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Sound absorption performance of various nickel foam-base multi-layer structures in range of low frequency

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Abstract: Commercial 3D reticular nickel foam and its composite structure were investigated on the sound absorption at 200−2000 Hz. The absorption performance of foam plates 1−5 layers (1-layer thickness: 2.3 mm; porosity: 89%; average pore-diameter: 0.57 mm) was found to be poor, and could be improved by adding backed cavum or front perforated thin sheet. The absorption coefficient could reach about 0.4 at 1000−1600 Hz for the composite structure of 5-layer foam with a backed 5 mm-thick cavum, and even 0.68 at about 1000 Hz for that of 2-layer foam with the same cavum and a perforated plate closely in front of the foam.

Key words: reticular metal foam; reticular nickel foam; composite structure for sound absorption; low frequency sound absorption

1 Introduction

Noise pollution is a worldwide hazard. To solve this problem, noise reduction is one of the main methods by using sound absorption materials [1−3]. Noise reduction materials are often made of porous foams due to their merits of low density and high specific surface area [4−7]. Metal foam is one kind of porous materials, which could be applied as effective sound absorption materials. It has both metallic and porous structured properties, and exhibits high strength as well as thermal resistance compared with polymer foams [8−12]. There are some studies on the sound absorption performance of metal foams, with most of them on cellular aluminum foams [8,9,13−16]. Sound wave is difficult to propagate into a closed-cell aluminum foam. Better sound absorption performance is achieved by punching holes in the closed-cell aluminum foam [11,17,18]. In addition, open-cell aluminum foam can be prepared by infiltration casting method, and its sound absorption is good even without extra post process [13,19−21].

It is well known that the sound absorption is found to be good for cellular open-cell metal foams, but poor for reticular metal foams, so few researches could be found on sound absorption performance of reticular metal foams [1,3,22,23]. For example, the pore surface area in cellular aluminum foam is abundant from the mature mass production. Viscous dissipation cannot be neglected in the interaction between the sound wave and air, because the air flow resistance is relatively large. The sound absorption performance is good in this case [22,24,25]. In comparison, the surface area of pore strut in 3D reticular aluminum foam is much small. Viscous dissipation can be neglected in the interaction between sound wave and air, because air flow resistance is little. Sound is difficult to be absorbed in this case, especially in the low frequency range. Nickel foam can be used in excessively high temperature environment, because the melting point of nickel foam is much higher than that of aluminum foam.

It is also worth pointing out that a good sound absorption structure can also be achieved from the reticular metal foam by proper design. In general, sound absorption performance of porous materials becomes worse as the sound wave frequency decreases. There are some researches on the sound absorption performance of metal foams at high and intermediate frequencies, but they are very limited at low frequencies. In this work, the sound absorption is investigated for the reticular nickel foam and its various designed composites in the low frequency range of 200−2000 Hz. The work is a trial study for sound absorption of composites of the reticular metal foam. It is expected to advance the applications of

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the reticular metal foam.

2 Sound absorption mechanisms of metal foams

There are four major sound absorption mechanisms [1,26−28]. The first mechanism is viscous dissipation inside the metal foam. Sound wave propagates into open-cell foams, air vibration occurs inside the pore, and vibration of the air around pore wall is suppressed by the viscous force. Frictions generated among the molecules in the air do work. Frictions generate heat, and loss of the sound wave energy occurs. Noise reduction is realized. The second mechanism is resonance dissipation between metal foams and their composites. Resonance of various pores in the multi-porous structure leads to sound energy dissipation. Part of the longitudinal sound wave transfers to transverse sound wave in the 3D reticular foam. Loss of sound energy is from these transfers. The third mechanism is impedance matching in composites. Impedance derivative is introduced from combination of different materials and tapered cavum shape. More sound waves are trapped inside the pores. The ratio of overall transmission to reflection is reduced. Noise reduction is realized by multi-scattering, multi-reflection, and multi-transmission in the multi-layered laminated metal foams. The fourth mechanism is elastic dissipation. Friction and elastic vibration inside the materials absorb the sound energy. Heat is generated and noise is reduced. Viscous dissipation, resonance dissipation, and impedance matching are relatively major factors to reduce noise for general rigid open-cell metal foams, and elastic dissipation is a relatively minor factor. Viscous dissipation is the most important factor for the metal foams in most cases.

Large quantities of nickel foams are widely produced by electric deposition method in many countries. Nickel foams are widely used as porous electrodes and catalysis bases. There are many merits for the nickel foams: uniformed structure, controllable pore size, mature production technology, good workability, and economy. The utilization of nickel foams is of great market value, which is used in noise reduction applications. However, the nickel foams have 3D reticulated structures, the surface area of the pore wall is relatively small, and the connection among holes reduces the air flow resistance. Then, sound energy absorption is weak. As discussed in the last section, most noise reduction mechanisms are suppressed for simple nickel foams. It is necessary to redesign the nickel foam composite structure, such as cavum and perforated thin sheet placements.

3 Experimental

3.1 Sample preparation

The porous round samples with a diameter of 10 cm in our experiment were cut from widely used 3D reticular nickel foams. They were produced by electrodeposition method [29]. The electric and mechanical properties were studied in some previous investigations [30−34]. The samples were chosen from nickel foam with porosity 89%, average pore diameter 0.57 mm, and thickness 2.3 mm. They were cut into round wafers as shown in Fig. 1.

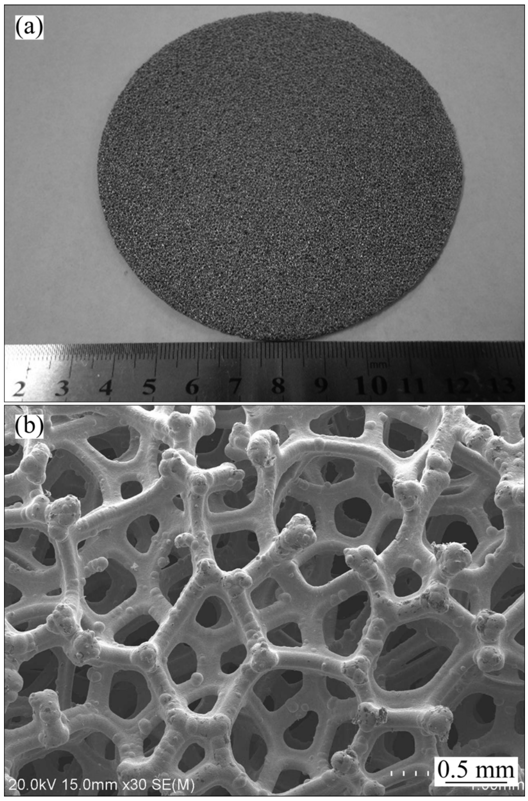

Fig. 1 Nickel foam sample for measurement of sound absorption coefficient: (a) Macroscopical; (b) Magnified

3.2 Method

Standing wave tube is applied to measuring the sound absorption coefficients of nickel foams and their composites in this work. The equipment is sketched in Fig. 2. The equipment is based on standing wave properties. The equipment consists of a standing wave tube with round smooth inner surface. The speaker is located on one side of the tube, and the sample is located on the other side of the tube. The surface of the sample is perpendicular to the standing tube axis [3].

The principle of the equipment is that when the incident sinusoidal plane wave propagates into the tube,

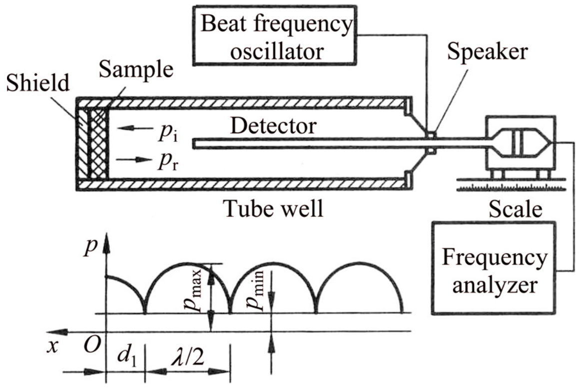

Fig. 2 Diagram of standing wave tube for measurement of sound absorption coefficient

there is a phase difference between the reflected wave and the incident wave, and the stable standing wave is formed by the overlapping of the incident and reflected waves in the tube. The sound pressure maximum p_{max} and minimum p_{min} distribute alternatively along the tube axis. The sound pressure distribution can be measured by a movable detector. Sound absorption coefficient with sound normal to material surface (α_N) is

$$\alpha_N = \frac{4\,p_{max}/p_{min}}{\left(1+p_{max}/p_{min}\right)^2} \tag{1}$$

The equipment is JTZB sound absorption system from Beijing Century Jiantong Technology Development Company, as shown in Fig. 3. It complies with Chinese standard GB/T18696.1−2004, and international standard ISO10534−1:1996. Sinusoidal sound signal is generated by a speaker. The standing wave is formed by the overlapping of the incident and the reflected wave from the sample surface. Sound level maximum L_{max} and minimum L_{min} are converted from the sound pressure maximum p_{max} and minimum p_{min} in the standing wave field by the detector. Sound absorption coefficient is calculated by

$$\alpha = \frac{4\times 10^{(L_{max}-L_{min})/20}}{\left(1+10^{(L_{max}-L_{min})/20}\right)^2} = \frac{4\times 10^{\Delta L/20}}{\left(1+10^{\Delta L/20}\right)^2} \tag{2}$$

The audible sound is in the frequency range of 20−20000 Hz. There was a report on the sound absorption performance in the typical audible range of 2000−4000Hz. The sound absorption performance at 200−2000Hz was discussed. The measurements were based on the above standing wave tube method. The measurements were performed at fixed frequencies of 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600 and 2000 Hz.

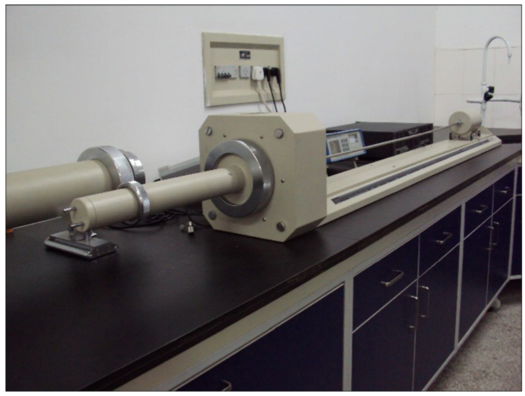

Fig. 3 JTZB sound absorption measurement system

4 Results and discussion

4.1 Laminated structure of nickel foam and cavum

Sound absorption coefficients of composites with one layer of nickel foam backed by cavum at different frequencies are shown in Fig. 4. As shown in Fig. 4, sound absorption performance is poor for composites with one layer of nickel foam backed by cavum thickness of less than 5 mm. The maximum sound absorption coefficient is less than 0.10. Because the nickel foam has an open-cell structure, with high porosity and thin thickness, it is easy for sound to transmit through. Sound absorptions of these composites are very weak. This is because the area of pore wall is small, i.e., the interaction area of sound and pore wall is small, so the viscous dissipation is small.

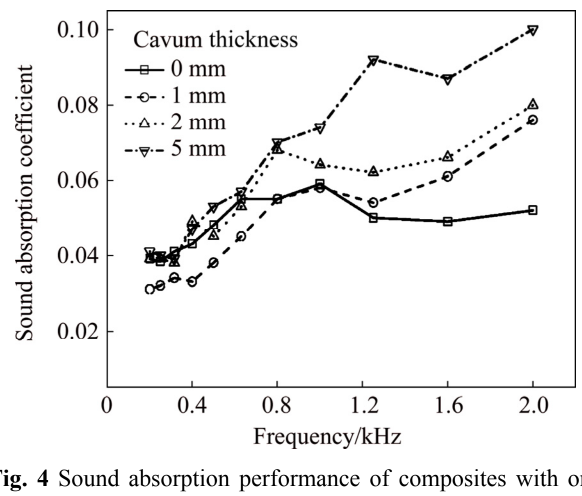

Fig. 4 Sound absorption performance of composites with one layer of nickel foam backed by cavum thickness of 0, 1, 2 and 5 mm

Nickel foam and the cavum of the composites form a combined sound absorption structure. Sound absorption performance improves from the resonance dissipation of sound waves in the combined structure. Sound absorption coefficients of composites with two layers of nickel foams backed by cavum are shown in Fig. 5. As shown in Fig. 5, sound absorption coefficients significantly increase for cases with cavum thickness of 5 mm. The first resonance frequency of 1200 Hz appears. The maximum sound absorption coefficient reaches 0.24 at 1200 Hz. The red shift of the resonance frequency is observed, when a cavum is placed at the back of the nickel foams.

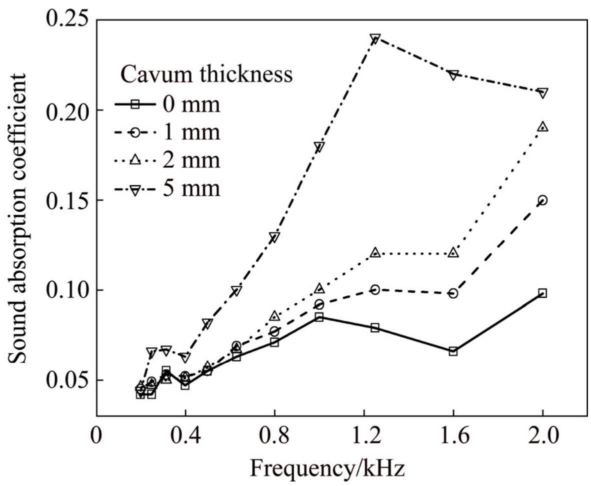

Fig. 5 Sound absorption performance of composites with two layers of nickel foams backed by cavum thickness of 0, 1, 2 and 5 mm

As the number of layers of nickel foams increases, the interaction area between the pore wall and the sound waves increases, and the viscous dissipation increases. Sound absorption coefficients of composites with three layers of nickel foams backed by cavum are shown in Fig. 6. Sound absorption of composites with three layers is better than that with two layers in general. The first obvious resonance frequency appears below 2000 Hz for nickel foams backed with cavum thickness of 5 mm. The maximum sound absorption coefficient reaches 0.29.

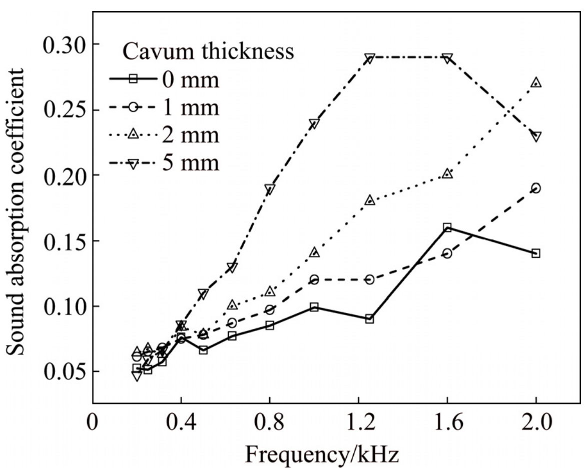

Fig. 6 Sound absorption performance of composites with three layers of nickel foams backed by cavum thickness of 0, 1, 2 and 5 mm

The absorption band width of three layers of nickel foams is also wider than that of two layers. Sound absorption performance is similar as shown in Figs. 5 and 6.

Sound absorption coefficients of composites with four layers of nickel foams backed by cavum are shown in Fig. 7. Total thickness of nickel foams is about 1 cm in these composites. Sound absorption performance does not improve a lot for the composites backed by cavum. The maximum sound absorption coefficient is 0.16 with nickel foams tightly against the tube wall. In this case, the impedance of nickel foams plays an important absorption role. It is shown that the impedance of nickel foam is low, flow resistance rate is not high. The maximum sound absorption coefficient is 0.36 for the nickel foams backed by cavum thickness of 5 mm. The coefficient with cavum is higher than previous coefficient without cavum, the main reason is that resonance absorption of the cavum plays an important absorption role.

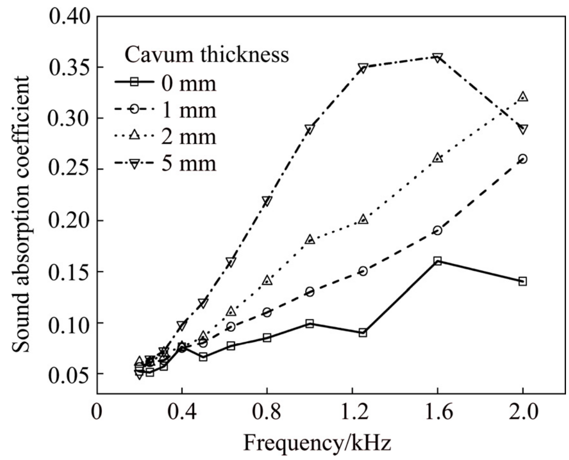

Fig. 7 Sound absorption performance of composites with four layers of nickel foams backed by cavum thickness of 0, 1, 2 and 5 mm

Sound absorption coefficients of composites with five layers of nickel foams backed by cavum are shown in Fig. 8. The maximum sound absorption coefficient of composites with five layers of nickel foams and without cavum is less than 0.20. The corresponding maximum sound absorption coefficient increases as the thickness of cavum increases. The first resonance frequency appears. Red shift of the maximum absorption frequency is observed as the thickness of cavum increases. The maximum sound absorption coefficient of 0.45 is found for the composites with cavum thickness of 5 mm.

4.2 Laminated structure of nickel foams and perforated thin sheet

It is found in the last subsection sound absorption coefficients of composites of multi-layer nickel foams do not significantly improve even if backed by cavum. In this subsection, a layer of polymer perforated thin sheet of thickness 0.1 mm is piled in front of the nickel foams. The round sample of the perforated thin sheet with diameter 10 cm is shown in Fig. 9. The diameter of each hole is 2−3 mm, and distance between two nearest holes is 1cm. Sound absorption coefficient of composites with perforated thin sheet significantly improves. With the front perforated thin sheet, the laminated structure is more suitable for sound absorption. Resonance dissipation of the sound waves inside the pores is significantly enhanced. In addition, the viscous dissipation also increases from the impedance of the perforated thin sheet for the propagated sound waves.

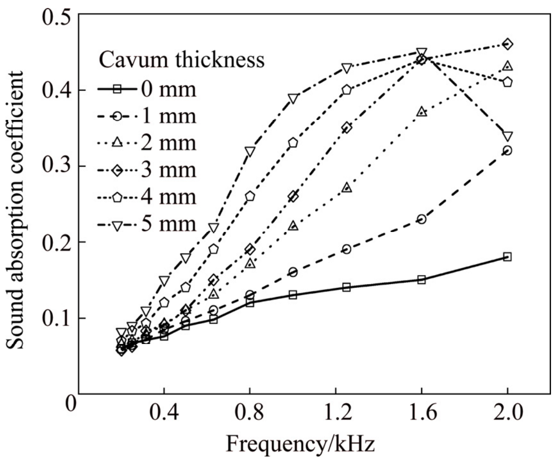

Fig. 8 Sound absorption performance of composites with five layers of nickel foams backed by cavum thickness of 0, 1, 2, 3, 4 and 5 mm

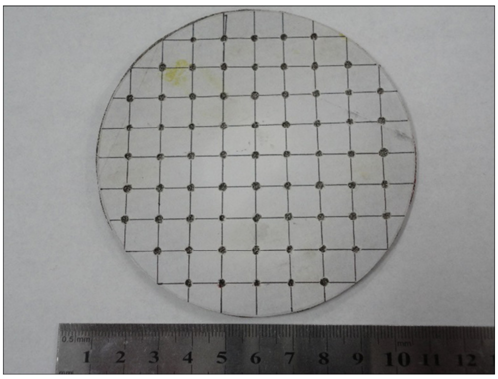

Fig. 9 Perforated thin sheet

Sound absorption coefficients for composites with one layer of perforated thin sheet, one layer of nickel foams, and cavum are shown in Fig. 10. Sound absorption coefficients of composites without cavum and with perforated thin sheet are found to be almost the same as those without perforated thin sheet. As the thickness of cavum increases from 1 to 5 mm, sound absorption coefficient significantly increases. For composites without and with cavum thickness of 2 mm, maximum sound absorption coefficients change from <0.08 to >0.5.

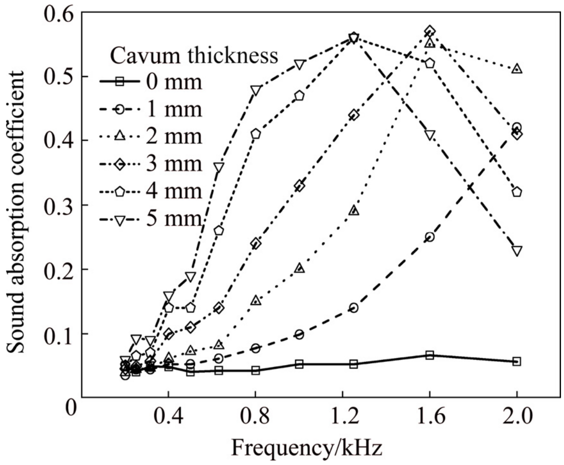

Fig. 10 Sound absorption performance of composites with perforated thin sheet, one layer of nickel foam backed by cavum thickness of 0, 1, 2, 3, 4 and 5 mm

As shown in Fig. 10, the sound absorption coefficient of the composites backed by cavum of length 1 mm improved a lot in general. The main reason is that when the perforated thin sheet is piled in front of the nickel foams, a resonance structure "perforated thin sheet + sound absorption materials + cavum" is formed [35,36]. This is a typical resonance structure of foam material.

The next modified structure contains a perforated thin sheet, two layers of nickel foams, and a cavum thickness from 0 to 5 mm. Sound absorption mechanisms are the same as mentioned before. The two structures are both "perforated thin sheet + sound absorption materials + cavum". The only difference is the thickness of nickel foams. Sound absorption performance increases with the increase of thickness of nickel foams. The measured sound absorption curves are shown in Fig. 11.

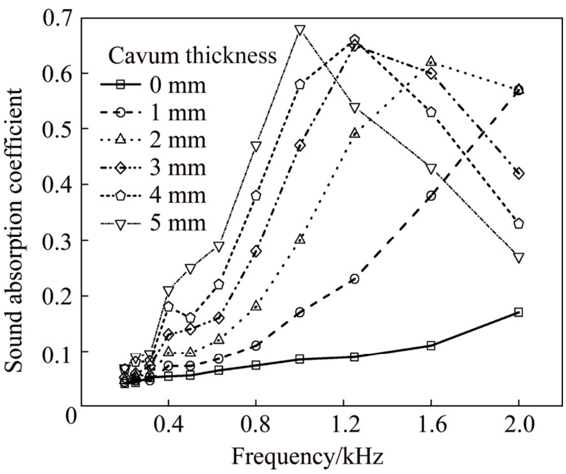

Fig. 11 Sound absorption performance of composites with perforated thin sheet, two layers of nickel foams backed by cavum thickness of 0, 1, 2, 3, 4 and 5 mm

The maximum sound absorption coefficient reaches 0.68. As the thickness of cavum increases, the maximum sound absorption coefficient is saturated, and a red shift of the first resonance frequency is observed.

5 Conclusions

1) As for the nickel foam with porosity 89%, thickness 2.3 mm and average pore diameter 0.652 mm, one layer of the foam plate backed by 1−5 mm cavum would have a quite poor sound absorption performance, presenting the maximum absorption coefficient of only 0.10. The sound absorption performance could increase gradually as the number of the foam plate layer increased from one to five. The sound absorption coefficient could reach about 0.4 with five overlapped layers of the nickel foam plate backed by 5 mm cavum in the frequency range of 1000−2000 Hz.

2) The sound absorption performance increased significantly for the composite structure with a perforated thin sheet closely in front of single and double layers of the nickel foam. The first resonance frequency appeared around 1000 Hz, at which the maximum sound absorption coefficient of 0.68 was measured for such composite structure with two layers of the nickel foam backed by 5 mm-thick cavum. This is mainly because of the absorption mechanism change: the modified structure absorbed sound waves by the combination of the perforated plate and the porous material backed by the cavum, so the sound absorption performance increased significantly with the structural design.

3) The sound absorption performance in the audible low frequency range is quite poor for the singly structured reticular nickel foam, it will become better by an appropriate structure design.

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不同泡沫镍基复层结构在低频区的吸声性能

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摘 要：探讨网状泡沫镍及其复合设计结构在声波低频区 200~2000 Hz 范围内的吸声性能。结果发现，对于孔隙率为 89%，厚度为 2.3 mm，平均孔径为 0.57 mm 的泡沫镍，1~5 层泡沫体的吸声效果都很差。加入背后空腔和前置穿孔薄板都可提高吸声系数：5 层叠加再加入 5 mm 厚的背腔，泡沫体的最大吸声系数在 1000~1600 Hz 内达到 0.4 左右；双层泡沫镍加入 5 mm 厚的背腔后，同时再在前面贴合一层穿孔薄板，泡沫体的吸声系数在 1000 Hz 左右时甚至达到了 0.68。

关键词：网状泡沫金属；网状泡沫镍；复合吸声结构；低频吸声

(Edited by Xiang-qun LI)