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MATRIX SYSTEM FOR LOW TEMPERATURE ENGINE REGENERATORS

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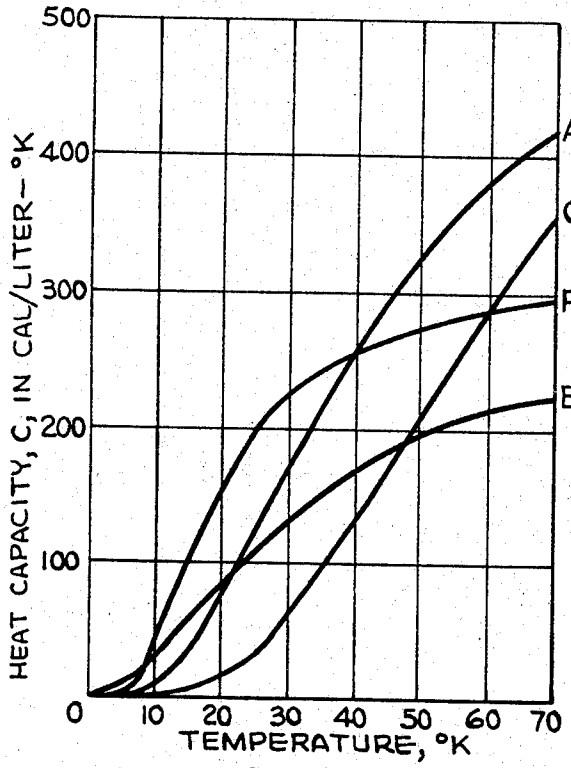


FIG. 1

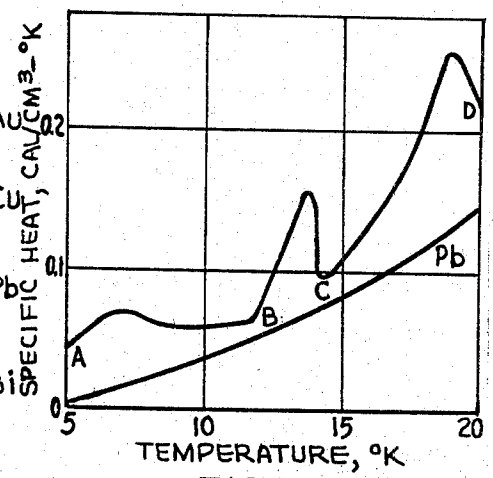


FIG. 2

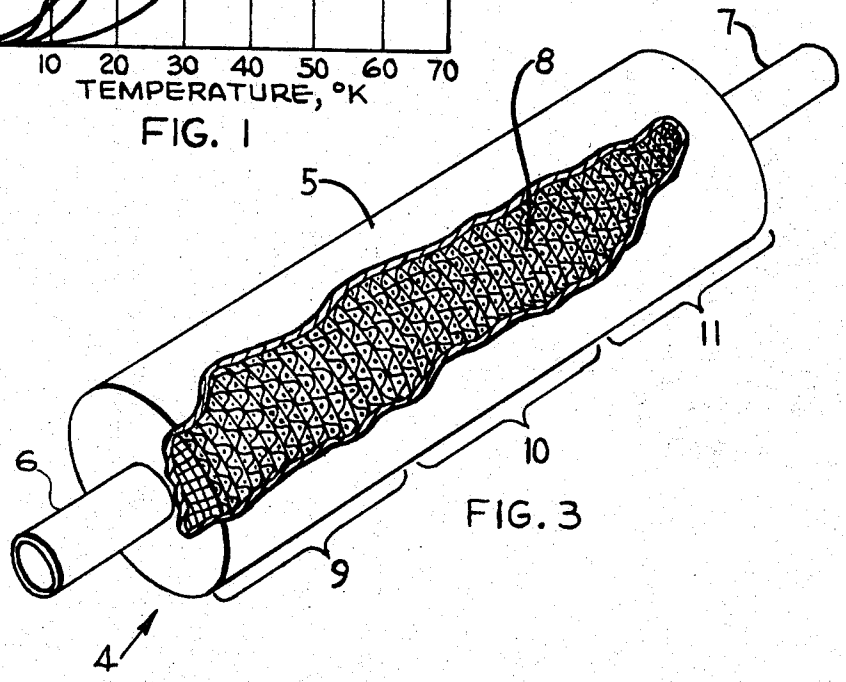


FIG. 3

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MATRIX SYSTEM FOR LOW TEMPERATURE ENGINE REGENERATORS

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This invention deals with matrix materials to be used as packing in regenerators of engines employed to develop low temperatures. More specifically, it relates to solid regenerator matrix materials which undergo reversible magnetic transformations at low temperatures, and which also exhibit exceptionally high increases in heat capacity in the neighborhood of their transformation temperatures. The materials, which are the subject of the present invention, must undergo transformations which are thermally reversible, as, for example, magnetic transformations to ferromagnetism or anti-ferromagnetism. Furthermore, such transformations must occur rapidly.

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 diffrent mechanical arrangements. Examples of such 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 very 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 0.10 inch in diameter. However, there are other solid materials than lead which may be used as matrices in very low temperature regenerators, and this invention encompasses the use of all solid matrix materials which may be formed and shaped.

The present invention will be more readily understood by reference to the accompanying drawing in which a preferred embodiment is described, and in which FIGURE 1 presents a temperature-heat capacity chart of a number of metals ordinarily used as matrix materials in regenerators. FIGURE 2 depicts a similar chart in which the upper curve represents matrix materials of the present invention, as compared with a conventional matrix material (lead) in the lower curve. FIGURE 3 illustrates a perspective side view (with end and side partially cut away) of a regenerator packed with screen disks of the matrix materials of the present invention.

According to the present invention, highly desirable matrix materials are obtained from solids which have reversible magnetic transformations occurring in the temperature range of about 4° K. to about 30° K. As can be seen from the accompanying FIGURE 1, at above 30° K., the more common materials, such as lead, gold, copper and bismuth, which do not undergo such transformations, are adequate for the purpose. Among the materials having characteristics found suitable for the present invention, are the rare earth metals, such as those listed in Table I:

Table I

Material:	Transformation temperature ° K.
Neodymium	5 to 11.8 and 25
Cerium	10
Erbium	19
Holmium	22
Samarium	11.8 to 14.3

FIGURE 2 presents the temperature-specific heat data of most of the aforesaid metals, in comparison with those of lead, which is the conventional materix material low employed in low temperature engine regenerators. The upper curve ABCD is a composite of data for

neodymium-samarium-erbium, while the lower curve shows the data for lead. The upper curve ABCD shows the specific heat per unit volume for the three materials, since volume is the critical factor in such regenerators. The section A–B, from 5° K. to 11.8° K., is for pure neodymium, the section B–C, from 11.8° K. to 14.3° K., is for pure samarium, while the section C–D, from 14.3° K. to 20° K. is for pure erbium. It will be noted that the magnetically transforming materials of the curve ABCD yield, over the whole temperature range from 5° K. to 20° K., a markedly higher specific heat per unit volume than the conventional material, lead, which has about the highest heat capacity for materials not capable of undergoing such transformations. Of particular interest is the region from 5° K. to 10° K., wherein, as can be seen from FIGURE 2, the ratio of the specific heat per unit volume for Nd to that for Pb is about 9:1 at 5° K. and about 1.7:1 at 10° K.

A preferred embodiment of the present invention is illustrated in FIGURE 3. The regenerator, indicated generally as **4**, comprises a thin-shelled metal cylinder **5** having an entrance tube **6** for entry thereto of the working fluid (such as helium), and an exit tube **7**. The inner space of cylinder **5** is packed tightly with close-fitting circular wire gauze disks **8** having a diameter of the inner diameter of the cylinder. The disks **8** may be made of the pure matrix material, such as pure rare earth metal. For example, if the working temperature range is 5° K. to 20° K., the disks **8** preferably would consist of, first layers **9** of neodymium wire, followed successively by layers **10** of samarium wire and layers **11** of erbium wire. However, the gauze screen can be interwoven with wires of different metals. The metals found most desirable are those of the lanthanide series, although other metals and other solid materials undergoing said transformations may be employed. The screens are desirably of small opening size, such as 200 mesh or higher.

It is also possible to employ the present matrix in the form of spaced strips wound in a coil and separated by insulating ribs in the manner described in copending application Ser. No. 481,051, filed on Aug. 19, 1965, by John G. Daunt.

In operation, the working fluid passes through the channels of the matrix material, giving up a portion of its heat to the matrix during the passage therethrough.

The transformation undergone by the matrix material must be within a short time period rapid enough to enable the matrix material to pass substantially completely through said transformation during a single pass of the working fluid through the regenerator. Also, the transformation must be reversible without deterioration of the matrix material so as to enable to obtain a commercially adequate matrix life. Also, the increase in heat capacity of the material because of the transformation must be adequate enough to justify the expense involved in using the material. In the temperature range of about 5° K. to about 20° K., a minimum ratio of the heat capacity per unit volume of the material to that of lead of about 1.30:1 is necessary.

I claim:

1. A regenerator for low temperature engines of the class described, and operating below about 30° K., comprising,

a hollow container having an inlet and a discharge and a channeled matrix materal tightly packed in said container, said material comprising a lanthanide metal of the class consisting of neodymium, cerium, erbium, holmium and samarium which metal undergoes at least one rapid reversible magnetic transformation in the temperature range of about 5° K. to about 20° K., wherein its heat capacity per unit volume is at least 1.30 times greater than that of lead within said temperature range.

2. A regenerator according to claim **1** in which said matrix material comprises a series of metals, beginning with neodymium at the entrance end of said regenerator, samarium at the central portion thereof, and erbium at the outlet portion thereof.

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