April 29, 1952 L. L. BERANEK 2,595,047

ACOUSTIC MATERIAL WHICH THERMODYNAMICALLY ABSORBS SOUND

Filed Dec. 10, 1947 2 SHEETS—SHEET 1

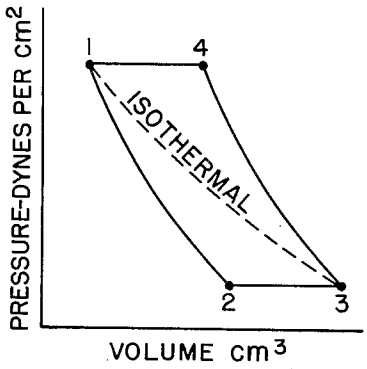


FIG. 1

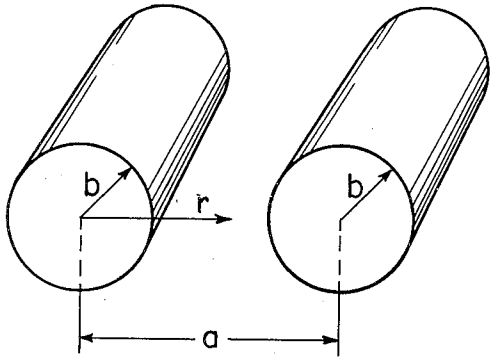


FIG. 2

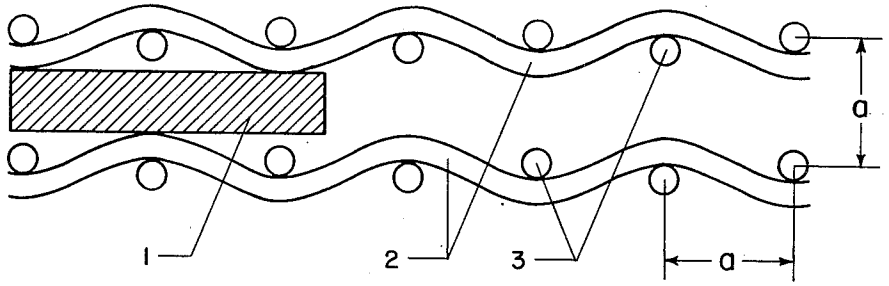


FIG. 3

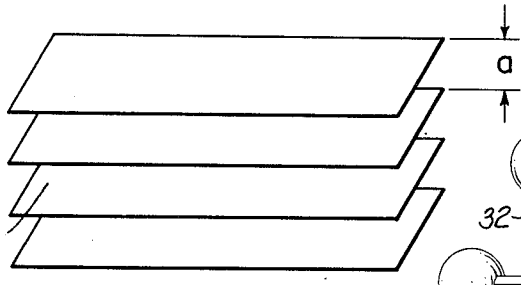


FIG. 4

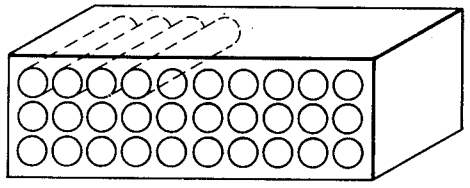


FIG. 5

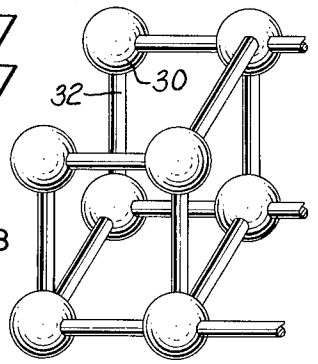


FIG. 8

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April 29, 1952 L. L. BERANEK 2,595,047

ACOUSTIC MATERIAL WHICH THERMODYNAMICALLY ABSORBS SOUND

Filed Dec. 10, 1947 2 SHEETS—SHEET 2

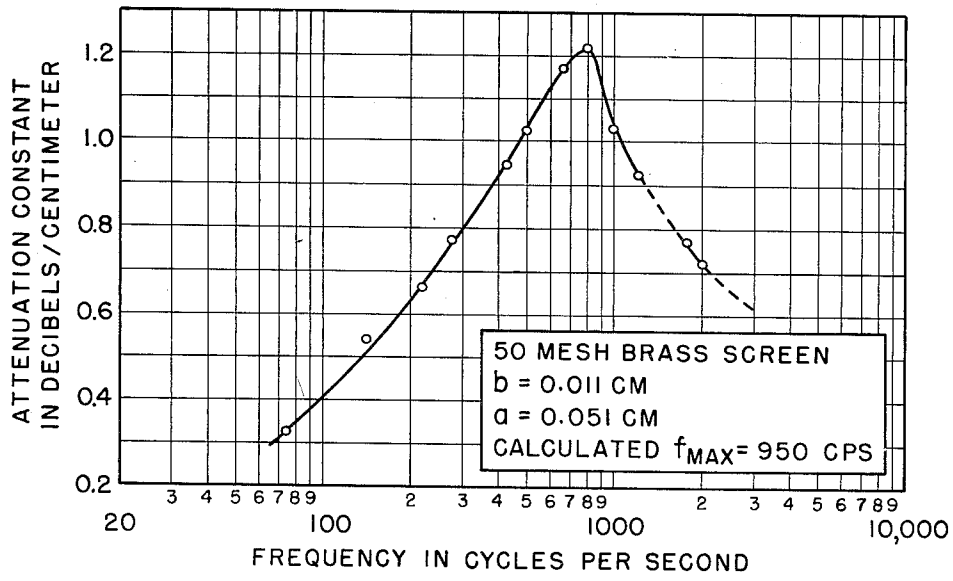


FIG. 6

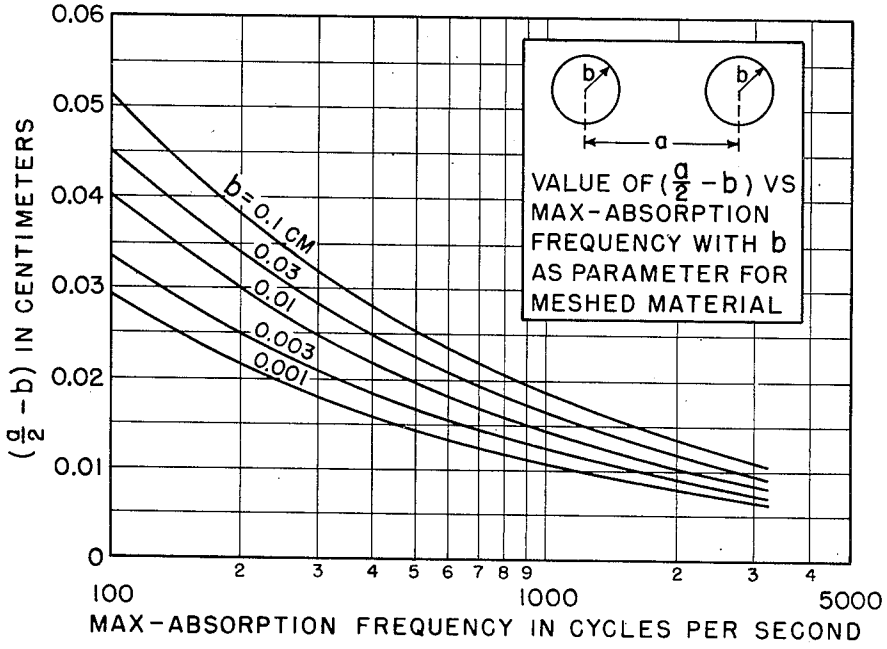


FIG. 7

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ACOUSTIC MATERIAL WHICH THERMODYNAMICALLY ABSORBS SOUND

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Application December 10, 1947, Serial No. 790,761

5 Claims. (Cl. 181—33)

1

This invention relates to novel methods and materials for absorbing sound, and especially to improved acoustic materials of novel intersticed character designed to provide for conversion of sound energy to heat by a thermodynamic process.

The term "acoustic material," as employed in the specification, is intended to define a body of matter which forms the active element of an acoustic filter or an acoustic absorbent.

The term "thermodynamic," as employed in the specification, is restricted to refer to the physical phenomenon whereby mechanical energy imparted to a gas is converted into heat energy, the heat energy being, in turn, absorbed in the walls of an intersticed body in which the gas may be contained; the conversion taking place during a cycle of compression and expansion of the gas; the cycle taking place at such a rate that a curve for the cycle of the gaseous pressure plotted against the volume of the gas encloses a substantial area; and the cycle taking place at a rate such that the acoustic power is absorbed; that is, the product of the rate, times the area, is substantially at, or near, a maximum for that intersticed body.

Acoustic materials of conventional type, as is known to those skilled in the art, produces sound absorption because of frictional losses between the solid surfaces inside the acoustic material and the vibrating particles of air set in motion by the sound wave. This method for absorbing sound has the very definite limitation that it is not possible to absorb certain tones in preference to others. For that reason, a type of acoustic material which produces sound absorption by friction is not particularly suitable for use with certain types of commercial machinery, for making precise acoustic measurements, or for carrying out other observations which may become desirable in connection with scientific studies of acoustic phenomena.

I have discovered a novel method of sound absorption and novel acoustic materials, the use of which is based upon a unique principle of thermodynamics, by which a conversion of mechanical energy to heat energy is known to occur. I find that I may achieve highly desirable absorption of sound in any desired restricted frequency range by interposing in the path of movement of a sound wave, a porous sound absorbing member whose interstices are defined by surfaces, oriented in such a relationship to each other as to cause loss of acoustic energy through heat exchange between the air (or other gas) and the solid matter

2

of the material according to the above defined thermodynamic process.

Another important feature of the invention is a material for producing maximum absorption of sound in any desirable restricted frequency range constructed from a series of parallel surfaces of any material having predetermined spacing with regard to one another so as to produce sound absorption by the above defined thermodynamic process.

Another feature of the invention is an acoustic material so constructed as to present a substantially porous body in which are found a relatively large number of interstices of approximately the same general size and shape and which cause a reduction of the amplitude of a sound wave by thermodynamic absorption of the sound in a given frequency range.

Another feature of the invention is a method and means for calculating the frequencies at which maximum thermodynamic absorption will take place in terms of the shape, size and spacing of the solid elements which produce the necessary opposing surfaces of a sound absorbing material. These and various other objects and novel features will appear from the following description of the invention.

In the accompanying drawings:

Fig. 1 is a diagrammatic view illustrating a Kelvin heat cycle;

Fig. 2 is another diagrammatic view illustrating the meaning of the notation used in the formulas employed in the description which follows;

Fig. 3 is a diagrammatic view of one type of acoustical element made of woven fibers employing the concepts of the invention;

Fig. 4 is a diagrammatic view of another type of acoustic material employing these concepts;

Fig. 5 is a diagrammatic view of still another type of acoustical material employing these concepts;

Fig. 6 is a graph illustrating the relative magnitude of absorption which will be obtained by the use of a woven fiber material such as is illustrated in Fig. 3; and

Fig. 7 is a chart for the calculation of the spacings and diameters of the woven fiber material of Fig. 3 which in turn constitute the opposing solid surfaces, which will provide maximum absorption at a specified frequency in cycles per second.

Fig. 8 is a diagrammatic view of a lattice formation including spherical pieces held together in spaced relationship.

The new method of sound absorption of the

invention depends upon a principle of thermodynamics which has been used for many years to describe the loss of efficiency of heat engines. In order to furnish a better basis for clearly understanding the invention, a brief outline of the theory involved will be given first. The principle of thermodynamics noted states that, if by applying force, a frictionless piston contained in a cylinder is made to move first outward and then inward, thus first expanding and then compressing a gas contained in the cylinder, absorption of energy in the cylinder walls will take place because of heat transfer, assuming the movement of the piston is executed at a proper rate.

In Fig. 1 a Kelvin perfect heat cycle is shown. If the cylinder of gas is initially in a compressed state and the piston is suddenly pulled outward, the gas will expand from point 1 to point 2, i. e., the pressure of the gas will decrease and the volume in which it is contained will increase. Because this movement takes place suddenly, there will be no time for heat to flow from the walls of the chamber to the gas, which means that at point 2 the gas will have a lower temperature than it had at point 1. This is true, because the temperature of an expanding gas always drops. In the next fraction of time, the gas will take on heat from the walls of the chamber and, if the pressure being exerted by the piston is held constant, the volume of air will expand until the gas has warmed up to the temperature of the walls of the cylinder. At that time the condition of the gas will be as indicated at point 3. Now if the piston is suddenly pushed inward, the gas will be compressed, its temperature and pressure will rise, and its volume will decrease. This is shown by the line from 3 to 4. Again, during this change there was no time for heat to flow from the gas to the side walls. In the next fraction of time, heat will flow from the gas to the side walls, and, if the pressure on the piston is held constant, the volume will decrease from 4 to 1 as it is cooled.

The four lines 1—2—3—4—1 enclose an area. According to the principle of thermodynamics, this area represents an expenditure of energy, i. e., work on the part of the prime mover supplying the pressure on the piston. The exact amount of work done for each alternation of the piston is computed by the formula:

$$W=\phi PdV$$

This formula states that W, the work performed, is equal to the line integral of the pressure P times the incremental volume dV, i. e., W is equal to the area enclosed by the solid lines of Fig. 1. The mechanical power P expended is the amount of work done in a unit length of time (usually one second) and is calculated by multiplying W by the number of traversals of the path 1—2—3—4—1 which occur in a unit length of time. It should be noted that an area will not necessarily be enclosed unless the backward and forward movement of the piston takes place at the proper rate. If the entire cycle of movement takes place very rapidly, there will be no time for exchange of heat between the side walls of the cylinder and the gas and hence WP approach zero. In this case, the lines 2—3 and 4—1 will shrink to zero in length. On the other hand, if the cycle takes place very slowly, the whole process will occur isothermally, i. e., the temperature of the gas will not rise or fall when the part of the cycle represented by the lines 1—2 and 3—4 takes place. In the latter instance,

motion in both directions will take place along the dotted line 1—3 of Fig. 1. It is apparent that in neither case, much too slow or much too fast, will the lines enclose any area, and no loss of energy will take place. As stated above, it is assumed that there are no frictional losses between the piston and cylinder. Even for cases in which motions between points 1 and 2 and between points 3 and 4 take place instantaneously, if the total time required to traverse the path 1—2—3—4—1 is large, the power P (rate of working) will be small despite the fact that in such a case W remains constant below a certain time for traversal of the path.

From the foregoing situations, it is evident therefore that there is a range of rates through which such a cycle of expansion and compression produces work, or in other words expends energy. It is concluded therefore that, at some particular rate of expansion and compression in this range, the mechanical power P dissipated will be at a maximum. The rate at which the work done will be at a maximum may conveniently be referred to as the frequency of maximum absorption and is designated in cycles per second. The process which tends to a maximum dissipation of mechanical power P has been defined above as a "thermodynamic process."

In accordance with the invention, this fundamental process can be utilized to produce a novel acoustical material which will absorb sound maximally at a certain frequency. Also, particular frequencies can be selected at will through the use of charts or formulas, varying with the physical dimensions of the sound absorbing mechanism which is employed. Acoustical materials of the invention can be made up of fibers, solid piece of material, or masses or sheets of material in which openings are located. In order to make use of thermodynamic absorption of the type described in the case of heat engines, for such acoustical materials it is necessary to recognize that a sound wave compresses and expands air through which it travels just as a piston does with the cylinder of the engine. In free space, this cycle of compression and expansion takes place adiabatically, i. e. there is no exchange of heat between the base and any solid matter with which it comes into contact. On the other hand, in the case of most ordinary acoustical materials against which the gas may be caused to impinge, the size of the interstices is so small that the cycle takes place isothermally, corresponding to the dotted line 1—3 of Fig. 1. Even for those few acoustic materials in which the interstices are sufficiently large, the effect of thermodynamic absorption is not observable because the shape and size of the interstices are very non-uniform, thereby producing a non-uniform relationship between absorbing surfaces in the material with the result that the absorption is insignificantly large at any particular frequency, and is, moreover, spread over a very wide frequency range.

Having in mind the foregoing limitations, I have designed an acoustical material so that its form is conducive to maximum absorption in a desired frequency range. This acoustic material is characterized by a construction which produces the above defined thermodynamic process by virtue of being formed with a number of opposing surfaces spaced apart in a regular and preselected manner, thereby producing an absorbing or filtering action in a narrow range of frequencies with appreciably large absorption for that range. In essence the acoustical absorbent or

filter comprises a number of opposing surfaces spaced apart regularly in a predetermined manner. The manner in which these surfaces are formed and their spacing will now be discussed.

In establishing forms of opposing surfaces which are conducive to maximum absorption in a desired frequency range, it is convenient to make a study of the conditions in which heat transfer occurs between a gas and the surfaces of the solid material in a porous acoustical material. I have found by means of theoretical and experimental studies that the thermal effects occurring in the vicinity of a surface over or along which a sound wave is travelling, can be represented by a thermal wave which coexists with the sound wave and which is produced by the sound wave. Such a thermal wave is analogous to a sound wave, that is to say, in thermal wave heat energy is transferred from one point to another, while in the sound wave sound energy is transferred. The thermal wave has a certain magnitude (amplitude) and a certain speed of movement much slower than that of the sound wave. In addition, the thermal wave has its greatest amplitude near the surface along or over which the sound wave travels, said amplitude decreasing approximately exponentially with distance as one moves away from the surface. The rapidity of decrease of amplitude as one moves away from the surface becomes greater as the frequency of the sound wave becomes greater.

To a first approximation, theory and experiments reveal that a condition of maximum power dissipation occurs when at a point halfway between two opposing surfaces the amplitude of the thermal wave has decreased to a value of approximately one-tenth of the value it has at either of the two surfaces. Because the rate of decrease of the amplitude of the thermal wave as one moves away from either of the two surfaces increases with frequency, there is some particular frequency at which maximum power dissipation occurs. This is the frequency of maximum absorption referred to previously.

Two opposing surfaces or a set of opposing surfaces in the acoustical material between which sound waves may travel can be obtained in a large number of ways. In Fig. 4 one form is illustrated. Here a number of parallel solid sheets, spaced apart distances a, is shown. Another way of producing opposing surfaces is illustrated in Figs. 2 and 3. In this case, the opposing surfaces are the exterior of cylindrical fibers spaced apart in a regular manner. Another way, not illustrated, would be to provide a lattice of spherical solid elements spaced apart in regular manner. Still another way is to form the opposing surfaces by drilling a series of holes in a solid block as illustrated in Fig. 5. Here the opposing surfaces are the opposite sides of any one hole; the opposite sides being those which would exist if the hole were split along its length by a plane passing through the axis of the hole.

The mathematical relations which lead to the spacing of the elements forming the opposing surfaces in the acoustical material are as follows:

A. For surfaces formed by spherical pieces of solid material in lattice formation, spaced a cm. apart on centers

$$T_1=T_0\frac{e^{-k_\alpha r}}{r} \tag{1}$$

where T_1 is the amplitude of the thermal wave at a point r measured from the center of a sphere; T_0 is a constant; $e=2.718$; k_α is the wave number

for a thermal wave and is equal to: the real part of

$$k=(1+j)\sqrt{\frac{\gamma\omega}{\alpha}} \tag{2}$$

γ is the ratio of specific heats for the gas; $\omega=2\pi f$, where f is the frequency of the sound wave in cycles per second; α is the ratio of the thermal conductivity of the gas to its density; j is equal to (-1) ; and the radius of a sphere is b. Obviously, r must always be greater than b. At the surface of the sphere $r=b$ and the value of T_1 will become:

$$T_1(\text{at } r=b)=T_0\frac{e^{-k_\alpha b}}{b} \tag{3}$$

In Fig. 8 there has been illustrated diagrammatically a lattice formation including spherical pieces **30** which may be either of solid or hollow material and which pieces are held together by spacing elements **32**. The experiments and theory shows, that for maximum absorption of sound due to thermodynamic effects the spacing between spheres should be so planned that the thermal wave developed around each sphere will have decreased to approximately $\frac{1}{10}$ of its amplitude at a point half-way between two adjacent spheres. In other words, the separation a between the centers of two adjacent spheres should be approximately equal to $2r$ where r is obtained from the equation:

$$\frac{e^{-k_\alpha(r-b)}}{r}=\frac{0.1}{b} \tag{4}$$

B. For surfaces formed by cylindrical pieces of solid material (see Figs. 2 and 3)

$$T_1=T_0H_0^{(1)}(k_\alpha r) \tag{5}$$

where $H_0^{(1)}$ is a Hankel function of the first kind; b is the radius of the cylinder and k_α is given by Equation 2. The separation a between the centers of two adjacent cylindrical fibers should be approximately equal to $2r$ where r is determined from the formula:

$$H_0^{(1)}(k_\alpha r)=0.1H_0^{(1)}(k_\alpha b) \tag{6}$$

C. For surfaces formed by a slotted material made up of thin sheets of metal with air spaces between each sheet (see Fig. 4) the value of T_1 is given by

$$T_1+T_0e^{-k_\alpha l} \tag{7}$$

where l is the distance measured perpendicular to the surface of a sheet. For maximum absorption the sheets should be separated approximately by a distance $2l=a$ where l is determined from the formula:

$$e^{-k_\alpha l}=0.1 \tag{8}$$

D. For surfaces formed by a material made of a solid block in which holes are drilled (see Fig. 5) the same considerations hold as before, namely, the thermal wave traveling inward from the side walls of the holes must have decreased at the center to approximately $\frac{1}{10}$ of value it had at the walls if maximum absorption at a given frequency is to be attained. Obviously, for maximum absorption the holes should be located as near each other as possible so that there will be a maximum number of holes for absorption to take place in.

In Fig. 6, a typical absorption curve is shown for a material made of wire mesh screen, in which the opposing surfaces are formed by fibers which are cylindrical in nature and are evenly spaced

as shown in Fig. 3. In the case of a relatively fine mesh screen, for example a screen with 50 meshes per linear inch, the frequency of maximum absorption, f_{max}, is seen to be about 950 cycles per second. In the case of a relatively coarser mesh, such as a 30-mesh, tests show that a peak similar to that shown in Fig. 6 will occur at approximately 190 cycles per second.

The results of the mathematical analysis already given in Equations 4, 6 and 8 are shown in graphical form in Fig. 7 for the case of a woven, cylindrical-fiber material. Fig. 7 shows a plot of the quantity $(a-b)$ versus f_{max} where r is the distance between centers of adjacent cylinders and f_{max} is the frequency at which the absorption will reach its maximum value.

As illustrative of one suitable method of making an acoustic material in accordance with the invention, I may employ a number of layers of wire or plastic mesh screen, piled one on top of another and suitably spaced apart as shown in Fig. 3. In forming the acoustic material from the layers of screen, adjacent layers are held apart by thin strips t in such a way that the distance a between the centers of adjacent wires will be the same in any direction. The spacing a is chosen according to Fig. 7. The purpose of choosing some particular value of a is to produce selective sound absorption in some particular frequency range for the given diameter b of cylindrical fibers chosen.

Another arrangement may consist of a number of layers of sheet metal, the layers being suitably spaced apart by narrow strips of thickness a as determined by Equation 8 noted above. These narrow strips can be made of any material whatsoever.

One example of the use to which this novel acoustic material has been put was as an acoustic filter in an acoustic delay line. As is well known, an acoustic delay line is an important part of a standby radio speech transmitter, wherein the output of the speech microphone is conducted through two channels. One channel controls a relay which in turn is connected to the power supply to the transmitter. The other channel contains the delay line and is connected to the speech input of the transmitter. The operation of the two channels is as follows: When the operator starts speaking the first channel turns on the transmitter. Because of the delay introduced by the delay line, the speech reaches the input after the transmitter is turned on and is operative.

The particular acoustic delay line in which this invention was introduced was made of a hollow conducting pipe closed at one end by a source of sound and at the other by an absorbing termination of conventional type to reduce echoes, and a microphone. A complex sound wave consisting of the speech frequencies plus ambient room noise was injected at one end. The wave in the tube was picked up at the other end, after a delay equal to the ratio of the length of the pipe to the velocity of sound, by the microphone placed in front of the sound absorbing termination of conventional type. Between the two ends, the novel acoustic material of this application was interposed with a thickness of several inches and made according to Fig. 3. After sound had passed through it they contained all except those tones in the speech wave and in the room noise which it was desired to eliminate. It so happened that the undesired tones lay within the narrow frequency range of 600 to 900 cps. and thus were readily eliminated by the acoustic material whose absorption characteristic was that shown in Fig. 6.

I claim:

1. An improved acoustic material comprising an intersticed body having a multiplicity of openings formed therein of substantially uniform character in which sound energy is absorbed themodynamically where the term thermodynamically is restricted to refer to the physical phenomenon whereby mechanical energy imparted to a gas is converted into heat energy, the heat energy being in turn absorbed in the walls of an intersticed body in which the gas may be contained; the conversion taking place during a cycle of compression and expansion of the gas; the cycle taking place at such a rate that a curve for the cycle of the gaseous pressure plotted against the volume of the gas encloses substantial area; and the cycle taking place at a rate such that the acoustic power absorbed, i. e., the product of the rate times the area, is substantially at or near a maximum for that intersticed body, and said intersticed body comprising a plurality of substantially fibrous elements lying in spaced-apart relation, this spacing being approximately equal to the value for "a" given by the following equation:

$$H_0^{(1)}\left(k_\alpha \frac{a}{2}\right)=0.1H_0^{(1)}(k_\alpha b)$$

where $H_0^{(1)}$ is a Hankel function of the first kind, "b" is the radius of the sphere, and k_α is given by the equation

$$k_\alpha=\sqrt{\frac{\gamma\omega}{\alpha}}$$

where γ is the ratio of specific heats; $\omega=2\pi f$, where f is the frequency of the sound wave in cycles per second; and α is the ratio of the thermal conductivity of the gas to its density.

2. An improved acoustic material comprising an intersticed body having a multiplicity of openings formed therein of substantially uniform character in which sound energy is absorbed thermodynamically where the term thermodynamically is restricted to refer to the physical phenomenon whereby mechanical energy imparted to a gas is converted into heat energy, the heat energy being in turn absorbed in the walls of an intersticed body in which the gas may be contained; the conversion taking place during a cycle of compression and expansion of the gas; the cycle taking place at such a rate that a curve for the cycle of the gaseous pressure plotted against the volume of the gas encloses substantial area; and the cycle taking place at a rate such that the acoustic power absorbed, i. e., the product of the rate times the area, is substantially at or near a maximum for that intersticed body, and said intersticed body comprising a plurality of plain sheets of material lying in spaced-apart relation, this spacing being approximately equal to the value of "a" given by the formula

$$e^{-k_\alpha \frac{a}{2}}=0.1$$

where $e=2.718$; and k_α is given by the equation,

$$k_\alpha=\sqrt{\frac{\gamma\omega}{\alpha}}$$

where γ is the ratio of specific heats; $\omega=2\pi f$, where f is the frequency of the sound wave in cycles per second; and α is the ratio of the thermal conductivity of the gas to its density.

3. An improved acoustic material comprising an intersticed body having a multiplicity of openings formed therein of substantially uniform character in which sound energy is absorbed thermodynamically where the term thermodynamically is restricted to refer to the physical phenomenon whereby mechanical energy imparted to a gas is converted into heat energy, the heat energy being in turn absorbed in the walls of an intersticed body in which the gas may be contained; the conversion taking place during a cycle of compression and expansion of the gas; the cycle taking place at such a rate that a curve for the cycle of the gaseous pressure plotted against the volume of the gas encloses substantial area; and the cycle taking place at a rate such that the acoustic power absorbed, i. e., the product of the rate times the area, is substantially at or near a maximum for that intersticed body, and said intersticed body comprising a plurality of spheres of material lying in spaced-apart relation, this spacing being approximately equal to the value of "a" given by the formula

$$\frac{2e^{-k_\alpha\left(\frac{a}{2}-b\right)}}{a}=\frac{0.1}{b}$$

where "b" is the radius of a sphere,; $e=2.718$; and k_α is given by the equation

$$k_\alpha=\sqrt{\frac{\gamma\omega}{\alpha}}$$

where γ is the ratio of the specific heats for the gas; $\omega=2\pi f$ where f is the frequency of the sound wave in cycles per second; and α is the ratio of the thermal conductivity of the gas to its density.

4. An improved acoustic material comprising an intersticed body having a multiplicity of openings formed therein of substantially uniform character in which sound energy is absorbed thermodynamically where the term thermodynamically is restricted to refer to the physical phenomenon whereby mechanical energy imparted to a gas is converted into heat energy, the heat energy being in turn absorbed in the walls of an intersticed body in which the gas may be contained; the conversion taking place during a cycle of compression and expansion of the gas; the cycle taking place at such a rate that a curve for the cycle of the gaseous pressure plotted against the volume of the gas encloses substantial area; and the cycle taking place at a rate such that the acoustic power absorbed, i. e., the product of the rate times the area, is substantially at or near a maximum for that intersticed body, and said intersticed body comprising a plurality of cylindrical holes in a material, lying adjacent

to each other, the radius of the holes being approximately equal to the value for "a" given by the following equation

$$e^{-k_\alpha a}=0.1$$

where k_α is given by the equation

$$k_\alpha=\sqrt{\frac{\gamma\omega}{\alpha}}$$

where γ is the ratio of specific heats; $\omega=2\pi f$, where f is the frequency of the sound wave in cycles per second; and α is the ratio of the thermal conductivity of the gas to its density.

5. An acoustic material for thermodynamically absorbing sounds by converting sound energy into heat which is in turn absorbed by said device, the material comprising an intersticed body having a multiplicity of openings of substantially uniform shape and size formed therein, said openings being bounded by opposite surface areas of said body, the spacing between said surface areas being such that the amplitude of the thermal wave created by the movement of sound waves along or over said surface areas travelling outward from each surface toward the other will have decreased at a point midway between said surface areas to approximately $\frac{1}{10}$ of the amplitude it has at the surface areas themselves at the frequency for which the maximum absorbing effect is desired, and where the term thermodynamically is restricted to refer to the physical phenomenon whereby mechanical energy imparted to a gas is converted into heat energy, the heat energy being in turn absorbed in the walls of an intersticed body in which the gas may be contained; the conversion taking place during a cycle of compression and expansion of the gas; the cycle taking place at such a rate that a curve for the cycle of the gaseous pressure plotted against the volume of the gas encloses substantial area; and the cycle taking place at a rate such that the acoustic power absorbed, i. e., the product of the rate, times the area is substantially near a maximum for that intersticed body.

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