision, and friction followed by a high penetration effect.^[41] Thus, porous materials presented poor absorption efficiency in this region although with an obvious change in cellular structure. Enhancement of absorption efficiency of porous materials in this region mostly depended on the macro-acoustic structural design including sharp structure and backing cavity.^[20,42]

When coming to band B region, the overall absorption coefficient continued to increase with the higher slope compared with that in band A region, the slope of PIF-2 even reached to 1.6/kHz. This was because except the increasing collision and friction among air molecules in cells, the increasing energy of sound wave was enough to produce friction, viscous effect, and resonance between sound waves and materials matrix.^[43] Thus, a larger attenuation occurred. However, the most obvious result in this region was that distinctive acoustic behavior happened with changing in cellular structure of IBPIF including the cell size, window opening rate, and so on. In this study, for samples from PIF-1 to PIF-6, in band B region, PIF-2 presented the best absorption performance with an average α reaching to 0.73, and slope of α curve arriving at 1.6/kHz. The highest α value of PIF-2 in 100–6300 Hz also occurred in this region at 600 Hz, which reached to 0.93. With increasing slurry temperature, the corresponding IBPIF showed a gradually weakening acoustic behavior in band B region. For PIF-4 and PIF-6, the average α value decreased to about 0.58 and with a falling about 0.15 compared with that of PIF-2. That was a great attenuation more than 20% for the acoustic behavior. The main reason for this phenomenon was that the closed-cell resonance effect played an important role in absorption of sound waves in band B for IBPIF with high closed pore rate. For sound waves in band B, it was also easy to be diffracted when encountering obstacles because of its long wavelength. The combination of small opening rate and cavity resonance forces consumed sound energy.^[44] In this case, the friction effect with the inner pore surface had little effect on the attenuation of

sound waves.

Sound waves at band C belonged to high frequency sound wave, which were easy to attenuate and dissipate during the propagation process in polymeric porous materials.^[45] The difference from the increase of α value with increasing sound waves frequency in band A and band B was that the overall α was basically stable in band C, especially in the region above 1100 Hz where the curves were basically straight lines. Meanwhile, in this study, with increasing slurry temperature from -10 and 0 °C to 40 °C, in band C region, the corresponding IBPIF showed a gradually stronger acoustic behavior until PIF-6. As listed in Table 2, from PIF-2 to PIF-6, the average α value in band C region gradually increased from 0.77 to about 0.88 with a promotion of about 14%. Due to the high collision probability of air medium molecules under action of sound waves in this region, higher opening rate provided more abundant channel through which sound waves in band C could be easily converted into heat energy and dissipated by friction with the pore wall.

The significant difference between PIF-1 and other samples in acoustic behavior maybe was caused by the too small cell size, uneven distribution, fewer opening rate, and so on.

In conclusion, PIF-2 with its unique cellular structure showed distinctive acoustic behavior in band B region compared with other samples prepared with high slurry temperature set in this study, but in band C the acoustic behavior was not excellent. PIF-6 with another unique cellular structure showed distinctive sound absorption performance in band C region compared with other samples prepared with low slurry temperature set in this study. In order to study the operable combination between foams with different distinctive acoustic behaviors for higher sound absorption performance of IBPIF in the whole region, PIF-2 and PIF-6 were selected as the basic samples in the following combination study and acoustic behavior research in the next section.

Acoustic Performance of the Combined IBPIF

Design of the combined IBPIF

Inspired by the Helmholtz resonance structure and considering the effect of sample order used as sound receiving surface and sample thickness on the final sound absorption performance of

the combined IBPIF, six operable combinations were designed in this study as shown in Fig. 8. The thickness of every combined IBPIF was also kept at 50 mm. Case A means sample PIF-2 sheet was placed in front and used as sound receiving surface. The samples were marked as CS-1, CS-2, and CS-3 and corresponded to the thickness of PIF-2 sheet set as 10, 20, and 30 mm, respectively. The corresponding thickness of PIF-6 sheet in CS-1, CS-2, and CS-3 was 40, 30, and 20 mm, respectively. Case B means sample PIF-6 sheet was placed in front and used as receiving surface of sound wave. The samples were marked as CS-4, CS-5, and CS-6 and corresponded to the thickness of PIF-6 sheet set as 10, 20, and 30 mm, respectively. The corresponding thickness of PIF-2 sheet in CS-4, CS-5, and CS-6 was 40, 30, and 20 mm, respectively.

The combination flowchart of combined IBPIF and ideal acoustic absorption schematic diagram are shown in Fig. 9. Taking CS-4 as an example, sample PIF-6 with a thickness of 10 mm was placed in front as the sound receiving surface, and sample PIF-2 with a thickness of 40 mm was placed close to the back side of PIF-6 sheet. Then combined IBPIF was placed into impedance tube with PIF-6 side facing to sonic transmitter.

Sound absorption performance of the combined IBPIF

The α curves of combined IBPIF are shown in Fig. 10. The average α of combined samples in different bands were calculated and listed in Table 3. In addition, the difference in average α of combined IBPIF samples compared to the highest value of original IBPIF samples in band B (0.73) and band C (0.88) were calculated and showed in Fig. 11. In band A region, the α curves of all combined samples were basically coincident with those of PIF-2 and PIF-6.

From Fig. 10(a) to Fig. 10(c), for case A, with increasing sheet thickness of PIF-2 which possessed the best acoustic behavior in band B as a sound absorption surface and decreasing sheet thickness of PIF-6 which possessed the best acoustic behavior in band C in this study, the absorption curves of combined IBPIF samples from CS-1 to CS-3 gradually approached that of PIF-2. The average α in band B increased from 0.67 to 0.73. As shown in Fig. 11, the difference compared to the highest value of 0.73 in band B was obviously decreased until it reached to zero in CS-3 and arrived at

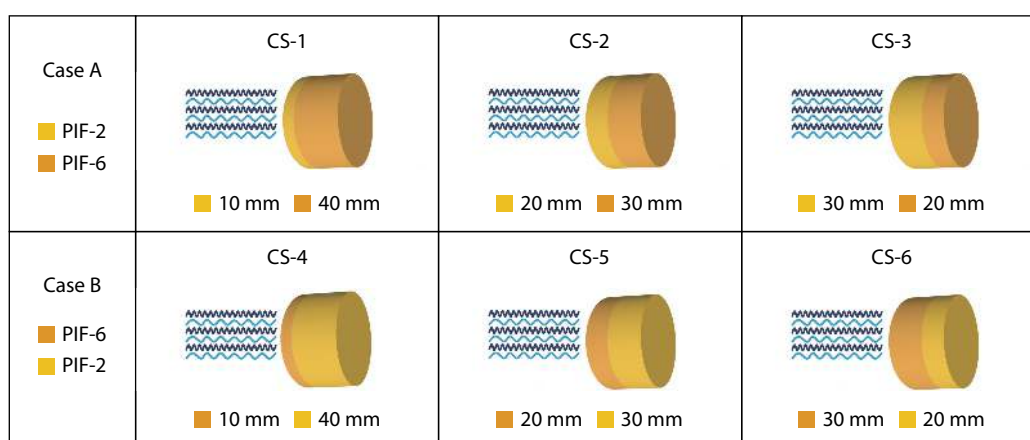


Fig. 8 The design of the combined IBPIF.

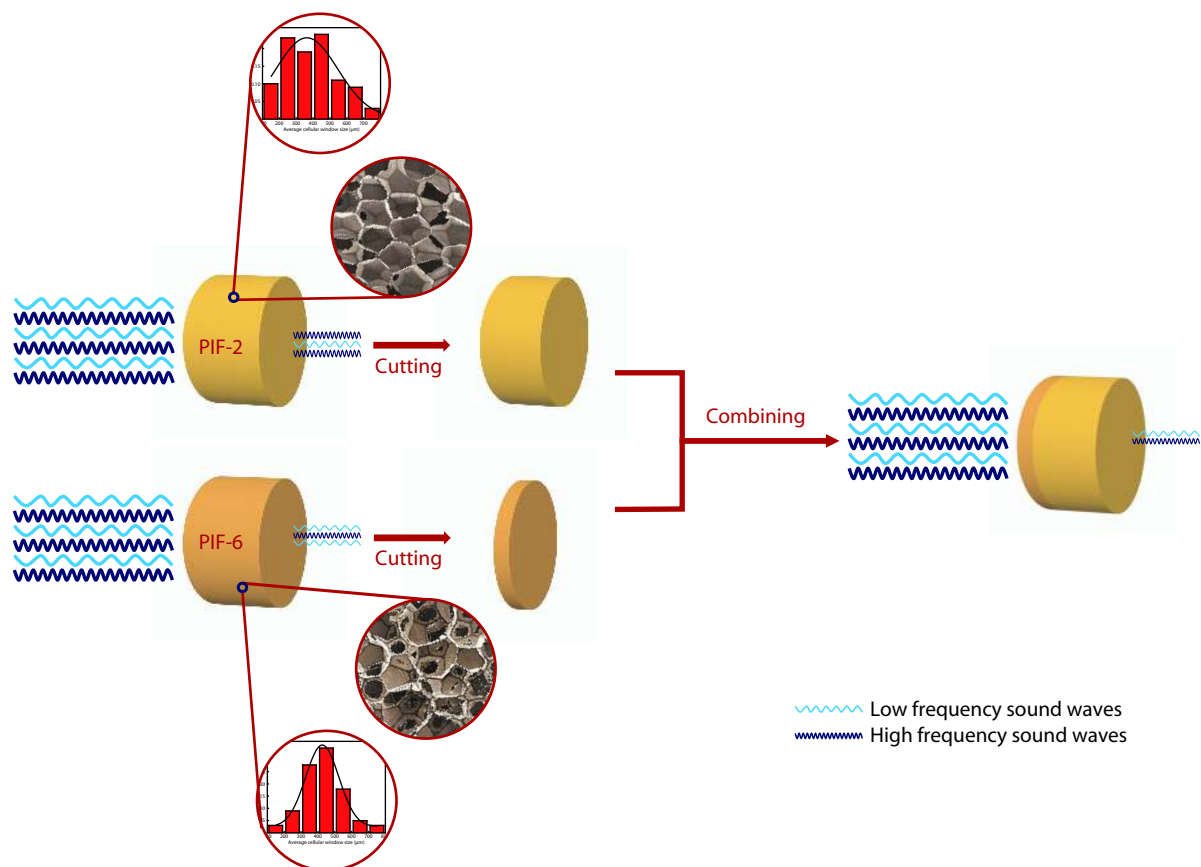


Fig. 9 The combination flowchart of the combined IBPIF and ideal acoustic absorption schematic diagram.

the level of PIF-2. However, from CS-1 to CS-3, average α in band C kept stable at 0.77 to 0.79 basically equalling to that of PIF-2. The difference compared to the highest value of 0.88 in band C was kept at about 0.10 corresponding to a 12% falling behind level of PIF-6. These results indicated that under this combination style the combined IBPIF could reach the best acoustic level in band B by adjusting in thickness of PIF-2 and PIF-6 sheets, but a not small difference still existed compared to the best acoustic level in band C and was unable to conquer.

From Fig. 10(d) to Fig. 10(f), for case B, with increasing sheet thickness of PIF-6 which possessed the best acoustic behavior in band C as a sound absorption surface and decreasing sheet thickness of PIF-2 which possessed the best acoustic behavior in band B in this study, the absorption curves of combined IBPIF samples from CS-4 to CS-6 gradually approached that of PIF-6. From CS-4 to CS-6, the average α in band C kept stable at 0.88 and the curves in this region were basically coincident with that of PIF-6. However, from CS-4 to CS-6, the average α in band B decreased from 0.67 to 0.60. As shown in Fig. 11, the difference compared to the highest value of 0.73 in band B became bigger and bigger, the lowest difference of 0.06 existing in CS-4 presented only an 8% falling below the level of PIF-2, the highest difference of 0.13 existing in CS-6 showed a falling reaching to 18% below the level of PIF-2. These results indicated that under this combination style the combined IBPIF could easily reach the

best acoustic level in band C with a thin PIF-6 sheet. Moreover, with increasing thickness of PIF-2 sheet in combined IBPIF, it could gradually approach to the best acoustic level in band B. Thus, in this style, the combined IBPIF could simultaneously realize the best acoustic level in band B and band C region in this study.

In conclusion, no matter what combination style, the acoustic behavior of combined IBPIF in band B region could be all significantly enhanced by increasing thickness of PIF-2 and could reach the best acoustic level in this study. However, when the sheet of PIF-2 was used as the sound receiving surface, the sheet of PIF-6 did nothing for the acoustic behavior of combined IBPIF in band C region even though with an increased thickness. But, in case B that the sheet of PIF-6 was used as the sound receiving surface, the acoustic behavior of combined IBPIF in band C region could easily reach the best acoustic level even though with only 10 mm thickness. The optimal combination between IBPIF with different distinctive acoustic behavior was CS-4 in this study. Moreover, the overall density of the combined samples kept at only 12–17 kg/m³. When the average α was close, the density of this combined IBPIF was reduced by about 70%–90% compared with previous study.^[20]

The difference between these two cases owed to the cellular structure of sound receiving surface which determined how much sound waves entering the material or reflecting to other places. When the sheet of PIF-2 was used as

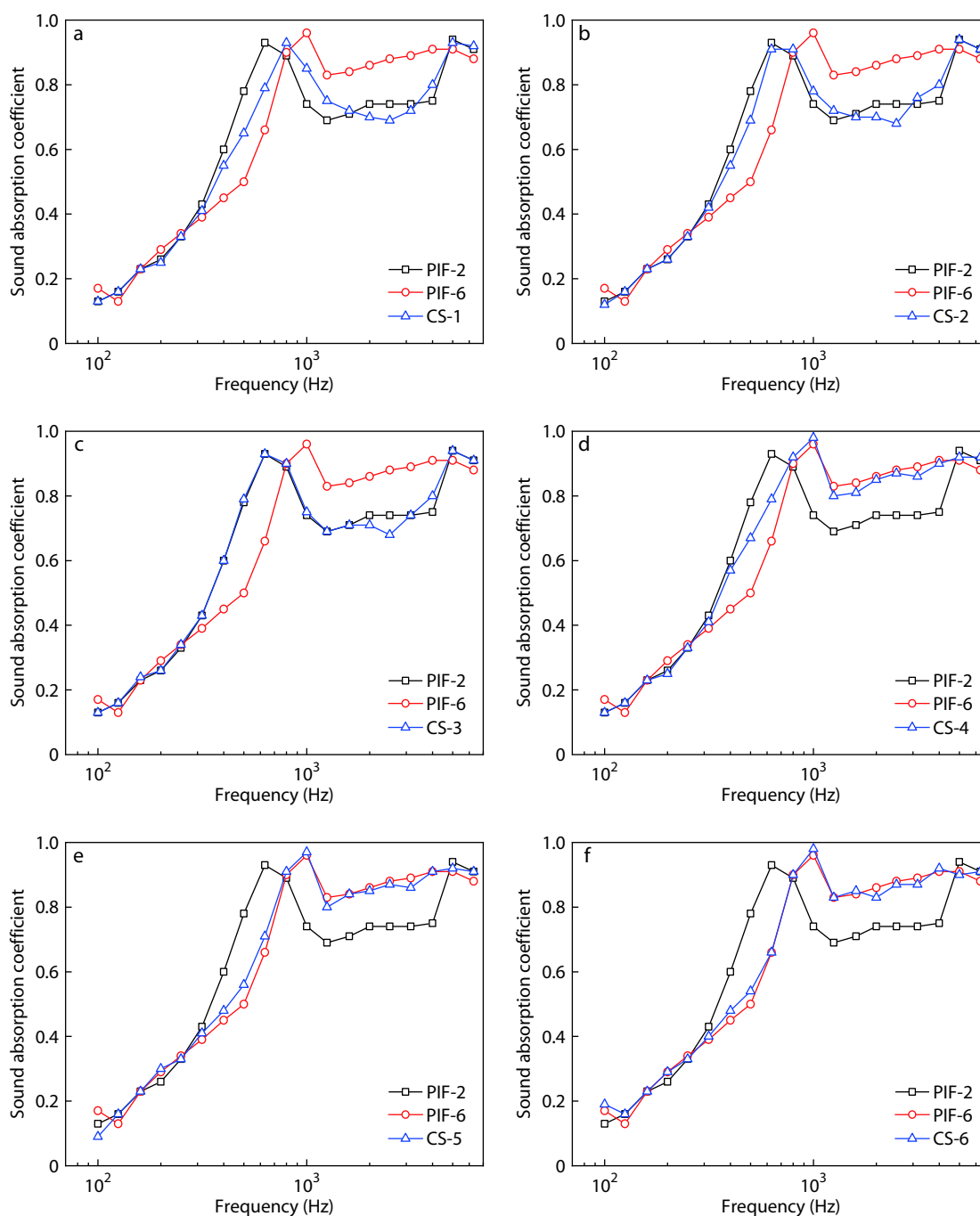


Fig. 10 The α curves of combined IBPIF: (a) CS-1; (b) CS-2; (c) CS-3; (d) CS-4; (e) CS-5; (f) CS-6.

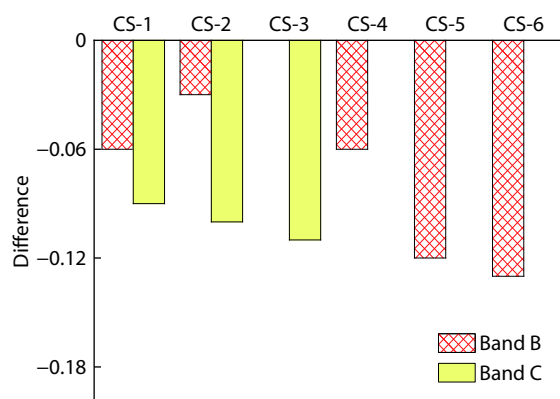
sound receiving surface, the higher closed cell structure impeded the propagation of sound waves and directly weakened the function of PIF-6 sheet. When the sheet of PIF-6 was used as sound receiving surface, the high window opening rate firstly ensured the effective incidence of sound waves. Afterwards, the friction and viscous effect between the sound waves and the bubble column, and the vibration action between the high energy sound waves and foam skeleton rapidly and effectively dissipated the energy of sound waves, especially in band C.

Meanwhile, for high window opening rate and big cell size,

after the sound waves with long wavelength corresponding to that in band B region propagating through the opening cells, it could easily transfer into cells of the back PIF-2 sheet. The cavity resonance effect of the closed foam played a major role in dissipating energy of sound waves in band B region. Thus, the combination continued to carry out the distinctive absorption for sound waves in band B region. Finally, under the synergistic effect of IBPIF with different distinctive pore structure, the sound absorption performance of the combined IBPIF was improved and case B showed a more excellent result. The detailed sound absorption mechanism of

Table 3 The average α of the combined IBPIF in different bands.

Sample number	The average α	
	315–800 Hz	800–6300 Hz
PIF-2	0.73	0.77
PIF-6	0.58	0.88
CS-1	0.67	0.79
CS-2	0.70	0.78
CS-3	0.73	0.77
CS-4	0.67	0.88
CS-5	0.61	0.88
CS-6	0.60	0.88

**Fig. 11** The difference in average α of combined IBPIF samples compared to the highest value of original IBPIF sample in band B and band C.

the combined IBPIF in case B is shown as Fig. 12.

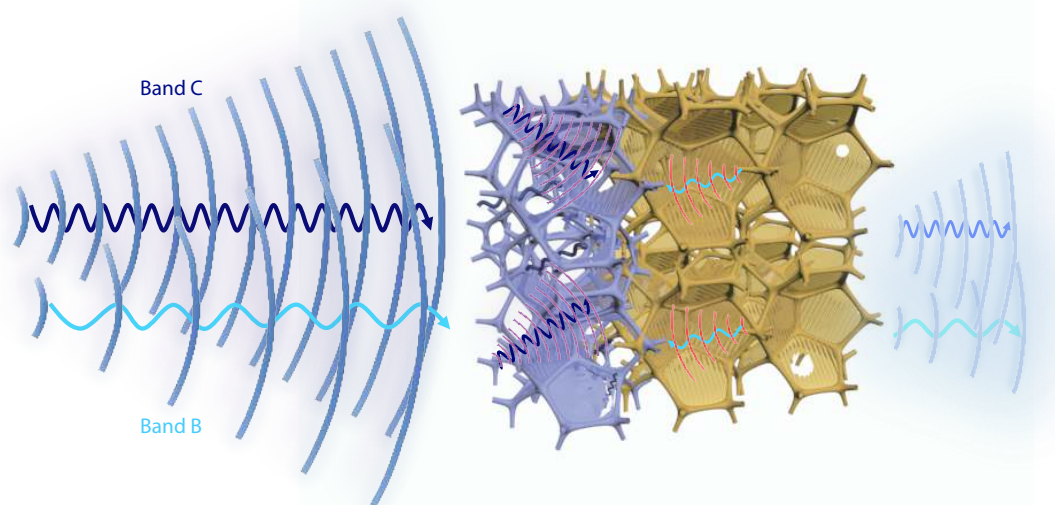
The reasons for different effects of sheet thickness on acoustic behavior in band B and band C region for combined IBPIF were the different characteristics of sound waves in these two regions. For high frequency sound waves in band C, it possessed high energy and could be easily consumed, as in previous reports the thickness of porous materials had almost no effect on their absorption behavior in band C region. Thus, in case A and case B, the average α in band C

all kept stable. For low frequency sound waves in band B, due to the longer wavelength, more thickness was usually required to increase the absorption for low-frequency sound waves.

CONCLUSIONS

In this work, cellular structure that decides distinctive acoustic performance of IBPIF was facilely and obviously adjusted by increased slurry temperature. The shape of cell was nearly spherical and cell size tended to gradually increase. The opposite change was found in pore distance. Moreover, the density of IBPIF could also be kept at only 12–17 kg/m³ and made it still possess excellent lightweight advantage. From 20 °C to 40 °C, the window opening rate was about doubled per 10 °C enhancement in slurry temperature. These results led to obvious change in distinctive acoustic properties of IBPIF. With changes in cellular structure, IBPIF showed a gradually weakening and ascending acoustic behavior in 315–800 and 800–6300 Hz regions, respectively. In particular, in this study PIF-2 and PIF-6 showed best and distinctive acoustic behavior in 315–800 and 800–6300 Hz regions, respectively.

Higher sound absorption performance of IBPIF was realized by operable and easy combination between different distinctive acoustic foams. When PIF-2 and PIF-6 were combined by operable and stitching combination, the results showed that sound absorption performance of the combined IBPIF was mainly affected by the sound receiving surface. Only when PIF-6 sheet used as sound receiving surface even though with thickness only 10 mm, the combined IBPIF could possess the excellent acoustic level in 800–6300 Hz region as PIF-6. For the acoustic behavior of combined IBPIF in 315–800 Hz region, no matter what samples were used as sound receiving surface it could be significantly enhanced by increasing thickness of PIF-2 and could reach or close to its acoustic level. Finally, the combined IBPIF could simultaneously realize the excellent acoustic level in the whole region in this study. The purpose of fabricating new ambient sound absorption materials that lightweight IBPIF

**Fig. 12** The sound absorption mechanism of the combined IBPIF in case B.

with excellent acoustic behavior from 100–6300 Hz was realized. This study and result could furtherly broaden application fields of IBPIF.

ACKNOWLEDGMENTS

This work was financially supported by the Fundamental Research Funds for the Central Universities (No. 3072020CF1019), Heilongjiang Provincial Postdoctoral Science Foundation (No. LBH-Z19137), and Natural Science Foundation of Heilongjiang Province (No. LH2019E038).

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