

Description

Title of Invention: Porous Composite for Sound Absorption

Technical Field

5 The present invention generally relates to porous composites useful for sound absorption and methods for absorbing sound.

Background Art

Noise is one of the vital factors in determining the quality of a person's life.

10 The harmful effects of noise pollution are well-recognized. For example, exposure to high noise levels can cause hearing loss. Even at low noise levels, noise disturbance can have a significant negative effect on psychological health and quality of life, and a reduction in working and learning efficiency. In extreme cases, exposure to high noise levels may lead to hearing loss. According to the 2007 to

15 2016 Workplace Safety and Health Reports conducted by The Workplace Safety and Health Institute of Singapore, noise-induced deafness is the leading occupational disease in Singapore.

Passive noise mitigation and active noise mitigation are two types of generally used methods for reducing noise. Active noise mitigation reduces sound

20 by the addition of a second sound specifically designed to cancel the first. Passive noise mitigation reduces sound using noise-isolating materials such as sound-absorbing materials. Passive noise mitigation is easy to implement and does not consume energy, which is in contrast to the active method.

Conventional sound-absorbing materials include porous materials. When

25 sound waves strike porous material, friction is generated between the pores and air, leading to heat dissipation thereby reducing noise intensity. It is possible to classify porous materials according to their availability to an external fluid, such as air. Pores that are isolated from their neighbouring pores are referred to as "closed" pores, while "open" pores have a continuous channel of connection with their

30 neighbouring pores. Porous sound-absorbing materials can also be classified as cellular, fibrous, or granular. Commercial porous sound-absorbing materials include mineral wool, plastic foams, textiles, cotton, and special acoustic plaster.

However, the efficiency of these porous materials is often insufficient, especially at lower frequency range below 2 kHz which is the main noise in urban ambient environments, such as from traffic and construction. It is from these industries where workers are most at risk of noise-induced deafness.

- 5 There is therefore a need to reduce noise transmission and to provide a sound absorbing material that overcomes, or at least ameliorates, one or more of the disadvantages described above.

Summary

- 10 In one aspect of the present disclosure, there is provided a sound-absorbing porous composite comprising:

(a) mechano-electrical conversion elements to convert sound mechanical energy into electric energy; and

- 15 (b) electro-thermal conversion elements to convert the converted electrical energy into thermal energy;

wherein said mechano-electrical conversion elements and electro-thermal conversion elements are homogenously mixed in said porous composite, and wherein the porosity of said porous composite is at least 85%, and wherein:

- 20 (i) the mechano-electrical conversion elements comprise polymeric electret; or

(ii) the mechano-electrical conversion elements comprise piezoelectric polymer when the electro-thermal conversion elements comprise dielectric lossy elements.

- 25 In another aspect of the present disclosure, there is provided a sound-absorbing porous composite when used to absorb sound, comprising:

(a) mechano-electrical conversion elements to convert sound mechanical energy into electric energy; and

(b) electro-thermal conversion elements to convert the converted electrical energy into thermal energy;

wherein said mechano-electrical conversion elements and electro-thermal conversion elements are homogenously mixed in said porous composite, and

5 wherein the porosity of said porous composite is at least 85%, and wherein:

(i) the mechano-electrical conversion elements comprise polymeric electret; or

(ii) the mechano-electrical conversion elements comprise piezoelectric polymer when the electro-thermal conversion elements comprise dielectric lossy elements; or

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(iii) the mechano-electrical conversion elements comprise piezoelectric polymer when the electro-thermal conversion elements comprise electrical conductive elements, wherein the concentration of said conductive elements is near conductivity percolation threshold.

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In a further aspect of the present disclosure, there is provided a method for absorbing sound, comprising the following steps:

(i) providing a sound-absorbing porous composite comprising:

(a) one or more mechano-electrical conversion element(s), ; and

20 (b) one or more electro-thermal conversion element(s);

wherein said mechano-electrical conversion element(s) and electro-thermal conversion element(s) are homogenously mixed in said porous composite, and wherein the porosity of said porous composite is at least 85%, and wherein

25 (i) the mechano-electrical conversion elements comprise polymeric electret, or

(ii) the mechano-electrical conversion elements comprise piezoelectric polymer when the electro-thermal conversion elements comprise dielectric lossy elements, or

(iii) the mechano-electrical conversion elements comprise piezoelectric polymer when the electro-thermal conversion elements comprise electrical conductive elements, wherein the concentration of said conductive elements is near conductivity percolation threshold;

(ii) converting sound mechanical energy into electric energy via said mechano-electrical conversion element(s);

(iii) converting the electrical energy produced by step (ii) into thermal energy via said electro-thermal conversion element(s).

The present disclosure provides a sound-absorbing porous composite comprising:

(a) mechano-electrical conversion elements to convert sound mechanical energy into electric energy; and

(b) electro-thermal conversion elements to convert the converted electrical energy into thermal energy;

wherein said mechano-electrical conversion elements and electro-thermal conversion elements are homogenously mixed in said porous composite, and wherein the porosity of said porous composite is at least 85%.

Advantageously, the disclosed porous composites are effective at absorbing sound and display high sound absorption coefficients.

Further advantageously, the combination of the mechanisms of converting sound mechanical energy into electric energy via the mechano-electrical conversion elements and converting the converted electric energy into thermal energy via the electro-thermal conversion elements provides a synergistic interaction which provides for more efficient sound absorption.

Further, having the porous composite be of at least 85% porosity adds additional sound energy dissipation mechanisms such as destructive interference in the pores, friction damping, and viscoelastic damping. This, in combination with the above-mentioned energy conversion mechanisms, provides for a highly efficient sound absorbing material.

The present disclosure also provides a method for absorbing sound, comprising the following steps:

(i) providing a sound-absorbing porous composite comprising:

(a) mechano-electrical conversion elements; and

5 (b) electro-thermal conversion elements;

wherein said mechano-electrical conversion elements and electro-thermal conversion elements are homogenously mixed in said porous composite, and wherein the porosity of said porous composite is at least 85%;

10 (ii) converting sound mechanical energy into electric energy via said mechano-electrical conversion elements; and

(iii) converting the electrical energy produced in step (ii) into thermal energy via said electro-thermal conversion elements.

15 Definitions

The following words and terms used herein shall have the meaning indicated:

As used herein, the term “mechano-electrical conversion element” refers to a material or substance that is capable of converting mechanical energy into electrical energy. The term “mechano-electrical conversion element” may be used
20 interchangeably with the terms “mechano-electrical conversion material” or the term “mechano-electrical conversion substance”.

As used herein, the term “electro-thermal conversion element” refers to a material or substance that is capable of converting electrical energy into thermal
25 energy. The term “electro-thermal conversion element” may be used interchangeably with the terms “electro-thermal conversion material” or the term “electro-thermal conversion substance”.

Sound is a form of mechanical energy as the source of sound is associated with the vibration of matter. Sound is a mechanical wave and consists physically in
30 oscillatory elastic compression and in oscillatory displacement of a fluid. As used

herein, the term “sound mechanical energy” or “sound (mechanical) energy” refers to the mechanical energy carried by sound.

As used herein, the term “homogeneously mixed” refers to the uniform mixing of mechano-electrical conversion elements and electro-thermal conversion elements within the porous composite, such that the concentration of each of the elements remains substantially consistent throughout the composition.

As used herein, the term “piezoelectric” refers to a class of materials that generate an electrical charge when subjected to an applied force that produces stress and strain (such as sound mechanical energy).

As used herein, the term “electret” refers to a material that has a quasi-permanent electric charge or dipole polarisation. An electret generates an electric field when subjected to an applied force that produces stress and strain (such as sound mechanical energy).

As used herein, the term “electrical conductive elements” refers to material or substance that is capable of conducting electrical energy. The term “electrical conductive element” may be used interchangeably with the terms “electrical conductive material”, or “electrical conductive substance”.

As used herein, the term “lossy” refers to a material which has relatively high energy absorption when subjected to alternating currents (AC) (electrical or magnetic). As used herein, the term “dielectric lossy elements” refers to materials which convert electric energy into heat when subjected to AC electrical fields. The term “dielectric lossy elements” may be used interchangeably with the terms “dielectric lossy materials” or “dielectric lossy substances”.

As used herein, the term “conductivity percolation threshold” refers to the threshold concentration at which the conductive particles in the composite just start to become connected, forming an incomplete network, such that the composite attains a critical point with transition between insulating and conducting state.

As used herein, the term “open-cell pores” refers to pores which have a continuous channel of connection with neighbouring pores.

The word “substantially” does not exclude “completely” e.g. a composition which is “substantially free” from Y may be completely free from Y. Where

necessary, the word "substantially" may be omitted from the definition of the invention.

Unless specified otherwise, the terms "comprising" and "comprise", and grammatical variants thereof, are intended to represent "open" or "inclusive" language such that they include recited elements but also permit inclusion of additional, unrecited elements.

As used herein, the term "about", in the context of concentrations of components of the formulations, typically means $\pm 5\%$ of the stated value, more typically $\pm 4\%$ of the stated value, more typically $\pm 3\%$ of the stated value, more typically, $\pm 2\%$ of the stated value, even more typically $\pm 1\%$ of the stated value, and even more typically $\pm 0.5\%$ of the stated value.

Throughout this disclosure, certain embodiments may be disclosed in a range format. It should be understood that the description in range format is merely for convenience and brevity and should not be construed as an inflexible limitation on the scope of the disclosed ranges. Accordingly, the description of a range should be considered to have specifically disclosed all the possible sub-ranges as well as individual numerical values within that range. For example, description of a range such as from 1 to 6 should be considered to have specifically disclosed sub-ranges such as from 1 to 3, from 1 to 4, from 1 to 5, from 2 to 4, from 2 to 6, from 3 to 6 etc., as well as individual numbers within that range, for example, 1, 2, 3, 4, 5, and 6. This applies regardless of the breadth of the range.

Certain embodiments may also be described broadly and generically herein. Each of the narrower species and subgeneric groupings falling within the generic disclosure also form part of the disclosure. This includes the generic description of the embodiments with a proviso or negative limitation removing any subject matter from the genus, regardless of whether or not the excised material is specifically recited herein.

Detailed Disclosure of Embodiments

The present invention relates to a sound-absorbing porous composite material with improved sound absorption ability. The improved sound absorption performance may be obtained by introducing combined mechano-electrical and

electro-thermal conversion mechanisms in the porous composite, in addition to conventional mechanical dampening and sound energy dissipation mechanisms.

The present invention relates to a sound-absorbing porous composite comprising:

5 (a) mechano-electrical conversion elements to convert sound mechanical energy into electric energy; and

(b) electro-thermal conversion elements to convert the converted electrical energy into thermal energy;

10 wherein said mechano-electrical conversion elements and electro-thermal conversion elements are homogenously mixed in said porous composite, and wherein the porosity of said porous composite is at least 85%.

The present disclosure also relates to a sound-absorbing porous composite comprising:

15 (a) mechano-electrical conversion elements for converting sound mechanical energy into electric energy; and

(b) electro-thermal conversion elements for converting the converted electrical energy into thermal energy;

20 wherein said mechano-electrical conversion elements and electro-thermal conversion elements are homogenously mixed in said porous composite, and wherein the porosity of said porous composite is at least 85%.

25 When sound mechanical energy strikes the porous composite, the mechano-electrical conversion elements within the porous composite convert or transform the sound mechanical energy into electrical energy. The electro-thermal conversion elements then convert the electrical energy converted from the sound mechanical energy into thermal energy.

30 The mechano-electrical conversion elements convert or transform sound mechanical energy into electrical energy. The mechano-electrical conversion elements may be selected from the group consisting of piezoelectric polymers, polymeric electrets and mixtures thereof, including a blend of piezoelectric and electret polymers.

The piezoelectric polymer may comprise the following elements: (a) the presence of permanent molecular dipoles; (b) the ability to orient or align the molecular dipoles; and (c) the ability to sustain this dipole alignment once it is achieved.

5 The piezoelectric polymer may be selected from the group consisting of polyvinylidene fluoride (PVDF) homopolymer, PVDF-based copolymer, such as poly(vinylidene fluoride-co-trifluoroethylene) (P(VDF-TrFE)), poly(vinylidene fluoride-hexafluoropropylene) (P(VDF-HFP), poly(vinylidene fluoride-trifluoroethylene-chlorofluoroethylene) (P(VDF-TrFE-CFE)) terpolymer, and other
10 piezoelectric polymers such as polyureas, polyamide, polyvinylidene chloride, and polyacrylonitrile. The piezoelectric polymers may have a dominant piezoelectric phase such as β -phase for PVDF-based polymers.

 The polymeric electret may be selected from the group consisting of polypropylene, polyethylene terephthalate, polytetrafluoroethylene, polyurethane,
15 polystyrene, polyethylene, polymethylmethacrylate, and ethylene vinyl acetate cyclic olefin copolymers.

 The piezoelectric effect of the polymeric electret may be obtained by poling the polymer. The poling may be done by applying a high electric field to the material (for example, at or above 30 MV/m), such as through the use of a corona
20 gun.

 The mechano-electrical conversion elements may comprise or consist of a blend of piezoelectric polymers and polymeric electrets. The mechano-electrical conversion elements may comprise or consist of a blend of (i) polyvinylidene fluoride (PVDF) homopolymer, PVDF-based copolymer, such as
25 poly(vinylidene fluoride-co-trifluoroethylene) (P(VDF-TrFE)), poly(vinylidene fluoride-hexafluoropropylene) (P(VDF-HFP), poly(vinylidene fluoride-trifluoroethylene-chlorofluoroethylene) (P(VDF-TrFE-CFE)) terpolymer, polyureas, polyamide, polyvinylidene chloride, and/or polyacrylonitrile, and (ii) polypropylene, polyethylene terephthalate, polytetrafluoroethylene, polyimide, polyurethane,
30 polystyrene, polyethylene, polymethylmethacrylate, and/or ethylene vinyl acetate cyclic olefin copolymers.

 The concentration of the mechano-electrical conversion elements may be 100 wt% minus the concentration of the electro-thermal conversion elements. The concentration of the mechano-electrical conversion elements may be about 70 wt%

to about 97 wt%. The concentration of the mechano-electrical conversion elements may be about 72 wt% to about 97 wt%, about 74 wt% to about 97 wt%, about 76 wt% to about 97 wt%, about 78 wt% to about 97 wt%, about 80 wt% to about 97 wt%, about 82 wt% to about 97 wt%, about 84 wt% to about 97 wt%, about 86 wt% to about 97 wt%, about 88 wt% to about 97 wt%, about 90 wt% to about 97 wt%, about 92 wt% to about 97 wt%, about 94 wt% to about 97 wt%, about 70 wt% to about 94 wt%, about 70 wt% to about 92 wt%, about 70 wt% to about 90 wt%, about 70 wt% to about 88 wt%, about 70 wt% to about 86 wt%, about 70 wt% to about 84 wt%, about 70 wt% to about 82 wt%, about 70 wt% to about 80 wt%, about 70 wt% to about 78 wt%, about 70 wt% to about 76 wt%, about 70 wt% to about 74 wt%, about 70 wt% to about 72 wt%, or about 70 wt%, about 71 wt%, about 72 wt%, about 73 wt%, about 74 wt%, about 75 wt%, about 76 wt%, about 77 wt%, about 78 wt%, about 79 wt%, about 80 wt%, about 81 wt%, about 82 wt%, about 83 wt%, about 84 wt%, about 85 wt%, about 86 wt%, about 87 wt%, about 88 wt%, about 89 wt%, about 90 wt%, about 91 wt%, about 92 wt%, about 93 wt%, about 94 wt%, about 95 wt%, about 96 wt%, about 97 wt%, or any value or range therein.

When the mechano-electrical conversion elements may comprise or consist of a blend of piezoelectric polymers and polymeric electrets, the concentration of the piezoelectric polymer may be in the range of about 10 wt% to about 80 wt%, and the concentration of the polymeric electret may be in the range of about 87 wt% to about 13 wt% for a total mechano-electrical conversion elements concentration of about 93 wt% to about 97 wt%, with the remaining amount being the concentration of the electro-thermal conversion elements. The concentrations of the (i) piezoelectric polymer and (ii) polymeric electret in the blend may be:

- (i) about 10 wt% to about 80 wt%, and (ii) about 87 wt% to about 13 wt%;
- (i) about 15 wt% to about 80 wt%, and (ii) about 82 wt% to about 13 wt%;
- (i) about 20 wt% to about 80 wt%, and (ii) about 77 wt% to about 13 wt%;
- (i) about 25 wt% to about 80 wt%, and (ii) about 72 wt% to about 13 wt%;

- (i) about 30 wt% to about 80 wt%, and (ii) about 67 wt% to about 13 wt%;
- (i) about 35 wt% to about 80 wt%, and (ii) about 62 wt% to about 13 wt%;
- 5 • (i) about 40 wt% to about 80 wt%, and (ii) about 57 wt% to about 13 wt%;
- (i) about 45 wt% to about 80 wt%, and (ii) about 50 wt% to about 13 wt%;
- 10 • (i) about 50 wt% to about 80 wt%, and (ii) about 47 wt% to about 13 wt%;
- (i) about 55 wt% to about 80 wt%, and (ii) about 42 wt% to about 13 wt%;
- (i) about 60 wt% to about 80 wt%, and (ii) about 37 wt% to about 13 wt%;
- 15 • (i) about 65 wt% to about 80 wt%, and (ii) about 32 wt% to about 13 wt%;
- (i) about 70 wt% to about 80 wt%, and (ii) about 27 wt% to about 13 wt%;
- 20 • (i) about 75 wt% to about 80 wt%, and (ii) about 22 wt% to about 13 wt%;
- (i) about 10 wt% to about 75 wt%, and (ii) about 87 wt% to about 18 wt%;
- (i) about 10 wt% to about 70 wt%, and (ii) about 87 wt% to about 23 wt%;
- 25 • (i) about 10 wt% to about 65 wt%, and (ii) about 87 wt% to about 28 wt%;
- (i) about 10 wt% to about 60 wt%, and (ii) about 87 wt% to about 33 wt%;

- (i) about 10 wt% to about 55 wt%, and (ii) about 87 wt% to about 38 wt%;
- (i) about 10 wt% to about 50 wt%, and (ii) about 87 wt% to about 43 wt%;
- 5 • (i) about 10 wt% to about 45 wt%, and (ii) about 87 wt% to about 48 wt%;
- (i) about 10 wt% to about 40 wt%, and (ii) about 87 wt% to about 53 wt%;
- 10 • (i) about 10 wt% to about 35 wt%, and (ii) about 87 wt% to about 58 wt%;
- (i) about 10 wt% to about 30 wt%, and (ii) about 87 wt% to about 63 wt%;
- (i) about 10 wt% to about 25 wt%, and (ii) about 87 wt% to about 68 wt%;
- 15 • (i) about 10 wt% to about 20 wt%, and (ii) about 87 wt% to about 73 wt%;
- (i) about 10 wt% to about 15 wt%, and (ii) about 87 wt% to about 78 wt%;

20 for a total mechano-electrical conversion elements concentration of about 93 wt% to about 97 wt%, with the remaining amount being the concentration of the electro-thermal conversion elements.

25 The electro-thermal conversion elements convert or transform the electrical energy converted by the one or more mechano-electrical conversion elements into thermal energy. The electrical energy may be converted into thermal energy by dissipation of the electrical energy as Joule heat through the electro-thermal conversion elements.

 The electro-thermal conversion elements may be selected from the group consisting of electrical conductive elements, dielectric lossy elements and mixtures thereof.

The electrical conductive elements may be selected from the group consisting of carbon nanotubes (such as single-walled carbon nanotube (SWCNT) or multi-walled carbon nanotube (MWCNT)), graphene, carbon black, and conductive metal particles (such as copper particles, aluminium particles, silver particles and gold particles). Advantageously, the concentration of the electrical conductive elements may be around the conductivity percolation concentration threshold to form a conductive network for optimum sound energy conversion absorption and such that the electrical conductivity can neither be too high to destroy the local piezoelectric effect, nor too low for poor charge dissipation. Although polymer composites comprising conductive elements may be known, the concentration of the conductive elements may be much lower than the percolation threshold and hence not suitable for forming a conductive network.

The concentration of the electrical conductive elements may be about 3 wt% to about 10 wt%. The concentration of 3 wt% to about 10 wt % may be near the conductivity percolation threshold of the composite. The concentration of the electrical conductive elements may be about 3 wt% to about 7 wt%, or about 3 wt% to about 5 wt%, about 5 wt% to about 9 wt%, about 5 wt% to about 7 wt%, or about 3 wt%, about 4 wt%, about 5 wt%, about 6 wt%, about 7 wt%, about 8 wt%, about 9 wt%, or about 10 wt%, or any range or value therein.

The dielectric lossy elements may be selected from the group consisting of hydrated or hygroscopic materials. The dielectric lossy elements may be aluminum nitrate nonahydrate ($\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$), aluminum chloride hexahydrate ($\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$), tetra-n-butylammonium chloride (TBAC), or ammonium acetate (NH_4OAc). The concentration of the dielectric lossy elements may be at least 10wt%, at least 15 wt%, at least 20 wt%, or at least 25 wt% of the porous composite. The concentration of the dielectric lossy elements may be about 10% to about 30%, or about 12 wt% to about 30 wt%, about 14 wt% to about 30 wt%, about 16 wt% to about 30 wt%, about 18 wt% to about 30 wt%, about 20 wt% to about 30 wt%, about 22 wt% to about 30 wt%, about 24 wt% to about 30 wt%, about 26 wt% to about 30 wt%, about 28 wt% to about 30 wt%, about 10 wt% to about 30 wt%, about 10 wt% to about 28 wt%, about 10 wt% to about 26 wt%, about 10 wt% to about 24 wt%, about 10 wt% to about 22 wt%, about 10 wt% to about 20 wt%, about 10 wt% to about 18 wt%, about 10 wt% to about 16 wt%, about 10 wt% to about 14 wt%, about 10 wt% to about 12 wt%, about 10 wt%, about 11 wt%, about 12 wt%, about 13 wt%, about 14 wt%, about 15 wt%, about 16 wt%, about 17 wt%, about 18 wt%, about 10 wt%, about 20 wt%, about 21 wt%, about 22 wt%, about

23 wt%, about 24 wt%, about 25 wt%, about 26 wt%, about 27 wt%, about 28 wt%, about 29 wt%, about 30 wt%, or any value or range therein. Advantageously, this concentration allows for high dielectric loss which may lead to improved sound energy conversion.

5 The mechano-electrical conversion elements and electro-thermal conversion elements may be homogenously mixed in the sound absorbing porous composite. With the homogenous mixing of the mechano-electrical conversion elements and electro-thermal conversion elements, the mechano-electrical conversion and electro-thermal conversion mechanism can interact locally
10 throughout the composite such that the electrical energy converted from the mechanical energy through the mechano-electrical conversion elements can be effectively dissipated into heat through the electro-thermal conversion elements at approximately the same location, which may advantageously result in an effective overall energy conversion process from mechanical to thermal energy.

15 The porosity of the sound absorbing porous composite may be at least 85%. The porosity may be at least 85%, at least 86%, at least 87%, at least 88%, at least 89%, at least 90%, at least 91%, at least 92%, at least 93%, at least 94%, at least 95%, at least 96%, at least 97%, at least 98%, or at least 99%. The porosity may be about 85%, about 86%, about 87%, about 88%, about 89%, about
20 90%, about 91%, about 92%, about 93%, about 94%, about 95%, about 96%, or about 97%. Advantageously, the high porosity of the composite allows for improved sound absorption of the composite.

 The sound absorbing porous composite may be a cellular type with open-cell pores. It is preferable for the sound wave to be able to penetrate deeply into
25 the porous material for achieving effective energy conversion between the fluid and solid in the porous composite. Therefore, open-cell porous materials are favourable sound absorbing material as they may have a large interface between the solid and fluid which advantageously enhances interactions and energy exchange.

 The pore size of the pores in the sound absorbing porous composite may
30 be in the range of about 50 μm to about 600 μm . The pore size may be in the range of about 50 μm to about 550 μm , about 50 μm to about 500 μm , about 50 μm to about 450 μm , about 50 μm to about 400 μm , about 50 μm to about 350 μm , about 50 μm to about 300 μm , about 50 μm to about 250 μm , about 50 μm to about 200 μm , about 50 μm to about 150 μm , about 50 μm to about 100 μm , about 100
35 μm to about 600 μm , about 150 μm to about 600 μm , about 200 μm to about 600

μm, about 250 μm to about 600 μm, about 300 μm to about 600 μm, about 350 μm to about 600 μm, about 400 μm to about 600 μm, about 450 μm to about 600 μm, about 500 μm to about 600 μm, about 550 μm to about 600 μm, or about 50 μm, about 100 μm, about 150 μm, about 200 μm, about 250 μm, about 300 μm, about 350 μm, about 400 μm, about 450 μm, about 500 μm, about 550 μm, about 600 μm, or any range or value therein.

The sound-absorbing porous composite may comprise:

- 10 • piezoelectric polymers as the mechano-electric conversion elements, and electrical conductive elements as the electro-thermal conversion elements;
- 15 • polymeric electret as the mechano-electric conversion elements, and electrical conductive elements as the electro-thermal conversion elements;
- 15 • blend of piezoelectric polymers and polymeric electrets as the mechano-electric conversion elements, and electrical conductive elements as the electro-thermal conversion elements;
- 20 • piezoelectric polymers as the mechano-electric conversion elements, and dielectric lossy elements as the electro-thermal conversion elements;
- 20 • polymeric electret as the mechano-electric conversion elements, and dielectric lossy elements as the electro-thermal conversion elements;
- 25 • blend of piezoelectric polymers and polymeric electrets as the mechano-electric conversion elements, and dielectric lossy elements as the electro-thermal conversion elements;
- 25 • piezoelectric polymers as the mechano-electric conversion elements, and mixture of electrical conductive elements and dielectric lossy elements as the electro-thermal conversion elements;
- 30 • polymeric electret as the mechano-electric conversion elements, and mixture of electrical conductive elements and dielectric lossy elements as the electro-thermal conversion elements;

- blend of piezoelectric polymers and polymeric electrets as the mechano-electric conversion elements, and mixture of electrical conductive elements and dielectric lossy elements as the electro-thermal conversion elements.

5 The sound-absorbing porous composite may comprise:

- polyvinylidene fluoride (PVDF)-based polymer as the mechano-electric conversion elements, and carbon nanotubes as the electro-thermal elements;
- 10 • polyvinylidene fluoride (PVDF)-based polymer as the mechano-electric conversion elements, and aluminum microparticles as the electro-thermal conversion elements;
- polypropylene, polyurethane, polystyrene, polyethylene, polyethylene terephthalate, polytetrafluoroethylene, polyimide, polymethylmethacrylate, or ethylene vinyl acetate cyclic olefin copolymers as the mechano-electric conversion elements, and carbon nanotubes as the electro-thermal elements;
- 15 • poly(vinylidene fluoride-co-trifluoroethylene) (P(VDF-TrFE)), poly[(vinylidene fluoride-co-trifluoroethylene) (PVDF), poly[vinylidene fluoride-hexafluoropropylene] (P(VDF-HFP), or poly[vinylidene fluoride-trifluoroethylene-chlorofluoroethylene] (P(VDF-TrFE-CFE)) terpolymer as the mechano-electric conversion elements, and Single-Walled Carbon Nanotube (SWCNT) or Multi-Walled Carbon Nanotube (MWCNT) as the electro-thermal conversion elements;
- 20 • P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE) as the mechano-electric conversion elements, and graphene as the electro-thermal conversion elements;
- 25 • P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE) as the mechano-electric conversion elements, and conductive metals (such as Cu, Al, Ag, Au particles) as the electro-thermal conversion elements;
- 30 • P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE) as the mechano-electric conversion elements, and aluminum nitrate

nonahydrate ($\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$) as the electro-thermal conversion elements;

- P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE) as the mechano-electric conversion elements, and aluminum chloride hexahydrate ($\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$) as the electro-thermal conversion elements;

- P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE) as the mechano-electric conversion elements, and tetra-n-butylammonium chloride (TBAC) as the electro-thermal conversion elements;

- P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE) as the mechano-electric conversion elements, and ammonium acetate (NH_4OAc) as the electro-thermal conversion elements;

- polypropylene (PP), polyurethane, polystyrene, or polyethylene as the mechano-electric conversion elements, and SWCNT or MWCNT as the electro-thermal conversion elements;

- polyethylene terephthalate as the mechano-electric conversion elements, and SWCNT or MWCNT as the electro-thermal conversion elements;

- polyimide as the mechano-electric conversion elements, and SWCNT or MWCNT as the electro-thermal conversion elements;

- polymethylmethacrylate as the mechano-electric conversion elements, and SWCNT or MWCNT as the electro-thermal conversion elements; or

- ethylene vinyl acetate cyclic olefin copolymer as the mechano-electric conversion elements, and SWCNT or MWCNT as the electro-thermal conversion elements.

- blend of (i) P(VDF-TrFE), PVDF, (P(VDF-HFP) or P(VDF-TrFE-CFE), and (ii) polypropylene, polyurethane, polystyrene, or polyethylene, as the mechano-electric conversion elements, and SWCNT or MWCNT as the electro-thermal conversion elements.

The sound-absorbing porous composite may comprise:

- 5 • About 90 to 97 wt% poly[(vinylidene fluoride-co-trifluoroethylene] (P(VDF-TrFE)), poly[(vinylidene fluoride-co-trifluoroethylene] (PVDF), poly[vinylidene fluoride-hexafluoropropylene] (P(VDF-HFP)), or poly[vinylidene fluoride-trifluoroethylene-chlorofluoroethylene] (P(VDF-TrFE-CFE)) as the mechano-electric conversion elements, and about 3 to 10 wt% SWCNT or MWCNT as the electro-thermal conversion elements;
- 10 • About 90 wt% to 95 wt% P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE) as the mechano-electric conversion elements, and 5 to about 10 wt% graphene as the electro-thermal conversion elements;
- 15 • About 90 to 92 wt% P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE) as the mechano-electric conversion elements, and 8 to 10 wt% conductive metals (such as Cu, Al, Ag, Au particles) as the electro-thermal conversion elements;
- 20 • About 90 wt% P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE) as the mechano-electric conversion elements, and about 10 wt% aluminum nitrate nonahydrate ($\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$) as the electro-thermal conversion elements;
- 25 • About 90 wt% P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE) as the mechano-electric conversion elements, and about 10 wt% tetra-n-butylammonium chloride (TBAC) as the electro-thermal conversion elements;
- 30 • About 85 wt% P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE) as the mechano-electric conversion elements, and about 15 wt% ammonium acetate (NH_4OAc) as the electro-thermal conversion elements;
- About 95 to 97 wt% polypropylene (PP), polyurethane, polystyrene, or polyethylene as the mechano-electric conversion elements, and 3

to 5 wt% SWCNT or MWCNT as the electro-thermal conversion elements;

- About 95 to 97 wt% polyethylene terephthalate as the mechano-electric conversion elements, and 3 to 5 wt% SWCNT or MWCNT as the electro-thermal conversion elements;

- About 95 to 97 wt% polyimide as the mechano-electric conversion elements, and 3 to 5 wt% SWCNT as the electro-thermal conversion elements;

- About 95 to 97 wt% polymethylmethacrylate as the mechano-electric conversion elements, and 3 to 5 wt% SWCNT or MWCNT as the electro-thermal conversion elements; or

- About 95 to 97 wt% ethylene vinyl acetate cyclic olefin copolymer as the mechano-electric conversion elements, and 3 to 5 wt% SWCNT or MWCNT as the electro-thermal conversion elements.

- About 90 to 97 wt% blend of PVDF and polyurethane as the mechano-electric conversion elements, and 3 to 10 wt% SWCNT or MWCNT as the electro-thermal conversion elements;

- blend of (i) about 10 to 80 wt% P(VDF-TrFE), PVDF, (P(VDF-HFP) or P(VDF-TrFE-CFE), and (ii) about 87 to 13 wt% polypropylene, polyurethane, polystyrene, or polyethylene, as the mechano-electric conversion elements for a total mechano-electrical conversion elements concentration of about 93 wt% to about 97 wt%, and about 3 to 7 wt% SWCNT or MWCNT as the electro-thermal conversion elements.

The sound-absorbing porous composite may comprise:

- About 90 wt%, 95 wt%, or 97 wt% poly[(vinylidene fluoride-co-trifluoroethylene] (P(VDF-TrFE)), poly[(vinylidene fluoride-co-trifluoroethylene] (PVDF), poly[vinylidene fluoride-hexafluoropropylene] (P(VDF-HFP)), or poly[vinylidene fluoride-trifluoroethylene-chlorofluoroethylene] (P(VDF-TrFE-CFE)) as the mechano-electric conversion elements, and 3 wt%, 5 wt% or 10 wt% SWCNT or MWCNT as the electro-thermal conversion elements;

- About 90 wt%, 93 wt%, or 95 wt% P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE) as the mechano-electric conversion elements, and 5 wt%, 7 wt%, or 10 wt% graphene as the electro-thermal conversion elements;
- 5 • About 90 wt%, 91 wt%, or 92 wt% P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE) as the mechano-electric conversion elements, and 8 wt%, 9 wt% or 10 wt% conductive metals (such as Cu, Al, Ag, Au particles) as the electro-thermal conversion elements;
- 10 • About 90 wt% P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE) as the mechano-electric conversion elements, and about 10 wt% aluminum nitrate nonahydrate ($\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$) as the electro-thermal conversion elements;
- 15 • About 90 wt% P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE) as the mechano-electric conversion elements, and about 10 wt% aluminum chloride hexahydrate ($\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$) as the electro-thermal conversion elements;
- 20 • About 90 wt% P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE) as the mechano-electric conversion elements, and about 10 wt% tetra-n-butylammonium chloride (TBAC) as the electro-thermal conversion elements;
- 25 • About 85 wt% P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE) as the mechano-electric conversion elements, and about 15 wt% ammonium acetate (NH_4OAc) as the electro-thermal conversion elements;
- 30 • About 95 wt%, 96 wt%, or 97 wt% polypropylene (PP), polyurethane, polystyrene, or polyethylene as the mechano-electric conversion elements, and 3 wt%, 4 wt%, or 5 wt% SWCNT or MWCNT as the electro-thermal conversion elements;
- 30 • About 95 wt%, 96 wt%, or 97 wt% polyethylene terephthalate as the mechano-electric conversion elements, and 3 wt%, 4 wt%, or 5 wt% SWCNT or MWCNT as the electro-thermal conversion elements;

- About 95 wt%, 96 wt%, or 97 wt% polyimide as the mechano-electric conversion elements, and 3 wt%, 4 wt%, or 5 wt% SWCNT as the electro-thermal conversion elements;
- 5 • About 95 wt%, 96 wt%, or 97 wt% polymethylmethacrylate as the mechano-electric conversion elements, and 3 wt%, 4 wt%, or 5 wt% SWCNT or MWCNT as the electro-thermal conversion elements; or
- 10 • About 95 wt%, 96 wt%, or 97 wt% ethylene vinyl acetate cyclic olefin copolymer as the mechano-electric conversion elements, and 3 wt%, 4 wt%, or 5 wt% SWCNT or MWCNT as the electro-thermal conversion elements.
- 15 • About 90 wt%, 95 wt%, or 97 wt% blend of PVDF and polyurethane as the mechano-electric conversion elements, and 3 wt%, 5 wt%, or 10 wt% SWCNT or MWCNT as the electro-thermal conversion elements;
- 20 • blend of (i) about 15 wt% P(VDF-TrFE), PVDF, (P(VDF-HFP) or P(VDF-TrFE-CFE), and (ii) about 80 wt%, 81 wt %, or 82 wt% polypropylene, polyurethane, polystyrene, or polyethylene, as the mechano-electric conversion elements, and about 3 wt%, 4 wt%, or 5 wt% SWCNT or MWCNT as the electro-thermal conversion elements.

The sound-absorbing porous composite may comprise:

- 25 • 95 to 97 wt% polyvinylidene fluoride (PVDF)-based polymer as the mechano-electric conversion elements and 3-5 wt% carbon nanotubes as the electro-thermal elements;
- 30 • 91 wt% polyvinylidene fluoride (PVDF)-based polymer as the mechano-electric conversion elements and about 9 wt% aluminum microparticles as the electro-thermal conversion elements;
- 30 • 95 to 97 wt% polypropylene, polyethylene terephthalate, polytetrafluoroethylene, polyimide, polymethylmethacrylate, or ethylene vinyl acetate cyclic olefin copolymers as the mechano-electric conversion elements and 3-5 wt% carbon nanotube as the electro-thermal conversion elements.

- blend of (i) P(VDF-TrFE), PVDF, (P(VDF-HFP), or P(VDF-TrFE-CFE), and (ii) polypropylene, polyurethane, polystyrene, or polyethylene, as the mechano-electric conversion elements and 3-5 wt% carbon nanotube as the electro-thermal conversion elements.

5 The sound-absorbing porous composite may have a sound absorption coefficient which is ≥ 0.50 at audible frequencies above 800 Hz with a thickness of 25 mm. The sound absorbing coefficient may be ≥ 0.55 , ≥ 0.60 , ≥ 0.65 , or ≥ 0.70 . The sound absorbing coefficient may be in the range of about 0.50 to about 0.70, or about 0.55 to about 0.70, or about 0.60 to about 0.70, or about 0.65 to about 0.70, or about 0.50 to about 0.65, or about 0.50 to about 0.60, or about 0.50 to about 0.55, or about 0.50, 0.51, 0.52, 0.53, 0.54, 0.55, 0.56, 0.57, 0.58, 0.59, 0.60, 0.61, 0.62, 0.63, 0.64, 0.65, 0.66, 0.67, 0.68, 0.69, 0.70, or any value or range therein.

15 The sound-absorbing porous composite may have a sound absorption coefficient which is ≥ 0.60 at audible frequencies above 1000 Hz with a thickness of 25 mm. The sound absorbing coefficient may be ≥ 0.65 , ≥ 0.70 , ≥ 0.75 , ≥ 0.80 , or ≥ 0.85 . The sound absorbing coefficient may be in the range of about 0.60 to about 0.85, about 0.65 to about 0.85, about 0.70 to about 0.85, about 0.75 to about 0.85, about 0.80 to about 0.85, about 0.60 to about 0.80, about 0.60 to about 0.75, about 0.60 to about 0.70, about 0.60 to about 0.65, or about 0.60, 0.61, 0.62, 0.63, 0.64, 0.65, 0.66, 0.67, 0.68, 0.69, 0.70, 0.71, 0.72, 0.73, 0.74, 0.75, 0.76, 0.77, 0.78, 0.79, 0.80, 0.81, 0.82, 0.83, 0.84, 0.85, or any value or range therein.

25 The sound-absorbing porous composite may have a sound absorption coefficient which is ≥ 0.75 at audible frequencies above 1200 Hz with a thickness of 25 mm. The sound absorbing coefficient may be ≥ 0.75 , ≥ 0.80 , ≥ 0.85 , ≥ 0.90 , or ≥ 0.95 . The sound absorbing coefficient may be in the range of about 0.75 to about 0.95, about 0.80 to about 0.95, about 0.85 to about 0.95, about 0.90 to about 0.95, about 0.75 to about 0.90, about 0.75 to about 0.85, about 0.75 to about 0.80, or about 0.75, 0.76, 0.77, 0.78, 0.79, 0.80, 0.81, 0.82, 0.83, 0.84, 0.85, 0.86, 0.87, 0.88, 0.89, 0.90, 0.91, 0.92, 0.93, 0.94, 0.95, or any value or range therein.

30 The sound-absorbing porous composite may have a sound absorption coefficient which is ≥ 0.80 at audible frequencies above 1400 Hz with a thickness of 25 mm. The sound absorbing coefficient may be ≥ 0.80 , ≥ 0.85 , ≥ 0.90 , or ≥ 0.95 . The sound absorbing coefficient may be in the range of about 0.80 to about 0.95, about 0.85 to about 0.95, about 0.90 to about 0.95, about 0.80 to about 0.90, about 0.80

to about 0.85, or about 0.80, 0.81, 0.82, 0.83, 0.84, 0.85, 0.86, 0.87, 0.88, 0.89, 0.90, 0.91, 0.92, 0.93, 0.94, 0.95, or any value or range therein.

The sound-absorbing porous composite may have a sound absorption coefficient which is about ≥ 0.90 at audible frequencies above 1.5 kHz with a thickness of 25 mm. The sound absorbing coefficient may be ≥ 0.90 , or ≥ 0.95 . The sound absorbing coefficient may be in the range of about 0.90 to about 0.99, about 0.93 to about 0.99, about 0.95 to about 0.99, about 0.97 to about 0.99, about 0.93 to about 0.97, about 0.93 to about 0.95, or about 0.90, 0.91, 0.92, 0.93, 0.94, 0.95, 0.96, 0.97, 0.98, or 0.99 or any value or range therein.

Brief Description of Drawings

The accompanying drawings illustrate a disclosed embodiment and serves to explain the principles of the disclosed embodiment. It is to be understood, however, that the drawings are designed for purposes of illustration only, and not as a definition of the limits of the invention.

Fig.1

[Fig. 1] is a schematic illustration of the combined energy conversion mechanisms involved in the sound absorbing porous composite of the present invention.

Fig.2

[Fig. 2] is a schematic illustration of the sound energy conversion to electrical and thermal energy in the porous composite of the present invention comprising mechano-electrical and electro-thermal conversion elements.

Fig.3

[Fig. 3] is a schematic illustration of an open-cell porous sound-absorbing composite of the present invention comprising piezoelectric polymer or polymeric electret with (a) conductive and (b) lossy elements as the electro-thermal conversion elements.

Fig.4

[Fig. 4] is a scanning electron microscope (SEM) image of a porous composite comprising piezoelectric P(VDF TrFE) with 5 wt% SWCNT of Example 1.

Fig.5

[Fig. 5] is a graph showing the sound-absorption coefficients of 25 mm thick porous composite of piezoelectric P(VDF-TrFE) with SWCNT at different concentrations of Example 1 in comparison with 25 mm thick polyurethane acoustic foam as a benchmark.

Fig.6

[Fig. 6] is a graph showing the volume resistivity of a porous composite comprising piezoelectric P(VDF-TrFE) and SWCNT of Example 1.

Fig.7

[Fig. 7] is a graph showing the dielectric loss of a porous composite comprising piezoelectric P(VDF-TrFE) with SWCNT of different concentrations of Example 1.

Fig.8

[Fig. 8] is a graph showing the sound-absorption coefficients of a porous composite comprising 25 mm thick piezoelectric PVDF with 5 wt% SWCNT in comparison with 25 mm thick polyurethane acoustic foam as a benchmark.

Fig.9

[Fig. 9] is fourier-transform infrared (FTIR) spectra of PVDF/SWCNT porous composites, comprising 3 wt% and 5 wt% SWCNT with dominant β -phase.

Fig.10

[Fig. 10] is a graph showing the dielectric loss of a porous composite comprising PVDF with and without SWCNT (5 wt%).

Fig.11

[Fig. 11] is a graph showing the sound-absorption coefficients of a porous composite comprising piezoelectric P(VDF-TrFE) with 9 wt% Al particles of Example 4.

Fig.12

[Fig. 12] is a graph showing the sound-absorption coefficient of a porous composite comprising blend of PVDF and polyurethane with 3 wt% MWCNT of Example 14 in comparison with porous PVDF with 3 wt% MWCNT.

Fig.13

[Fig. 13] shows porous composites comprising piezoelectric P(VDF-TrFE) with SWCNT at concentrations of a) 0 wt%, b) 1 wt%, c) 2 wt%, and d) 5 wt%.

Fig.14

5 [Fig. 14] is a diagram depicting the ASTM E1050-08 method.

Detailed Description of Drawings

10 In conventional acoustic porous materials, sound is absorbed by the dissipation of sound energy as a result of the friction with air and destructive interference in the pores. With reference to Fig. 1, in this invention, in addition to absorbing sound by friction and destructive interference, sound mechanical energy is converted into electrical energy by mechano-electrical conversion elements and the converted electrical energy is converted into thermal energy by the electro-thermal conversion elements.

15 With reference to Fig. 2, incident noise as mechanical sound energy can induce vibrations in the composite. These vibrations generate electrical charges (depicted as the + and – symbols) through the piezoelectric and/or electret effect of the mechano-electrical conversion elements. It should be noted that the piezoelectric or electret effect can be a local effect that converts mechanical
20 energy into electric energy (charges) at localized regions, and the whole composite does not necessarily exhibit an overall piezoelectric or electret performance.

The charges generated in the composite are dissipated as Joule heat through the eletro-thermal conversion elements. The combined effect of the mechano-electrical energy conversion and electro-thermal conversion mechanism
25 increase sound absorption efficiency.

When conductive elements are present in the composite, as illustrated in Fig. 3a, the concentration of the conductive elements is preferably near the conductivity percolation threshold, such that the electrical conductivity can neither be too high to destroy the local piezoelectric effect, nor too low for poor charge
30 dissipation.

When dielectric lossy elements are present in the composite, as illustrated in Fig. 3b, the dielectric lossy elements are homogeneously distributed in the

porous composite as illustrated and can enhance the conversion of electrical energy into heat.

Examples

5 Non-limiting examples of the invention will be further described in greater detail by reference to specific Examples, which should not be construed as in any way limiting the scope of the invention.

10 **Example 1 – Poly[(vinylidene fluoride-co-trifluoroethylene] (P(VDF-TrFE)) and Single-Walled Carbon Nanotube (SWCNT)**

Sound absorbing porous composites comprising P(VDF-TrFE) as the piezoelectric mechano-electrical conversion elements and single-walled carbon nanotube (SWCNT) at different concentrations as the conductive electro-thermal conversion elements were prepared (100 wt% P(VDF-TrFE), 98 wt% P(VDF-TrFE) / 2 wt% carbon nanotubes, 95 wt% P(VDF-TrFE) / 5 wt% carbon nanotubes, 90 wt% P(VDF-TrFE) / 10 wt% carbon nanotubes). To obtain said composites, P(VDF-TrFE) solid (33.3 g) was dissolved in an organic mixed solvent of dimethylformamide (DMF) and acetone (50:50 in volume, 300 ml). Carbon nanotubes (0 wt %, 2 wt %, 5 wt % and 10 wt %, respectively, in the final solid composite) were dispersed in DMF/acetone and sonicated in an ultrasonic bath. Both solutions were then mixed and heated at 50 °C to obtain a precursor composite solution. The resulting composite solution was sonicated for mixing. Baker's sugar or salt (different size of particles, preferably ~50 µm - 600 µm in diameter) was mixed into the composite solution until a soft dough was formed. The dough was placed in a mould and slightly pressed. Ratios of 85 to 97 Vol % sugar or salt per composite solution were used to achieve the desired porosities. The moulded samples were heated at 100 °C for 12 hours to ensure complete drying. To create the porous composite, the fully dried samples were placed in hot water to dissolve the sugar or salt. After drying at a temperature of 100°C, the porous composites were annealed at 135 °C for 5 hours. Fig. 4 shows the morphology of the porous composite of P(VDF-TrFE) with 5 wt% SWCNT.

The porosities were calculated using the ethanol saturation method:

$$\emptyset = [\rho_{\text{sat}} - \rho_{\text{dry}}] / \rho_{\text{ethanol}}$$

where ρ_{sat} , ρ_{dry} , and ρ_{ethanol} are the densities of ethanol-saturated porous material, dry porous material, and ethanol, respectively. The porosity of porous P(VDF-TrFE)/ SWCNT at 3 wt % and 5 wt % was ~87 % and the pore size was in range of ~50-600 μm . The thickness of the porous composite was 25 mm.

The sound absorption coefficient of the porous composites were measured according to the ASTM E1050-08 procedure utilizing a standard commercial acoustic tube (Brüel & Kjær). Fig. 14 is a diagram illustrating the ASTM E1050-08 method.

In the ASTM E1050-08 procedure, the transfer function, H , between two microphones spaced s apart, and a distance l from sample with microphone is evaluated to get the sound absorption coefficient using the following equations:

$$R = \frac{H_1 - H_i}{H_r - H_1} e^{j2k(l+s)}$$

$$\alpha = 1 - |R|^2$$

where

R : Reflection factor,

H_1 : Frequency resonance function (FRF)

H_i : FRF associated with the incident component

H_r : FRF associated with the reflection component

k : Wave number

l : Distance between microphone 2 (14) and sample (mm)

s : Spacing between Microphone 1 (12) and Microphone 2 (14) (mm)

α : Sound absorption coefficient

According to this standard technique, frequency is limited by microphone spacing (s), as well as the diameter of the tube (22). It is also recommended that to guarantee the plane wave propagation, the following formula applies:

$$0.05 \frac{c}{s} < f < 0.45 \frac{c}{s}$$

C : Speed of sound

With reference to Fig, 14, sound is generated by a speaker (10).

10: Speaker

12 and 14 : Microphones 1 and 2

16: Sound absorbing porous composite

18: Sound wave from speaker

20: Sound wave bouncing off porous composite

22: Tube

In the ASTM E1050-08 procedure used in the present disclosure, the distance between Microphone 1 (12) and Microphone 2 (14) is 50 mm, and the diameter of the impedance tube (22) is 100 mm.

Fig. 5 shows the sound absorption coefficients of 25mm thick porous P(VDF-TrFE)/SWCNT composites at different SWCNT concentrations of Example 1 compared to 25 mm - thick polyurethane acoustic foam with 95 % porosity which has no piezoelectric effect. As shown in Fig. 5 and Table 1, it was found that the sound absorption coefficient of the P(VDF-TrFE)/ SWCNT porous composites were substantially higher than that of the polyurethane acoustic foam.

It was further found that the sound absorption coefficient of the P(VDF-TrFE)/SWCNT porous composites is strongly dependent on the amount of SWCNT. As shown in Fig. 5, the sound absorption coefficient of P(VDF-TrFE)/5 wt% SWCNT is significantly higher than that of porous P(VDF-TrFE) composite at 2 wt% and 10 wt% SWCNT. Table 1 shows the sound absorption coefficients of ~87% porosity, pore size ~50-600 μm , and 25 mm thick porous P(VDF-TrFE)/SWCNT composites at SWCNT concentrations of 2 wt%, 5 wt% and 10 wt% compared to 95% porosity and 25 mm thick polyurethane acoustic foam.

Table 1

	Sound Absorption Coefficient			
Frequency for sound absorption coefficient measurement (Hz)	P(VDF- TrFE)/2 wt% SWCNT	P(VDF- TrFE)/5 wt% SWCNT	P(VDF- TrFE)/10 wt% SWCNT	Polyurethane foam
200	0.053	0.083	0.031	0.05
400	0.12	0.23	0.07	0.11
600	0.21	0.44	0.12	0.14
800	0.32	0.66	0.18	0.18
1000	0.46	0.82	0.25	0.20

	Sound Absorption Coefficient			
Frequency for sound absorption coefficient measurement (Hz)	P(VDF- TrFE)/2 wt% SWCNT	P(VDF- TrFE)/5 wt% SWCNT	P(VDF- TrFE)/10 wt% SWCNT	Polyurethane foam
1200	0.57	0.91	0.30	0.23
1400	0.68	0.96	0.38	0.26
1500	0.77	0.98	0.42	0.3

Fig. 6 shows that 5 wt% concentration of SWCNT is near conductivity percolation threshold of SWCNT in P(VDF-TrFE) composite. The formation of conductive channels with optimum high resistance near the conductivity percolation threshold in a porous composite of P(VDF-TrFE)/5 wt% SWCNT is crucial to achieving high sound absorption coefficient. This shows that the concentration of the SWCNT as the conductive element is near conductivity percolation threshold, such that the electrical conductivity is neither too high to destroy the local piezoelectric effect, nor too low for poor charge dissipation.

Fig. 7 shows that the dielectric loss of a porous composite containing 5 wt% SWCNT in P(VDF-TrFE) composite was much higher than porous composites with 2 wt%. With a further increase of SWCNT to 10 wt%, SWCNT particles may come into intimate contact with one another, and thus dielectric loss further increased with the increased conductivity. However, mechanical energy to electrical energy conversion may become ineffective due to the destroyed piezoelectric effect which resulted in the absorption coefficient dropping significantly.

Example 2 - Poly[(vinylidene fluoride-co-trifluoroethylene) (PVDF) and Single-Walled Carbon Nanotube (SWCNT)

A sound absorbing porous composite comprising PVDF homopolymer as the piezoelectric mechano-electrical conversion element and 5 wt% single-walled

carbon nanotube (SWCNT) was prepared with the same method as described in Example 1. The thicknesses of the porous composite was 25 mm. The porosity of porous composites was ~ 89% and pore size was in range of ~50-600 μm .

Fig. 8 shows the sound absorption coefficient of the porous PVDF/5 wt% SWCNT in comparison with polyurethane acoustic foam as a benchmark. It was found that sound absorption coefficient of PVDF/5 wt% SWCNT porous composite is significantly higher than that of commercial 25 mm thick polyurethane acoustic foam with 95 % porosity which has no piezoelectric effect. Table 2 shows the sound absorption coefficients of about 89% porosity, pore size ~50-600 μm , and 25 mm thick porous PVDF/5 wt% SWCNT composite compared to 95% porosity and 25 mm thick polyurethane acoustic foam.

Table 2

Frequency for sound absorption coefficient measurement (Hz)	Sound Absorption Coefficient	
	PVDF / 5 wt% SWCNT	Polyurethane foam
200	0.07	0.05
400	0.23	0.11
600	0.44	0.14
800	0.66	0.18
1000	0.81	0.20
1200	0.91	0.23
1400	0.96	0.26
1500	0.99	0.30

The porous composite of PVDF/SWCNT exhibited a piezoelectric β phase, as confirmed with Fourier-transform infrared spectroscopy (FTIR) (Fig. 9). Therefore, porous composite of PVDF/SWCNT is piezoelectric active and can

convert sound mechanical energy into electrical energy with the piezoelectric PVDF as the mechano-electrical conversion elements.

As shown in Fig. 10, adding 5 wt% SWCNT to PVDF significantly improves dielectric loss, at least partially due to the formation of conductive channels near percolation threshold. The high dielectric loss can contribute to dissipating the electrical energy generated by piezoelectric elements to thermal energy.

Example 3 - PVDF or P(VDF-TrFE) and Graphene

Open-cell porous composite of PVDF or P(VDF-TrFE) as the piezoelectric mechano-electrical conversion elements with graphene as the conductive element was prepared with the same method as described in Example 1. Preferably, the concentration of graphene is 3-7 wt%.

Example 4 - PVDF or P(VDF-TrFE) and particles of conductive metals (such as Cu, Al, Ag, Au,..)

Open-cell porous composite with PVDF or P(VDF-TrFE) as the piezoelectric mechano-electrical conversion elements with particles of conductive metals (such as Cu, Al, Ag, Au,..) as the conductive element was prepared with the same method as described in Example 1. In this example carbon nanotube was replaced with conductive metals (such as Cu, Al, Ag, Au,..). Percolation threshold of the micro particles of aluminium was near 10 wt%. Figure 11 shows the sound absorption coefficient of porous P(VDF-TrFE)/9 wt% Al composite. Table 3 shows the sound absorption coefficients of 87% porosity, ~300µm pore size, and 25 mm thick porous P(VDF-TrFE)/9% Al.

Table 3

	Sound Absorption Coefficient
Frequency for sound absorption coefficient measurement (Hz)	P(VDF-TrFE)/9 wt% Al

	Sound Absorption Coefficient
Frequency for sound absorption coefficient measurement (Hz)	P(VDF-TrFE)/9 wt% Al
200	0.05
400	0.22
600	0.44
800	0.61
1000	0.73
1200	0.79
1400	0.81
1500	0.82

Example 5 - PVDF and aluminum nitrate nonahydrate ($\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$)

Open-cell porous composites with PVDF as the piezoelectric mechano-electrical conversion elements with aluminum nitrate nonahydrate ($\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$) as the dielectric lossy element for electro-thermal conversion was prepared. To fabricate this porous composite, $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ (10 wt % and 20 wt % in the final solid film) was dissolved in DMF/acetone solvent. PVDF was added to the above solution. The solutions were then heated at 50 °C to obtain a composite precursor solution. Baker's salt was mixed into the composite solution until soft dough formed. The dough was placed in a mould and slightly pressed. Ratios of 85 to 95 Vol % salt per composite solution were used to achieve the desired porosity. The moulded samples were heated at 100 °C to ensure complete drying. To produce the porous composite, the fully dried samples were placed in hot water to dissolve the salt. After drying at 100 °C, the porous composites were annealed in an oven at 135 °C.

Example 6 - PVDF and aluminum chloride hexahydrate ($\text{AlCl}_3\cdot 6\text{H}_2\text{O}$)

Open-cell porous composites with PVDF as the piezoelectric mechano-electrical conversion elements with aluminum chloride hexahydrate ($\text{AlCl}_3\cdot 6\text{H}_2\text{O}$) of 10 wt% - 25 wt% as the dielectric lossy element for electro-thermal conversion was prepared with the same method as in Example 5.

Example 7 - PVDF and tetra-n-butylammonium chloride (TBAC)

Open-cell porous composites with PVDF as the piezoelectric mechano-electrical conversion elements with 10 to 30 wt% tetra-n-butylammonium chloride (TBAC) as the lossy element for electrothermal conversion were prepared with the same method as in Example 5.

Example 8 - PVDF and ammonium acetate (NH_4OAc)

Open-cell porous composites with PVDF as the piezoelectric mechano-electrical conversion elements with 10 to 25 wt% ammonium acetate (NH_4OAc) as the dielectric lossy element for electro-thermal conversion was prepared with the same method as in Example 5.

Example 9 - Polypropylene (PP) and SWCNT

Open-cell porous composites with polypropylene (PP) as a polymeric electret for the mechanoelectrical energy conversion with SWCNT as the conductive elements for electrothermal energy conversion were prepared. PP was dissolved in toluene at 80 °C. SWCNT (3 wt %-5 wt % in the final solid film) were dispersed in toluene and sonicated in ultrasonic bath. Both solutions were then mixed and heated at 80 °C to obtain a composite precursor solution. Baker's sugar (different size of particles of ~50 µm - 600 µm in diameter) was mixed into the composite solution until soft dough formed. The dough was placed in a mould and slightly pressed. Ratios of 85 to 96 Vol % sugar in composite solution were used to achieve the desired porosities. The moulded samples were completely dried at 100 °C. To produce the porous composite, the dried samples were placed in hot water

to dissolve the sugar, and dried at 100 °C. The dried porous composites were annealed at 125 °C and electrically poled with corona gun.

Example 10 - Polyethylene terephthalate and SWCNT

Open-cell porous composites with polyethylene terephthalate as the polymeric electret for mechano-electrical energy conversion with SWCNT as the conductive elements for electro-thermal energy conversion were prepared with the same method as described in Example 9. Concentration of SWCNT was 3 wt%-5 wt%.

Example 11 - Polyimide with SWCNT

Open-cell porous composites with polyimide as the polymeric electret for mechano-electrical energy conversion with SWCNT as the conductive elements for electrothermal energy conversion were prepared with the same method as described in Example 9. The concentration of SWCNT was 3 wt%-5 wt%.

Example 12 - Polymethylmethacrylate with SWCNT

Open-cell porous composites with polymethylmethacrylate as polymeric electret for mechano-electrical energy conversion with SWCNT as conductive elements for electrothermal energy conversion were prepared with the same method as described in Example 9. Concentration of SWCNT was 3 wt%-5 wt%.

Example 13 - Ethylene vinyl acetate cyclic olefin copolymer and SWCNT

Open-cell porous composites with ethylene vinyl acetate cyclic olefin copolymer as the polymeric electret for mechano-electrical energy conversion and with SWCNT as the conductive elements for electro-thermal energy conversion were prepared with the same method as described in Example 9. Concentration of SWCNT was 3 wt%-5 wt%.

Example 14 – Blend of PVDF/polyurethane and MWCNT

Open-cell porous composites with a blend of PVDF and polyurethane as the mechano-electrical energy conversion elements, and MWCNT as the conductive elements for electro-thermal energy conversion were prepared. 15 wt% PVDF, 82 - 80 wt% polyurethane, and 3 - 5 wt% MWCNT were mixed. The porous composite was annealed at 135 °C for 5 hours. Fig. 12 shows the sound absorption coefficients of 25 mm thick porous 82 wt% polyurethane/15 wt% PVDF/3 wt% MWCNT in comparison with 97 wt% PVDF/3 wt% MWCNT. Table 4 shows the sound absorption coefficients of 85% porosity, ~200-300 µm pore size porous 82 wt% polyurethane/15 wt% PVDF/3 wt% MWCNT in comparison with 87% porosity, ~200-300 µm pore size, 97 wt% PVDF/3 wt% MWCNT

Table 4

Frequency for sound absorption coefficient measurement (Hz)	Blend of PVDF and polyurethane/ 3 wt% MWCNT	PVDF / 3 wt% MWCNT
200	0.08	0.08
400	0.20	0.21
600	0.42	0.42
800	0.66	0.67
1000	0.83	0.83
1200	0.92	0.92
1400	0.94	0.97
1500	0.93	0.99

Industrial Applicability

The porous composites of the present invention may be useful in reducing noise levels.

The combination of the mechanisms of converting sound mechanical energy into electric energy via the mechano-electrical conversion elements and converting the converted electric energy into thermal energy via the electro-thermal conversion elements provides a synergistic interaction which provides for more efficient sound absorption.

Further, having the porous composite of at least 85% porosity adds additional sound energy dissipation mechanisms such as destructive interference in the pores, friction damping, and viscoelastic damping. This, in combination with the above-mentioned energy conversion mechanisms, provides for a highly efficient sound absorbing material.

It will be apparent that various other modifications and adaptations of the invention will be apparent to the person skilled in the art after reading the foregoing disclosure without departing from the spirit and scope of the invention and it is intended that all such modifications and adaptations come within the scope of the appended claims.

Claims

1. A sound-absorbing porous composite comprising:

5 (a) mechano-electrical conversion elements to convert sound mechanical energy into electric energy; and

(b) electro-thermal conversion elements to convert the converted electrical energy into thermal energy;

10 wherein said mechano-electrical conversion elements and electro-thermal conversion elements are homogenously mixed in said porous composite, and wherein the porosity of said porous composite is at least 85%, and wherein:

(i) the mechano-electrical conversion elements comprise polymeric electret; or

15 (ii) the mechano-electrical conversion elements comprise piezoelectric polymer when the electro-thermal conversion elements comprise dielectric lossy elements.

2. A sound-absorbing porous composite when used to absorb sound, comprising:

(a) mechano-electrical conversion elements to convert sound mechanical energy into electric energy; and

20 (b) electro-thermal conversion elements to convert the converted electrical energy into thermal energy;

wherein said mechano-electrical conversion elements and electro-thermal conversion elements are homogenously mixed in said porous composite, and wherein the porosity of said porous composite is at least 85%, and wherein:

25 (i) the mechano-electrical conversion elements comprise polymeric electret; or

(ii) the mechano-electrical conversion elements comprise piezoelectric polymer when the electro-thermal conversion elements comprise dielectric lossy elements; or

(iii) the mechano-electrical conversion elements comprise piezoelectric polymer when the electro-thermal conversion elements comprise electrical conductive elements, wherein the concentration of said conductive elements is near conductivity percolation threshold.

- 5 3. The sound-absorbing porous composite in accordance with Claim 1 or 2, wherein the electro-thermal conversion element(s) comprise electrical conductive elements.
4. The sound-absorbing porous composite in accordance with Claim 1 or 2, wherein the electro-thermal conversion elements comprise dielectric lossy elements.
- 10 5. The sound-absorbing porous composite in accordance with any one of Claims 1 to 4, wherein the piezoelectric polymer is selected from the group consisting of polyvinylidene fluoride (PVDF), PVDF-based polymers, homopolymer and copolymers containing a major portion of vinylidene fluoride, poly(vinylidene fluoride-trifluoroethylene), poly(vinylidene fluoride-hexafluoropropylene) copolymers, poly(vinylidene fluoride-trifluoroethylene-chlorofluoroethylene) and terpolymer.
- 15 6. The sound-absorbing porous composite in accordance with any one of Claims 1 to 4, wherein the polymeric electret is selected from the group consisting of polypropylene, polyurethane, polyethylene, polystyrene, polyethylene terephthalate, polytetrafluoroethylene, polyimide, polymethylmethacrylate, and ethylene vinyl acetate cyclic olefin copolymers.
- 20 7. The sound-absorbing porous composite in accordance with any one of Claims 1 to 6, wherein the mechano-electrical conversion elements comprise a blend of a piezoelectric polymer and a polymer electret.
- 25 8. The sound-absorbing porous composite in accordance with any one of Claims 1 to 3 and 5 to 7, wherein the electrical conductive elements are selected from the group consisting of carbon nanotubes, graphene, carbon black, and conductive metal particles.
- 30 9. The sound-absorbing porous composite in accordance with any one of Claims 1, 2 and 4 to 7, wherein the lossy elements are selected from the group consisting of hydrated or hygroscopic materials.

10. The sound-absorbing porous composite in accordance with any one of Claims 1 to 3, and 5 to 8, wherein the electro-thermal conversion elements comprise electrical conductive elements, and the concentration of the conductive elements is near conductivity percolation threshold.
- 5 11. The sound-absorbing composite in accordance with any one of Claims 1 to 3, 5 to 8 and 10, wherein the electro-thermal conversion elements comprise electrical conductive elements, and the concentration of the conductive elements is 3 wt% to 10 wt%.
- 10 12. The sound-absorbing porous composite in accordance with any one of Claims 1, 2, 4 to 7 and 9, wherein the concentration of lossy element is ≥ 10 wt % of said composite.
13. The sound-absorbing porous composite in accordance with any one of Claims 1 to 12, wherein the porous composite is cellular type with open-cell pores.
14. The sound-absorbing porous composite in accordance with any one of Claims 15 1 to 13, wherein the pore size is in range of 50-600 μm .
15. The sound-absorbing porous composite in accordance with Claim 2, wherein the composite comprises polyvinylidene fluoride (PVDF)-based polymer as the mechano-electric conversion elements and 3 - 5 wt% carbon nanotubes as the electro-thermal conversion elements.
- 20 16. The sound-absorbing porous composite in accordance with any one of Claims 1, 2, 4, 5, 7, 9 and 12 to 14, wherein said composite comprises polyvinylidene fluoride (PVDF)-based polymer as the mechano-electric conversion elements and about 9 wt% aluminum microparticles as the electro-thermal conversion elements.
- 25 17. The sound-absorbing porous composite in accordance with any one of Claims 1 to 3, 6 to 8, 10, 11, 13 and 14, wherein said composite comprises polypropylene, polyurethane, polyethylene, polystyrene, polyethylene terephthalate, polytetrafluoroethylene, polyimide, polymethylmethacrylate, or ethylene vinyl acetate cyclic olefin copolymers as the mechano-electric conversion elements and 3-5 wt% carbon nanotube as the electro-thermal conversion elements.
- 30 18. The sound-absorbing porous composite in accordance with any one of Claims 1 to 17, wherein the sound absorption coefficient for the porous composite is ≥ 0.50 at audible frequencies above 800 Hz with a thickness of 25 mm.

19. The sound-absorbing porous composite in accordance with any one of 1 to 17, wherein the sound absorption coefficient for the porous composite is not lower than about ≥ 0.90 at audible frequencies above 1.5 kHz with a thickness of 25 mm.

20. A method for absorbing sound, comprising the following steps:

5 (i) providing a sound-absorbing porous composite comprising:

(a) one or more mechano-electrical conversion element(s), ; and

(b) one or more electro-thermal conversion element(s);

10 wherein said mechano-electrical conversion element(s) and electro-thermal conversion element(s) are homogenously mixed in said porous composite, and wherein the porosity of said porous composite is at least 85%, and wherein

(i) the mechano-electrical conversion elements comprise polymeric electret, or

15 (ii) the mechano-electrical conversion elements comprise piezoelectric polymer when the electro-thermal conversion elements comprise dielectric lossy elements, or

20 (iii) the mechano-electrical conversion elements comprise piezoelectric polymer when the electro-thermal conversion elements comprise electrical conductive elements, wherein the concentration of said conductive elements is near conductivity percolation threshold;

(ii) converting sound mechanical energy into electric energy via said mechano-electrical conversion element(s);

25 (iii) converting the electrical energy produced by step (ii) into thermal energy via said electro-thermal conversion element(s).