RESEARCH ON EXPERIMENTAL SOUND ABSORPTION PERFORMANCE UNDER HIGH TEMPERATURE AND HIGH SOUND INTENSITY COUPLING CONDITIONS

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In order to test the acoustic properties of porous metal materials under high temperature and high sound intensity coupling conditions to expand its applications in aero-engine acoustic liner, we will conduct the following researches on the impedance tube testing equipment under high temperature and high sound intensity coupling environments: Choose a reasonable heating method and heating power according to the working conditions inside the impedance tube; Simulation on the temperature field inside the impedance tube and get the sound pressure distribution; Select a right impedance tube length to ensure that the temperature inside the impedance tube is a constant in order to achieve the plane-wave propagation; Choose a right speaker and select the geometric parameters of the tapered tube reasonably according to the simulation results in order to improve the sound pressure level to the range which we need in the experimental test with the sound-collection effect of the tapered tube; Carry out the sound absorption performance tests of porous metal fibrous materials under high temperature and high sound intensity coupling conditions based on the experimental test equipment designed above, which is of great practical significance.
Keywords: porous metal materials, sound absorption performance, high temperature, high sound intensity

1. Introduction

Porous metal fibrous material is a new multi-functional material which appears in recent years with fast development in materials technology. It is widely used in aviation, aerospace, defense and other fields as a result of its excellent acoustic properties---high specific strength, high specific stiffness, good acoustic energy dissipations and applications in complex environments [1]. In recent years a lot of studies have been conducted on porous metal materials, which focus on the establishment of theoretical models of sound absorption performances. Biot [2, 3] gave constitutive equations for sound waves propagating in fluid saturated porous mediums, which provided an important theoretical basis for studying sound absorption performances of porous metal materials. Johnson [4] proposed the concept of viscous characteristic dimension and gave formulas to calculate the effective density and dynamic tortuosity of porous metal materials. The calculation formula of dynamic bulk modulus was given by Champoux [5] by introducing thermal characteristic dimension. Allard [5] introduced two new parameters when studying high porosity porous materials. One was related to the pore structure and the other was related to the ratio between viscous characteristic length and thermal characteristic length. Attenborough [6] gave theoretical calculations for the acoustical performances of rigid fibrous soil. Zwikker and Kosten [7] calculated the complex density and bulk modulus for rigid porous materials where the pores inside porous mediums were considered as circular ones. Tarnow [8,9] gave formulas to calculate compressibility and dynamic resistivity of porous fibrous material when considering it as periodically arranged parallel fibers porous structure. Zhang and Chen [10] proposed the extended Biot-Allard model to calculate sound absorption performances when considering the changes of temperature on the wall of porous mediums, which showed that the results obtained by the extended Biot-Allard model were in good agreement with experimental tests. Delany and Bazley [11] put forward empirical formulas of characteristic impedance and wave number. However, the Delany and Bazley empirical model was only effective in a specific frequency range, which was decided by the flow resistivity of porous metal materials. Miki [12] made a modification on the empirical formulas for acoustic impedance and propagation constant given by Delany and Bazley, which obtained a more exact result than before. Wu [13] researched on sound absorption performances of porous metal materials under high temperature and high sound intensity coupling conditions based on the turbulence analogy. For the experimental testing studies the most widely used method to test sound absorption performances of porous metal materials is the Transfer Function Method at the moment. Tang [14] conducted experimental tests on sound absorption performances of fibrous porous materials gradient structure. Belov [15] et al. studied the acoustic properties of porous bronze and analyzed the influences of different factors on sound absorption performances experimentally. Utsuno [16] conducted experimental tests on characteristic impedance and propagation constant of porous materials based on the transfer function method. Han [17, 18] et al. researched on sound absorption properties of open-celled aluminum foam experimentally. Hakamada [19] conducted experimental studies on sound absorption performances of porous aluminum fabricated by the spacer method.

Now sound absorption performance studies of porous metal materials mainly focus on normal temperature and sound pressure level conditions. There aren’t any reports about experimental tests and theoretical studies of sound absorption performances of porous metal materials under high temperature and high sound intensity coupling conditions at the moment. As the sound absorption liner of the aero-engine works in high temperature， high intensity and strong airflow environments, the theoretical and experimental researches on sound absorption performances of porous metal materials under the extreme conditions becomes particularly necessary, this is of great theoretical significance and practical value. The content and structure of the paper are as follows: Second, Design of the high temperature module and the high sound intensity module; Third, Experimental test of sound absorption performances under high temperature and high sound intensity coupling environments; Fourth, conclusions.

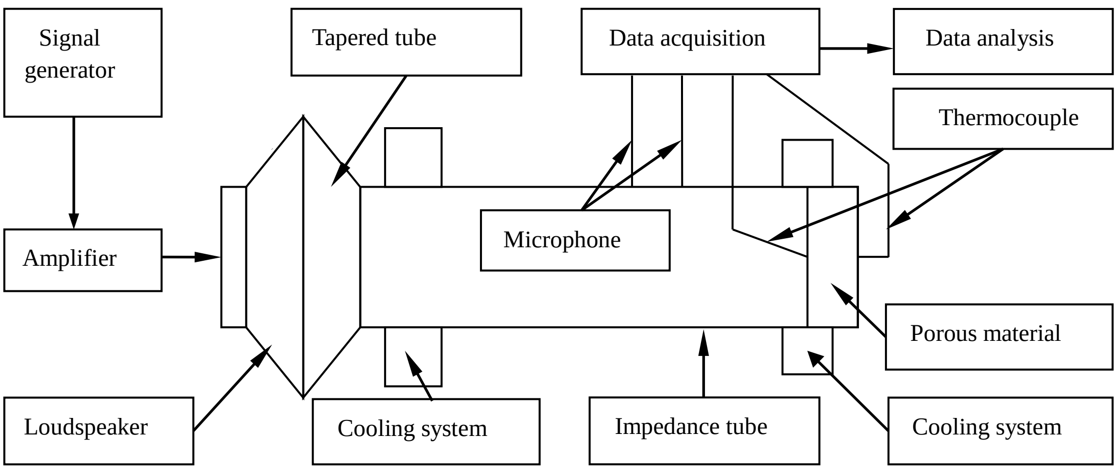


Figure 1: The overall configuration of the experimental testing device of sound absorption performances under high temperature and high sound intensity coupling conditions.

2. First page of the manuscript

The paper designs the experimental equipment of sound absorption performances under high temperature and high sound intensity coupling conditions based on two-microphone transfer function method, and complete sound absorption performance tests of porous metal materials under the complex environments. The designed experimental equipment of sound absorption performances under high temperature and high sound intensity coupling conditions is shown in Fig. 1.

2.1 Design of the high temperature module

In order to achieve the sound absorption performance tests under high temperature (up to 900K), we will conduct the design from the following aspects according to the overall configuration of the experimental equipment: Heating system, Cooling system, Temperature detection system, Temperature control system. And we also carry out the simulation of the temperature inside the impedance tube to verify the applicability of the transfer function method.

2.1.1 Heating system

In order to get the high temperature which is needed in the experimental test, we need to heat the material sample. The paper adopts a local heating method and sets two heating positions in the experimental equipment. One is at the outside of the impedance tube before the porous material sample to ensure that the impedance tube has long enough constant temperature area; and the other is at the rear face of the porous material sample to ensure the temperature of the sample satisfies the experimental test.

Now heating methods widely used in the industry are resistive furnace heating, electric arc furnace heating, and plasma heating. Compared with another two heating methods, resistance furnace heating method has a lot of advantages: high speed, high temperature, easy to control, which satisfies the requirements of the experimental device. Therefore, we choose the resistance furnace heating method.

2.1.2 Cooling system

The cooling system in the experimental equipment aims at protecting the loudspeaker (The maximum temperature is 150℃) and achieving the gradient temperature condition of porous metal material sample, thus completing the sound absorption performance test under uniform temperature field and gradient temperature field.

Now cooling methods widely used in the industry are air cooling, oil cooling, water cooling, and liquid nitrogen cooling. Compared with other cooling methods, forced water-cooling method has the following advantages: high efficiency, low cost, simple manufacturing process, which meets the cooling requirements of the experimental device. Based on the analysis above, we choose the forced water-cooling method.

2.1.3 Temperature detection and controlling system

In order to get the sound absorption performances of porous metal materials at different temperatures, we need to detect the temperature inside the impedance tube at each experimental test. We choose the constantan thermocouple to detect the temperature in the experimental device, which has high accuracy, good stability and meets the experimental testing requirements.

Besides the temperature detection system we also need to control the temperature inside the impedance tube in order to avoid a great change in temperature which may lead a wrong result. Considering the accuracy and stability of different controlling methods, we choose the PID control in the experimental device, which is based on the principle of feedback, including proportional, integral and differential parts. The control accuracy can reach to ±0.5℃ and meets the temperature control requirements. Thus, the experimental device chooses the SCR actuator based on the analysis above.

2.1.4 Simulation verification of temperature field and sound field

In order to verify the temperature field inside the impedance tube satisfies the experimental test requirements, we adopt the finite element software-FLUENT to carry out the temperature field simulation inside the impedance tube. Based on the sound absorption performance testing device under high temperature and high sound intensity coupling conditions designed above, we establish the three dimension geometry model firstly, then mesh and set boundary conditions, lastly introduce the model to FLUENT and get the simulation result, which is shown in Fig. 2 and Fig. 3.

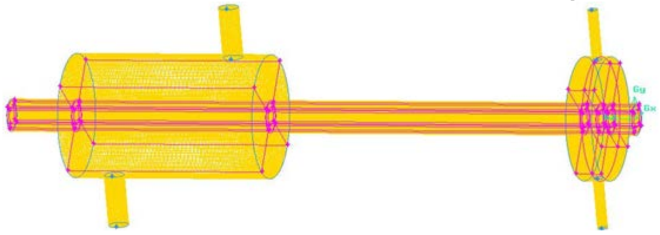
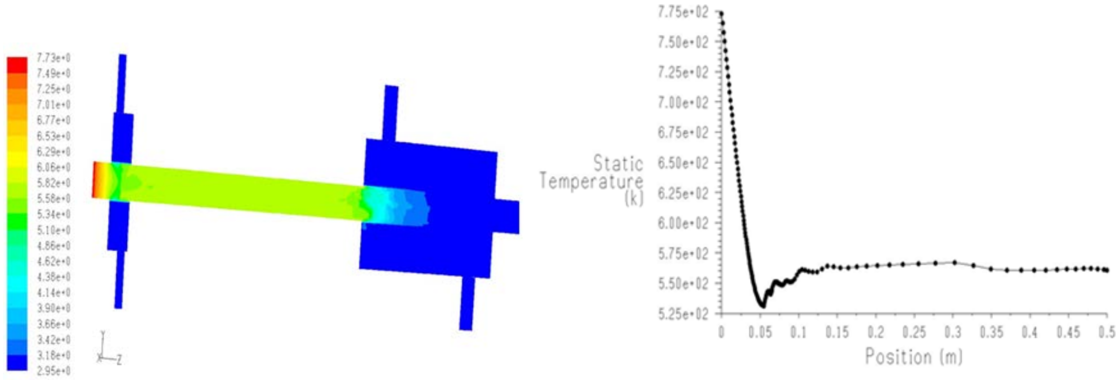


Figure 2: Gambit entity modeling model.



(a) (b)

Figure 3: The temperature field distribution inside the impedance tube, (a) The temperature distribution of the whole system, (b) The temperature distribution of the central axis.

According to the temperature field distribution inside the impedance tube, we can get that the temperature inside the impedance tube is uniform when the distance from the testing point to the microphone exceeds 0.15m (three times of the impedance tube diameter), which ensures the plane-wave propagation in the impedance tube. The high temperature module designed above satisfies the application conditions of the transfer function method and thus verifies the rationality of the experimental test device.

2.2 Design of the high sound intensity module

In order to achieve the sound absorption performance tests under high sound pressure level (up to 150dB), the key problem is how to produce the high sound pressure level sound waves. Ordinary loudspeakers have a low radiation power and can't produce high sound pressure level sound waves which are needed in the experimental tests. This paper proposes to set a tapered pipe at the outlet of the loudspeaker and adopt the finite element software-COMSOL Multiphysics to conduct the simulation of the sound-collection effect of the tapered pipe to acquire reasonable structural parameters. Then we choose right impedance tube length to ensure plane-wave propagation inside the tube.

2.2.1 Selection of the loudspeaker

Now methods widely used for producing high intensity acoustic waves are mainly explosion sound, electrical sound and fluid sound. Considering the overall configuration of the impedance tube testing system and the requirements of the experimental tests, explosion sound and fluid sound can't satisfy the conditions. Based on the analysis above, we choose the electric loudspeaker as the high sound intensity sound source.

Electric loudspeaker is also called electric horn, which changes the electrical signal into the acoustic signal. Through the survey on the horn speaker market, we choose the WS-4600 model horn combined with the expectations of the experiment tests. The corresponding technical parameters are shown in Table 1.

Table 1: The technical parameters of the WS-4600 model horn

Technical index	Value
Rated power	600W
Maximum power	1000W
Input impedance	8Ω
Frequency response	150-7000Hz
Sensitivity	120dB
Rated SPL	130dB
Dimensions	480mm×350mm×500mm
Net weight	26kg

2.2.2 *Design of the structural parameters of the tapered tube*

In order to achieve a good fit between the tapered tube and the horn, we need to design the geometric dimensions of the tapered tube. Considering that the face of the WS-4600 model horn is circular in shape and the diameter of the outlet of the horn is 480mm, thus the diameter of the large end face is 500mm. And the diameter of the small end face is 50mm in order to have a good coordinate with the impedance tube. We adopt Pro/E to build the geometric model and get the three-dimension model of the tapered tube and the impedance tube. According to the analysis discussed above, we have known that taper is an important factor which affects the sound-collection effect of the tapered tube. We change the taper by adjusting the distance L between the large end face and the small end face. In the paper we choose thirteen group values of the distance L between 200mm and 800mm to conduct the simulation of the sound-collection effect of the tapered tube. Based on the simulation calculations, we get the sound pressure level distribution when the frequency is 2000Hz and the distance is 500mm, which is shown in Fig. 4.

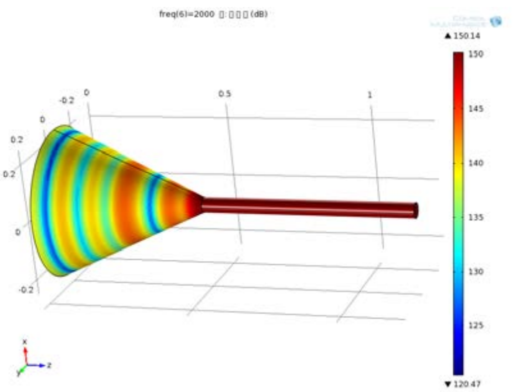


Figure 4: The sound pressure level distribution of frequency-2000Hz and distance-500mm.

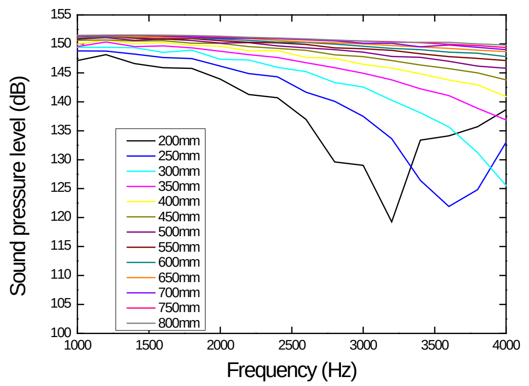


Figure 5: The sound pressure level curves with frequencies of the central axis of the right end face.

According to the sound pressure level distribution in Figure.4, We can get that the sound pressure level inside the impedance tube is uniform and the sound pressure level can reach to 150dB at the right end face of the impedance tube. Then we extract the sound pressure level of the central axis of the right end face under different tapered tube and different frequencies and get the sound pressure level curves with frequencies, which are shown in Fig. 5.

According to the sound pressure level curves with frequencies in Figure.5, we get that the sound-collection effect of the tapered tube becomes stronger and the sound pressure level is more stable with an increase of the distance L. The sound-collection effects don't appear obvious changes when the distance L increases to a relative higher level. And when the distance L is 750mm, the sound pressure level of the right end face can reach to 150dB and is uniform at different frequencies. Therefore, we choose the tapered tube whose distance L is 750mm as the sound-collection device of high sound intensity.

Based on the parameters discussed above, we complete the design of high sound intensity module. We also conduct experimental tests of sound pressure levels inside the impedance tube and get that the sound pressure level is uniform which is in accordance with the simulation results, thus verifying the correctness of the simulation calculations and the rationality of the experimental device design.

3. The sound absorption performance tests under high temperature and high sound intensity coupling conditions

We conduct the sound absorption performance tests of porous metal materials under high temperature and high sound intensity coupling conditions based on the experimental device designed above. The sound absorption coefficient curves for the special porous material samples are shown in Fig. 6 and Fig. 7.

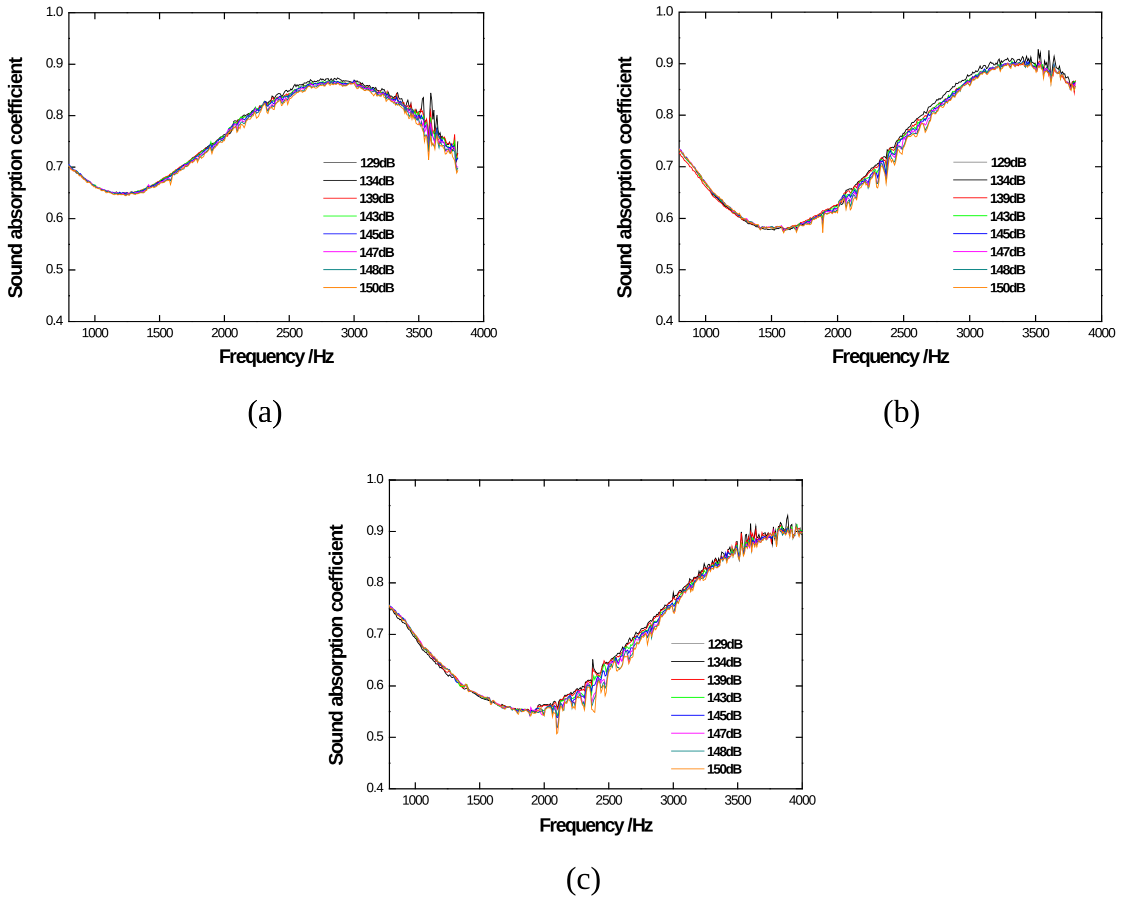


Figure 6: Sound absorption coefficient curves under different sound pressure levels (Experimental testing temperature: a-373K, b-573K, c-773K).

According to sound absorption coefficient curves shown in Fig. 6 and Fig. 7, we can get sound absorption coefficient curves under different sound pressure levels have the same trend with in the whole frequency range. The sound absorption coefficients begin to go down with an increase of the sound pressure level and high sound pressure level has a greater effect on sound absorption performances of the peak frequency than those of other frequencies. The temperature has a great effect on sound absorption performances of porous metal materials. The sound absorption coefficients decrease with an increase of the temperature and the peak moves towards high frequency, which results in bad sound absorption performances of porous metal materials in the low frequency range. The experimental device has good testing accuracy and repeatability and completes the experimental tests of sound absorption performances under high temperature and high sound intensity coupling conditions well.

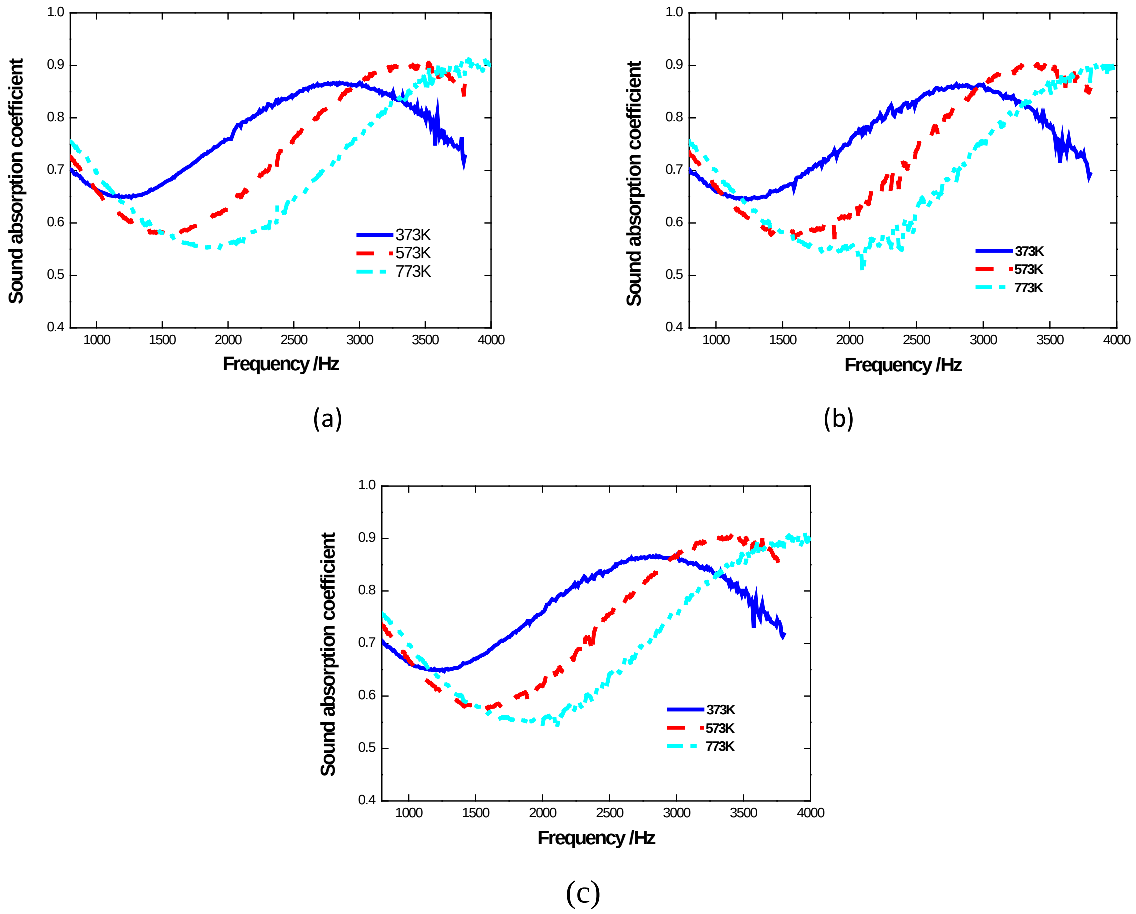


Figure7: Sound absorption coefficient curves under different temperatures (Sound pressure level: a-139dB, b-145dB, and c-150dB).

4. Conclusions

We complete the design of the sound absorption performance testing device under high temperature and high sound intensity coupling conditions and conduct the sound absorption performance tests of porous metal materials which have different structural parameters. The experimental device has good testing accuracy and repeatability.

The next generation experimental device should consider the influence of the strong flowing air to simulate the working conditions of the sound absorption liner of the aero-engine better so that we can predict the sound absorption performances of porous metal materials under high temperature, high sound intensity and strong flowing air coupling conditions, which provides an important basis to expand its applications in aero-engine.

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References

1 Lu Tianjian, He Deping, Chen Changqing, et al. The multi- functionality of ultra-light porous metals and their applications, [J]. Advances in Mechanics, 36(4), 517-535, (2006). (in chinese)

2 Biot M A. Theory of propagation of elastic waves in a fluid-saturated porous solid. I. Low-frequency range, J Acoust Soc Am, 28, 168-178, (1956).

3 Biot M A. Theory of propagation of elastic waves in a fluid-saturatedporous solid. II. Higher frequency range, J Acoust Soc Am, 28, 179–191, (1956).

4 Johnson D L, Koplik J, Dashen R. Theory of dynamic permeability and tortuosity influid-saturated porous-media, J Fluid Mech, 176, 379–402, (1987).

5 Champoux Y, Allard J F. Dynamic tortuosity and bulk modulus inair-saturated porous-media, J Appl Phys, 70, 1975–1979, (1991).

6 Attenborough K. Acoustical characteristics of rigid fibrous absorbentsand granular materials, J Acoust Soc Am, 73, 785–799, (1983).

7 Zwikker C, Kosten C W. Sound Absorbing Materials, New York:Elsevier, 26–34, (1949).

8 Tarnow V. Compressibility of air in fibrous materials, J Acoust Soc Am, 99, 3010–3017, (1996).

9 Tarnow V. Calculation of the dynamic air flow resistivity of fiber materials, J Acoust Soc Am, 102, 1680–1688, (1997).

10 Zhang B, Chen T. Calculation of sound absorption characteristics of porous sintered fiber metal, J Appl Acoust, 70, 337–346, (2009).

11 Delany M E, Bazley E N. Acoustical properties of fibrous absorbentmaterials, Appl Acoust, 3, 105–116, (1970).

12 Miki Y. Acoustical properties of porous materials–Modifications of Delany-Bazley models, J Acoust So Jap (E), 11, 19–24, (1990).

13 Wu Jiuhui, Hu Zhiping and Zhou Han. Sound absorbing property of porous metal materials with high temperature and high sound pressure by turbulence analogy, J Appl Phys, 113(19), 194905, (2013).

14 Tang Huiping, Zhu Jilei, Ge Yuan, et al. Sound Absorbing Characteristics of Fibrous Porous Materials Gradient Structure, [J]. RARE METAL MATERIALS AND ENGINEERING, 36(12), 2220-2223, (2007). (in chinese)

15 Belov SV, Terekhin AS, Balantsev SK, et al. Acoustic characteristics of porous bronze, [J]. Poroshkovaya Metallurgiya, 22-25, (1983).

16 Utsuno H, Tanaka T, Fujikawa T, et al. Transfer function method for measuring characteristic impedance and propagation constant of porous materials, [J]. Journal of the Acoustical Society of America, 86 (2), 637-643, (1989).

17 Han FS, Seiffert G, Zhao YY, et al. Acoustic absorption behaviour of an open-celled aluminum foam, [J]. Journal of Physics D: Applied Physics, 36, 294-302, (2003).

18 Han FS, Zhu ZG, Liu CY. Examination of acoustic absorption characteristics of foamed aluminum, [J]. Acta acoustics, 84 (3), 573-576, (1998).

19 Hakamada M, Kuromura T, Chen YQ, et al. High sound absorption of porous aluminum fabricated by spacer method, [J]. Applied Physics Letters, 88, 1-3, (2006).