Aug. 20, 1968 J. G. DAUNT 3,397,738

REGENERATOR MATRIX SYSTEMS FOR LOW TEMPERATURE ENGINES

Filed Aug. 19, 1965 3 Sheets-Sheet 1

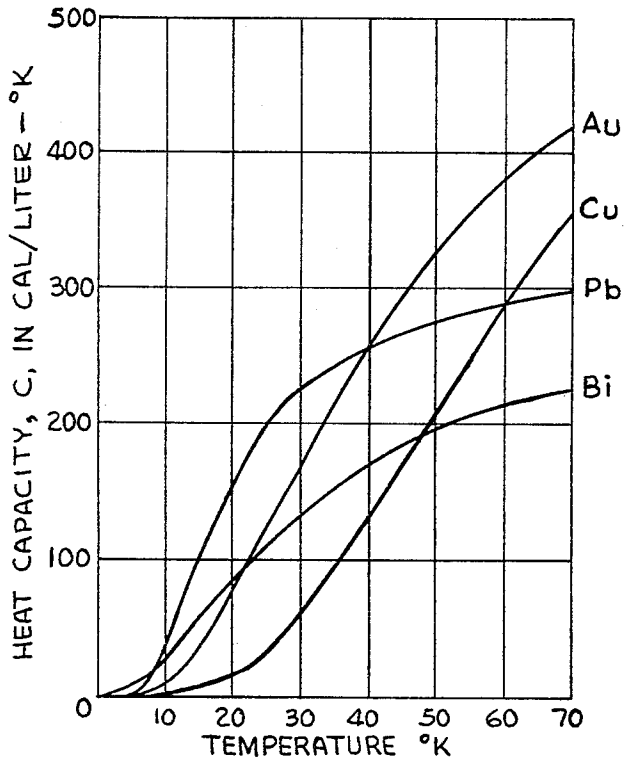
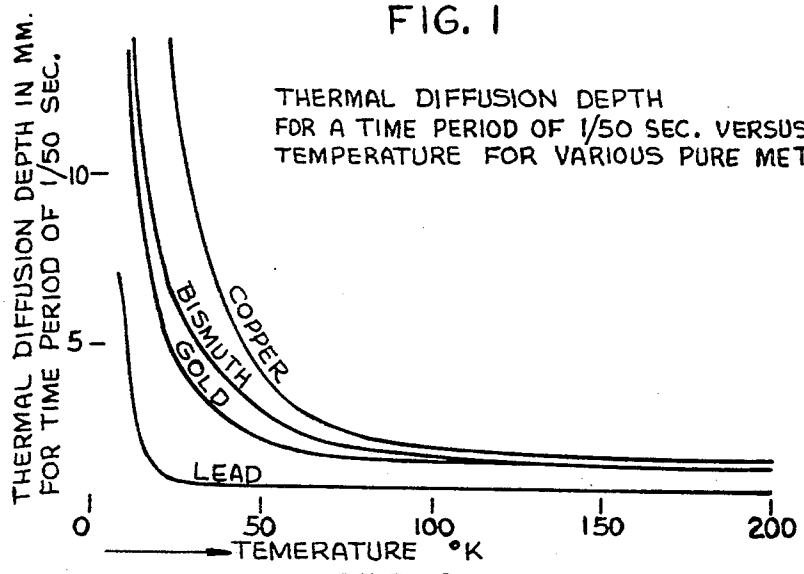


FIG. 1



THERMAL DIFFUSION DEPTH FOR A TIME PERIOD OF 1/50 SEC. VERSUS TEMPERATURE FOR VARIOUS PURE METALS.

FIG. 2

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REGENERATOR MATRIX SYSTEMS FOR LOW TEMPERATURE ENGINES

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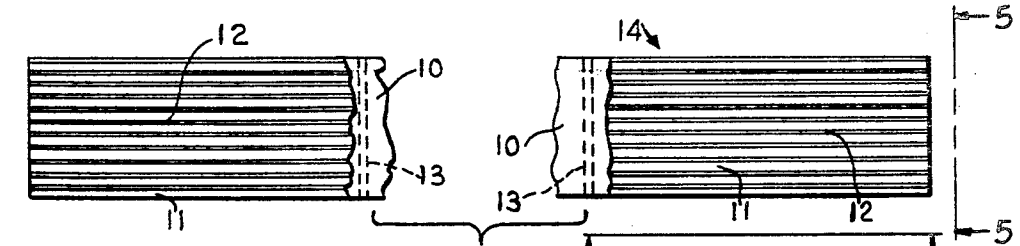


FIG. 3

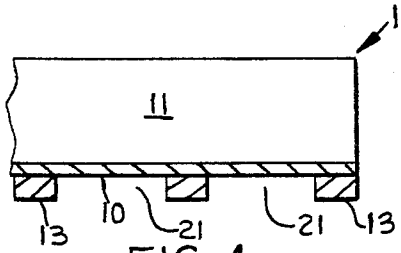


FIG. 4

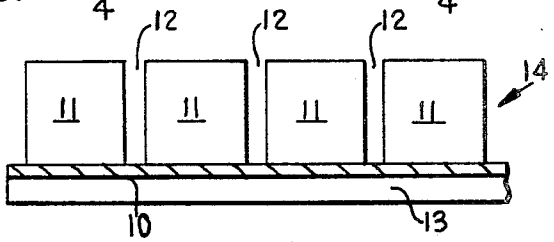


FIG. 5

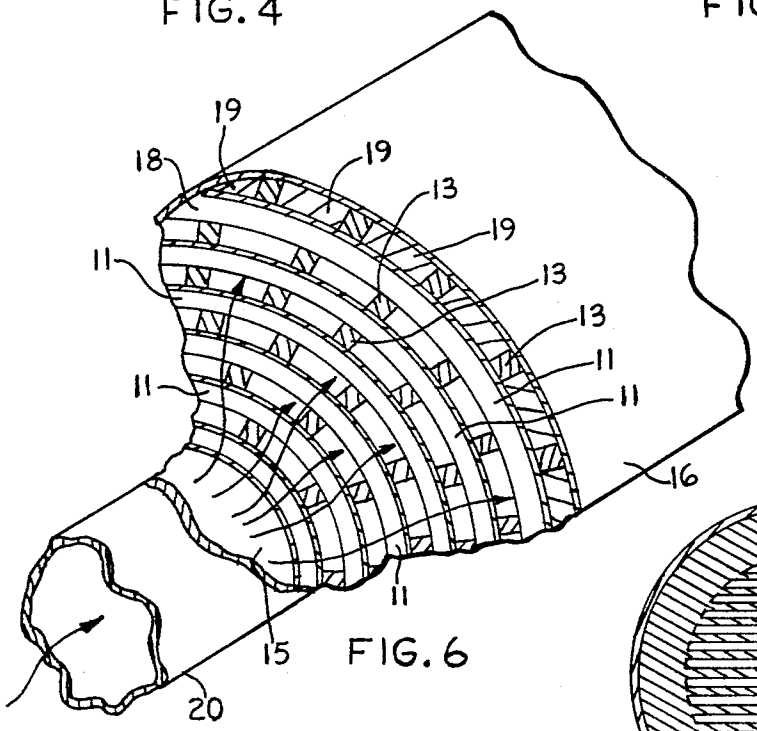


FIG. 6

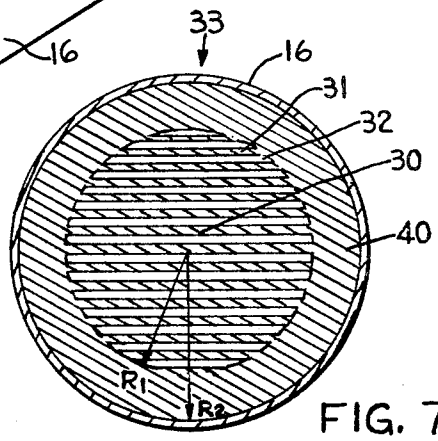


FIG. 7

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REGENERATOR MATRIX SYSTEMS FOR LOW TEMPERATURE ENGINES

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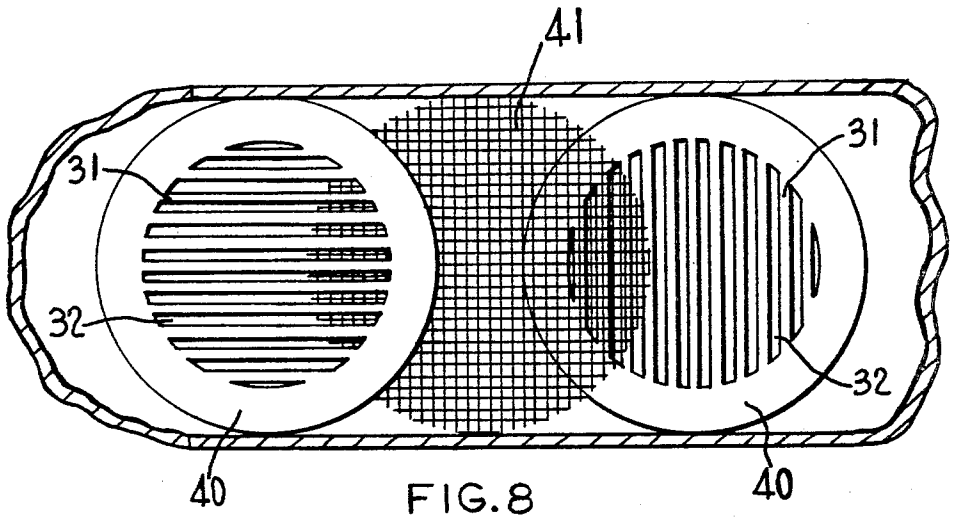


FIG. 8

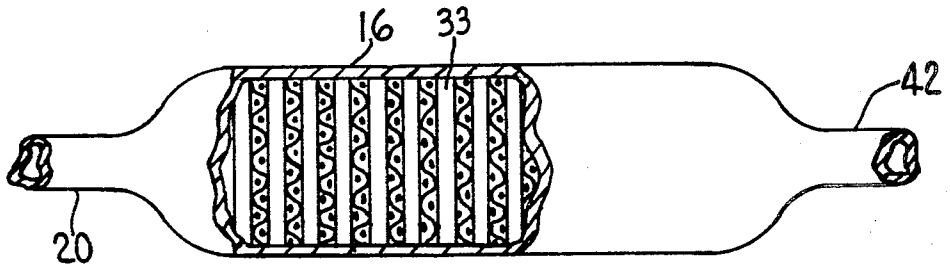


FIG. 9

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REGENERATOR MATRIX SYSTEMS FOR LOW TEMPERATURE ENGINES

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2 Claims. (Cl. 165—10)

ABSTRACT OF THE DISCLOSURE

This invention relates to the regenerators and matrices used therein, employed in cryogenic engines, such as those of the modified Stirling cycle type, and through which the working fluid (such as helium) is recycled. These matrix materials are solid masses having open channeling means which, in turn, have an average maximum geometric configuration such that the heat absorbed by the matrix from the fluid passing once therethrough is able to diffuse thermally along average paths (in the matrix) having average lengths approximating the thermal diffusion depth in the matrix material for the operating temperature range and for the fluid single passage period through the regenerator.

Such a matrix system can consist of strips coiled around an axially directed plug centrally disposed in the regenerator, the coil layers being separated by ribs of thermal insulating material. A series of spaced strips of matrix material, such as lead, are adhered circumferentially onto the bottom surface of the sheet. Another matrix system consists of adjacently-disposed one-piece slices of solid matrix material having a solid peripheral body and an inner integrally-connected screening of the same material, the screening having channeling means through which the operating fluid is cycled.

This invention relates to regenerators employed in engines used to develop low temperatures. More specifically, it deals with a regenerator matrix system made of coiled strips of insulating material on top of which are adhered a circumferentially-directed series of spaced strips of metal, and having an axially-directed series of spaced insulating strips adhered to the bottom thereof.

Increasing use is being made of closed-cycle refrigerator engines using gas, such as helium, as the working fluid, their operation being based on a number of thermodynamic cycles, and variants thereof, and on a number of different mechanical arrangements. Examples of such engines are described in the Malaker and Daunt Patents 3,074,244, 3,147,600 and 3,718,288. These particular engines operate on a modified Stirling cycle, and their successful operation depends, to a great extent, on the utilization of highly efficient regenerators which have efficiencies in the range of 90% to 99%.

In a regenerator of the type under consideration, the matrix material thereof absorbs heat from the working fluid as it leaves the compression cylinder when the direction is from hot to cold. When the flow of working gas is reversed, the matrix releases its stored heat to the working gas flowing past it. For high efficiency, the ratio, U, of the heat capacity of the working gas passing in one period to the heat capacity of the matrix mass in the regenerator must be kept as small as possible. This ratio, U, is called the utilization factor, and it is a measure of the degree to which the matrix mass is utilized for heat storage.

The behavior of regenerators has been studied analytically, and workers have shown that their efficiency or "thermal recovery," η, is defined by the expression:

$$1-\eta=\frac{\Delta T}{T_H-T_C}$$

where T_H is the inlet temperature of the hot gas, T_C is the inlet temperature of the cold gas, and ΔT is the difference in temperature between the inlet hot gas and the mean exit temperature of the cold gas. The equation can be expressed as a function of the "reduced length," Λ, of the regenerator and its utilization factor, U, as follows:

$$1-\eta=\frac{2}{\Lambda+2-f(U)}$$

where $f(U)$ is a monatonic function of U such that $f(U)$ increases positively as U increases. For a constant Λ, therefore, the efficiency η decreases as U increases.

In refrigerating machines using regenerators, the ratio of heat losses, ΔQ, associated with the regenerator inefficiencies to the heat extracted, Q_e, per cycle at the low temperature, is proportional to $(1-\eta)$. The minimum temperature to which such machines can reach, therefore, is determined by the fall-off of the efficiency of the regenerators at low temperatures, which fall-off is due to the increase in the value of U as the temperature is diminished.

The increase in the value of the utilization factor, U, with diminishing temperature is due to the fact that, for all known solid matrix materials, their heat capacity per unit volume decreases with decreasing temperature. For most solid materials not undergoing phase or other transformations, their heat capacity per unit volume, C, can be closely approximated by the expression:

$$C=(d/A)\{D(T/\theta)+\gamma T\}$$

where d is the density of the material, A is the atomic weight, $D(T/\theta)$ is the molar Debye function, θ is the Debye characteristic temperature, and γ is the molar Sommerfeld electronic specific heat term. In general, for T less than about $\theta/20$, $D(T/\theta)$ can be approximated by $1950(T/\theta)^3$ joules/mole-deg.

For successful operation of regenerators at very low temperatures, matrix materials must be used which have high heat capacities of the matrix per unit volume. To achieve this with solid materials which do not undergo phase or other transitions, materials must be chosen which have maximum values of (d/A) and minimum Debye characteristic temperatures, θ. A survey of materials suitable for regenerator matrices shows that, for example, below about 50° K., gold, bismuth and lead show values of C larger than that of copper and bronze. FIGURE 1 depicts a plot of observed values of C versus T for gold, copper, lead and bismuth. It will be noted that, below 40° K., lead has the largest C values. For this reason, the use of lead as a matrix material for low temperature regenerators has been common for some time (e.g., as in Patent No. 2,966,035), and its use has generally been in the shape of small balls of about 0.01 to 0.03 inch in diameter. However, there are other solid materials than lead which may be used as matrices in regenerators, and this invention encompasses the use of all solid matrix materials which may be formed and shaped.

By means of the present invention the effective heat capacity of the matrix material in the regenerator can be increased sufficiently to permit high regenerator efficiencies to be obtained at low temperature. It is to be noted that, although the specific heat, C, per unit volume of materials such as are used for matrix materials in regenerators, decreases with decreasing temperature, the ther-

mal conductivity, K, increases with decreasing temperature. This results in an increasing thermal diffusion coefficient, $D=K/C$, as the temperature is reduced. In consequence, the thermal diffusion depth, X, defined as the distance through which a temperature wave diffuses to i/e of its value in a time, τ, and expressed as $X^2=\tau D$, also increases with decreasing temperature. FIGURE 2 presents an evaluation of the thermal diffusion depth, X, in mm. for pure copper, bismuth, lead and gold, as calculated from known values of the specific heat, C, per unit volume (see FIGURE 1), and from observed values of the thermal conductivity, K, as a function of temperature. The data of FIGURE 2 are calculated for a time period of 1/50 sec., which is the gas flow period used in a practical miniature regenerator, of the type described in Patent 3,074,244. It is noted that, below 30° K., the diffusion depth for these periods become very large in these materials, being of the order of several millimeters. These diffusion depths are many times greater than the diameters of the wires used in gauze-packed regenerators (about a few thousandths of an inch) or than the diameters of the spheres heretofore used to fill regenerators (about 0.005" to 0.030").

According to the present invention, the matrix of the regenerator is given a configuration which would take advantage of such greater diffusion depths and thus allow larger effective matrix heat capacities to be realized. In the design of these configurations, it will be observed that two basic requirements of the regenerator are satisfied: (1) The heat transfer surface area and the heat transfer coefficient are adequate to permit the flow of heat between the gas flow and the matrix material to occur in each period without excessive temperature difference, and the void volume is as small as possible consistent with the maintenance of adequate heat transfer coefficient and sufficiently small pressure drop; and (2) the heat capacity of the matrix material is substantially greater than that of the gas flowing in one period, i.e., the utilization factor is adequately small. It is noteworthy that these two requirements are independently satisfied by the present invention.

The present invention, broadly, comprises the use of a series of strips of matrix material having a thickness sufficiently great to provide adequate total matrix mass in the regenerator, said strips being thermally insulated from each other. In the preferred embodiment the strips are straight lengths extending over the length of the insulated sheet to which they are attached in a row. Below the sheet are attached a series of spaced insulating ribs disposed at right angles to the matrix strips. The sheet, then, is coiled around a blank cylindrical core axially and centrally disposed within the regenerator, with the top of the lead strips being disposed adjacent the wall of the core.

The invention will be more readily understood by reference to the accompanying drawings in which a preferred embodiment is described, and in which FIGURE 1, as already mentioned, is a graph on the heat capacity of various metals at very low temperatures, while FIGURE 2, as already outlined, is a graph showing the thermal diffusion depth for a time period of 1/50 second at various temperasures for the four metals shown in FIGURE 1. FIGURE 3 depicts a top or plan view of a portion of a matrix sheet on an enlarged scale, with the center portion cut away, to be formed into a coil for regenerator use. FIGURE 4 depicts a side view of the strip of FIGURE 3, while FIGURE 5 illustrates an end view thereof. FIGURE 6 shows a perspective quarter side view section of the inlet portion, with inlet tube partly cut away, of a regenerator containing thes coiled sheet of FIGURES 3–5 for use in a refrigeration engine. FIGURE 7 depicts a cross-sectional view of another embodiment of the matrix element. FIGURE 8 shows an alternate arrangement of matrix slice elements, of the type depicted in FIGURE 7, spread out at right angles to the direction of mounting, and as separated by screen elements, while FIGURE 9 depicts a side view of a regenerator of the present invention, on a reduced scale, and partly cut away to show such alternate slice and screen arrangement for the matrix system. The same numerals refer to similar parts in the various figures.

Referring again to the drawings, numeral **10** indicates a sheet of thermal insulating material, such as nylon, stainless steel, polyester, phenolic resin, or the like, onto which are cemented square strips of lead **11** laid in parallel relation, and spaced away from each other by spaces **12**, the space being adequate to provide thermal insulation between each strip. Cemented to the bottom of insulation sheet **10**, in spaced relation, and disposed in a direction at right angles to that of strips **11**, are ribs **13** made of thermal insulating material, such as nylon, polyester, stainless steel, phenolic resin, or the like. These ribs may be smaller than strips **11**, and may be spaced farther apart.

The matrix sheet, indicated generally as 14, and having the lead strip and insulating ribs cemented thereon, is coiled around a centrally-disposed blanked off cylinder or plug **15** (FIGURE 6), in a manner so that the ribs **13** are disposed axially and the lead strips **11** are disposed circumferentially with respect to plug cylinder **15**, with the free upper surface of the lead strips wrapped adjacent to and around plug **15**. The ends of the lead strips, such as at upper end **18** of the sheet, are chamfered to the contour of the inner regenerator surface, and the free spaces there may be filled with epoxy composition **19** so as to insure against gas by-passing. The working gas, such as helium, of the engine, would leave the engine compressor cylinder through tube **20**, enter the regenerator in the direction of the arrow, and leave through outlet **42** (FIG. 9). Since it cannot pass through plug **15**, it passes through spaces **21** between insulator ribs **13**, in the directions of the arrows, and gives off its heat to lead strips **11**, after which it leaves regenerator **16** (and is then recycled).

The lead strips **11** serve, in the present embodiment of FIGURES 3–6, as the matrix material. Here the lead strips, as an example, may be 0.04" wide and 0.04" thick, with spacings **12** therebetween of 0.005". The polyester insulating ribs **13** on the back of the 0.002" thick insulating sheet **10** of "Mylar" polyester are 0.01" wide, 0.005" thick, and spaced apart 0.07". This composite sheet carrying the lead matrix is coiled as a tight spiral around plug **15**, the surface of the plug being in contact with the lead surface portion of the coil, the lead strips **11** being disposed in a direction at right angles to the axis of the regenerator **16**. The insulating ribs **13** form spaces **21** between the coil layers, which spaces permit the gas to flow therethrough and contact the upper surfaces of lead strips **11** in a direction at right angles thereto. In this embodiment, these gas channels are 0.07" wide (forming the arc of a circle), and 0.005" thick (radially).

In designing the dimensions to be used in these embodiments, the following considerations must be taken into account. The width of the lead strips determines the number of lead strips or lead "spirals" along the length of the regenerator. Since each strip at any particular time will be at uniform temperature throughout its length, it is desirable to have a large number of strips in a given regenerator in order to minimizez the temperature jump between one strip and the next. For example, in a typical regenerator referred to below, using lead strips 0.04" wide and employing a total regenerator length of 2", there would be 44 lead strips in the matrix. The regenerator would be designed, in this case, to operate between 15° K. and 25° K., and hence, the average temperature jump between one lead strip and the next would be (25–15)/44=0.23° K., which would lead to a maximum efficiency of 97.7%.

The thickness of the strips would be determined by the required total mass of matrix material in the regenerator. In the present design, the thickness clearly can be varied between wide limits without, for example, altering the

size of the gas passages, i.e., without changing the heat transfer surface area, the heat transfer coefficient, the pressure drops, or, and most importantly, the void volume in the regenerator, which is an advantageous basic feature of the present invention. There is, of course, one limit to the thickness of the lead strips, namely, that they must be equal to or less (in thickness), than the "diffusion depth" in the material at the temperature of operation. As is apparent from FIGURE 2, typical diffusion depths below, say 30° K., are very large for pure materials, and this limitation therefore is not a serious one for regenerators operating at very low temperatures.

The thickness, width, and spacing of the insulating ribs are determined by the design requirements of the gas channels for adequate heat transfer area, heat transfer coefficient, pressure drop, and void volume.

A typical generator for operation in the temperature range of 15° K. to 25° K., in line with the present embodiment, consists of five layers of composite matrix sheet **14** (in a coil), as dimensioned and defined above, for a length of 2", wound over a plug tube **15** of ⅜" outside diameter, and within a regenerator casing **16** of 0.855" inside diameter. This results in an "open" cross-sectional area for gas flow of 3.5×10^{-2} square inches, and a matrix mass of 108 g. of lead. For comparison, a regenerator of 2" length made of a stack of 200 mesh lead screening, with the same open cross-sectional area for gas flow would have a matrix mass of only 12 g.

It will be noted that one feature of the present invention is that it makes use of the low temperature phenomenon of the large thermal diffusion depth for the diffusion of heat into the matrix. Various geometric designs are possible for gas channel configuration, satisfying the requirements of surface area, heat transfer, void volume, and pressure drop. FIGURE 7 depicts one cross-sectional configuration wherein each thin slice of the cylindrical matrix mounted within regenerator **16** has the shape shown. The thermal ballast material between radii R_1 and R_2 is solid matrix material, such as lead, while the material within radius R_1 consists of a slotted screen having alternately solid strips **31** of the same material and open slots **32** through which working fluid is cycled. These slices of matrix designated as **33**, are desirably arranged so that each alternate slice has its strips **31** disposed at right angles to those of the strips of adjacent slices. Also, it is desirable to separate each slice by a strip of conventional screen **41** of, say, 200 mesh, as in FIGS. 8 and 9. The dimension of the slot channels are chosen to give the required heat transfer coefficient, heat transfer surface area, void volume, and pressure drop in the regenerator. The dimensions R_1 and R_2 are chosen so that the heat absorbed from the gas passing through the center of the regenerator, as for example, a channel near point **30** of FIGURE 7, can diffuse thermally to the perimeter near point **40** during the period of a single gas passage through the regenerator. The requirement for this is that the distance **30–40** be less than the thermal diffusion depth X in the material at the temperature of operation, and that the temperature drop along the matrix material in the region of radius R_1 be small. For the large values of X shown in FIGURE 2 below 20° K., quite large values of R_1 and R_2 may be employed. In the geometric configuration of the matrix of FIGURE 7, the heat capacity per matrix slice has effectively an extra component due to the mass of thermal ballast material between radii R_1 and R_2, which material does not form a part of the gas channels within the generator matrix.

It is to be understood that the examples given are employed for the purpose of illustrating the invention which is not to be limited thereby. For example, although an insulating sheet **10** is depicted in FIGURES 3–6, it is to be understood that, in lieu of such sheet, one may use thin strips of such material disposed over and attached to each insulating rib **13**, with its other side attached to lead strips **11**. Also, although lead is mentioned as the example of matrix material, other solid materials may be employed, particularly those selected for maximum heat capacity at the working temperature range of the regenerator.

I claim:

1. A regenerator matrix system for low temperature engines of the type described and operating in a low temperature range and using a working fluid, comprising:

a cylindrical casing having an inlet at one end and an outlet at the other end,

a cylindrical plug centrally and axially disposed in said casing,

a thermal insulating sheet coiled around said plug, and filling the free space in said casing,

a series of spaced strips of matrix material adhered circumferentially onto the bottom surface of said sheet and having a thickness no greater than the thermal diffusion depth of said material for the operating temperature range for the fluid single passage period through the regenerator, said thermal diffusion depth, X, being defined as the distance through which a temperature wave diffuses to $1/e$ of its value in time, τ, and expressed as $X^2=\tau D$, where D is the thermal coefficient, and

a series of spaced ribs of thermal insulating material adhered axially onto the top surface of said sheet.

2. A regenerator matrix system for low temperature engines of the type described and operating in a low temperature range and using a working fluid, comprising:

a cylindrical casing having an inlet at one end and an outlet at the other end,

a cylindrical plug centrally and axially disposed in said casing,

a thermal insulating sheet coiled around said plug, and filling the free space in said casing,

a series of spaced strips of matrix material adhered circumferentially onto the bottom surface of said sheet, and

a series of spaced ribs of thermal insulating material adhered axially onto the top surface of said sheet.

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