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Bland, deceased

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[54] **STIRLING CYCLE ENGINE WITH CATALYTIC REGENERATOR**

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[51] **Int. Cl.** **F03g 7/03,** F25b 9/00, H02p 9/00

[58] **Field of Search** 60/517, 526, 649

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[57] **ABSTRACT**

A modified Stirling engine has a regenerator with catalytic surfaces for inducing reversible chemical reaction in the working fluid. The basic Stirling engine has an expansion space and compression space with one or more pistons for periodically transferring the working fluid therebetween. Heat is added to the working fluid in the expansion space to maintain temperature during expansion and heat is extracted from the compression space to counteract compression heating. A regenerator, which is a temporary heat reservoir, is provided in the fluid flow path between the expansion and compression spaces. In this improvement, the working fluid is subject to a reversible chemical reaction which is endothermic in one direction and exothermic in the other direction, and has less specific volume when driven in the exothermic direction. The volume difference arises since there are more moles of gas in the higher temperature regime than in the lower. Particularly suitable is the endothermic dehydrogenation and exothermic hydrogenation of hydrocarbons. In such a system the quantity of working fluid being compressed is minimized so that there is less cooling required. The volume of working fluid being expanded is maximized thereby enhancing power output. Thermodynamic efficiency is significantly enhanced by such a working fluid and catalytic regenerator.

12 Claims, 3 Drawing Figures

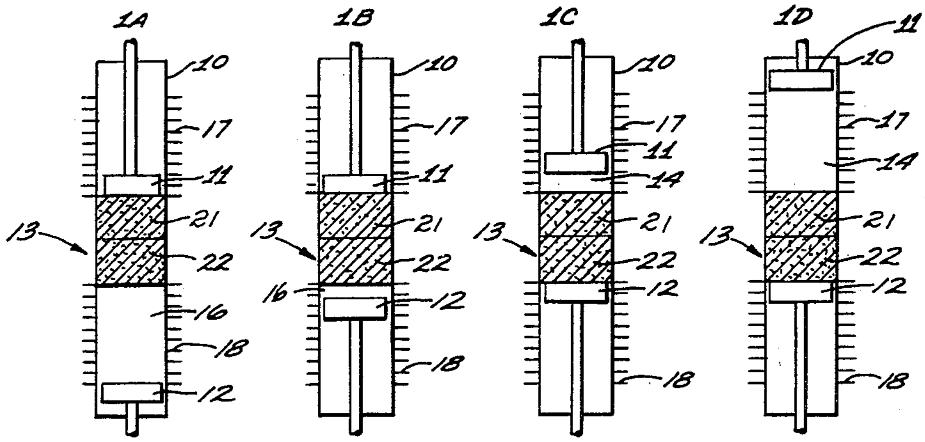


Fig. 1

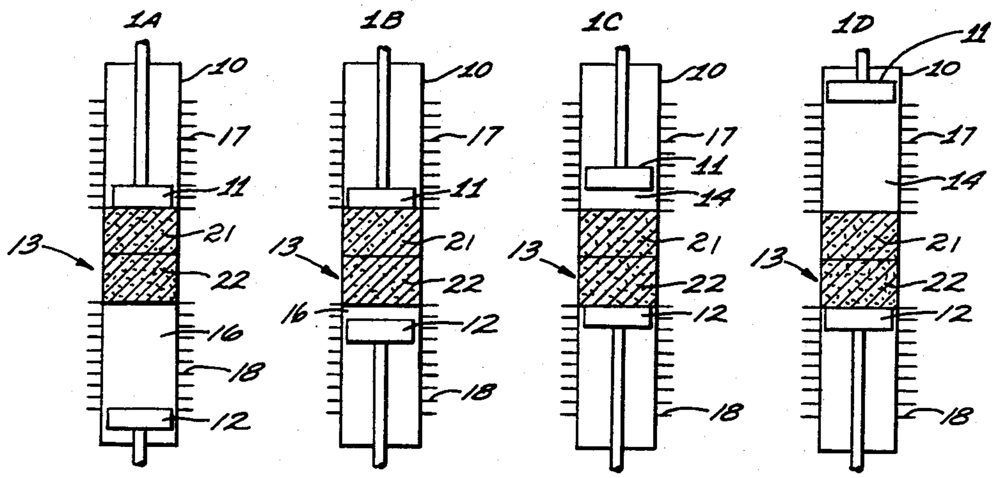


Fig. 3

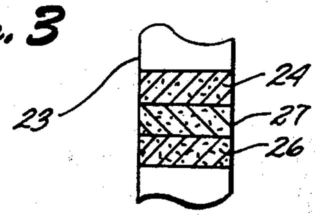
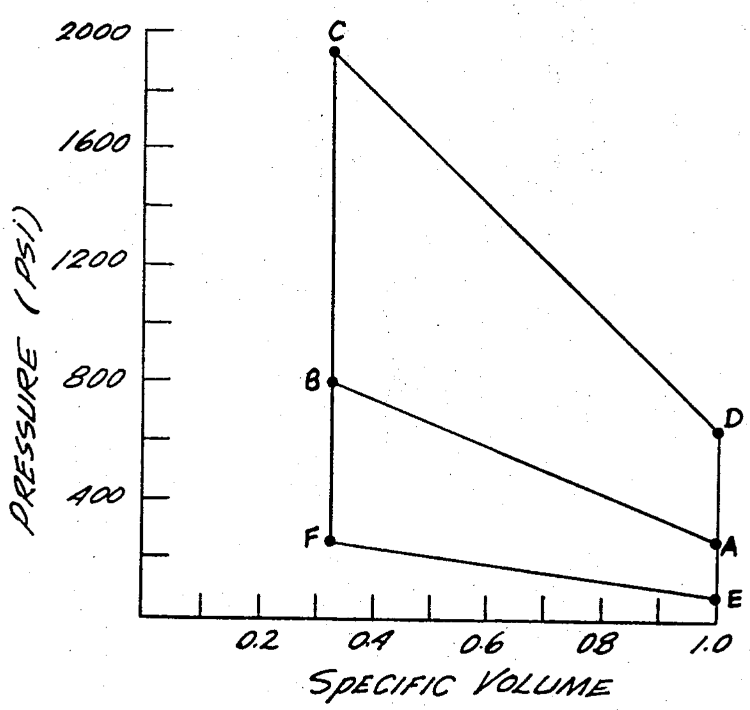


Fig. 2



STIRLING CYCLE ENGINE WITH CATALYTIC REGENERATOR

BACKGROUND

Many people regard the Stirling cycle engine as holding great promise for generation of mechanical energy from heat energy. Power available for a given quantity of fuel is quite favorable and since combustion is external and can be controlled with some precision there is very little atmospheric pollution. Further, since there is external combustion a great variety of fuels can be used for powering the engine. Stirling engines have been proposed or actually run using heat inputs from liquid fuel consumption, charcoal braziers, sunlight, and radioactive decay.

One problem with a Stirling engine is the rather substantial cooling load from the compression space of the engine when a high power rating, low volume engine is needed, such as, for example, for automotive applications. Special radiators need to be provided for rapidly and efficiently cooling the cold side of the engine. If the engine efficiency, namely the power output for a given heat input can be increased, the cooling load problems can be alleviated.

Any heat engine has a theoretical efficiency limit based on the Carnot cycle. The maximum work than can be obtained is defined by the area within the thermodynamic diagram in a pressure-volume plane. Any means for increasing the area of the pressure-volume cycle, such as, for example, by increasing the temperature difference between the hot and cold ends of the heat engine increases the available power. Clearly, to reduce cooling requirements and increase available mechanical power it is desirable to provide means for increasing the efficiency of a Stirling engine.

BRIEF SUMMARY OF THE INVENTION

There is, therefore, provided in practice of this invention according to a presently preferred embodiment, a Stirling engine having expansion and compression spaces and means for periodically transferring working fluid therebetween. A heat source adds heat to the working fluid adjacent the expansion space and a heat sink removes heat from the working fluid adjacent the compression space. The working fluid in the engine is subject to a reversible reaction so that the molal volume of fluid in the expansion space is greater than the molal volume of fluid in the compression space. The regenerator in the fluid flow path between the expansion and compression spaces has catalytic surfaces for inducing the reversible reaction in the working fluid.

DRAWINGS

These and other features and advantages of the present invention will be appreciated as the same becomes better understood by reference to the following detailed description of a presently preferred embodiment when considered in connection with the accompanying drawings wherein:

FIG. 1 illustrates schematically a Stirling engine constructed according to principles of this invention in each of four stages of its operation;

FIG. 2 is a pressure-volume diagram for the engine of FIG. 1; and

FIG. 3 is a fragmentary view of another catalytic regenerator of a Stirling engine.

DESCRIPTION

The Stirling cycle engine has been known for about 150 years and some commercial applications have been made of it. It is a heat engine heated in one region and cooled in another with one or more pistons for alternately and cyclically compressing and expanding a working fluid and gaining useful work. A variety of mechanical embodiments of the Stirling cycle engine have been developed and described in the literature with the operating mechanisms seeking higher efficiencies, lower costs and lower weights. In practice of this invention the specific mechanical configuration is of little criticality and the principles can be explained by means of idealized schematic illustrations.

Thus, in FIG. 1 which consists of four subparts, 1A, 1B, 1C, and 1D a Stirling cycle engine is illustrated schematically in each of four stages of engine operation. It will be recognized, of course, that many mechanical adaptations of this idealized cycle can be made, and that under practical operating conditions with parts operating harmonically, the idealized cycle is not actually achieved. Even so, the thermodynamic efficiency of the engine is enhanced in practice of this invention.

As illustrated in FIG. 1, the Stirling engine has a closed cylinder **10** which is sealed so that the working fluid of the engine is permanently contained therein. A power piston **11** is contained in one end of the cylinder **10** for stroking along its length. A displacer piston **12** is in the opposite end of the cylinder for stroking along its length. A regenerator **13**, described in greater detail hereinafter, is provided in the central portion of the cylinder between the two pistons **11** and **12.** The variable space **14** between the power piston **11** and regenerator **13** is typically termed the expansion space. The variable volume between the displacer piston **12** and the regenerator is typically called the compression space.

A heat source indicated schematically in FIG. **1** by fins **17** is provided for heat transfer to working fluid in the expansion space. Similarly, a heat sink indicated schematically by fins **18** permits the extraction of heat from working fluid in the compression space **16.** The two pistons **11** and **12** move in synchronism as controlled by external mechanisms (not shown) for cyclically operating the engine.

It will be recognized that having a pair of opposed pistons in a single cylinder is provided for purposes of exposition and that a number of mechanical arrangements differing from this but similar in principle can be provided. Thus, for example, single acting Stirling engines have been devised with two pistons in a single cylinder and concentric drives so that the space between the pistons defines the compression space and the regenerator is external to the cylinder. Wankel arrangements are feasible and multiple cylinders each with a single piston can be used with regenerators between adjacent cylinders. A variety of other mechanical arrangements will be apparent to one skilled in the art.

The regenerator **13** is a temporary heat reservoir in the fluid flow path between the expansion space and the compression space that, during operation of the engine, absorbs heat from the working fluid during part of the cycle and surrenders that heat to the working fluid in another part of the cycle. Typically such a regenerator is a matrix of fine metal wires or strips, or other permeable substance with high heat capacity and ability to transfer heat rapidly to working fluid passing through the regenerator.

A full cycle of operation of the Stirling engine consists of four overlapping parts. As an arbitrary initial point it is assumed that the displacer piston **12** is at its outermost travel in the cylinder so that the compression space **16** has its largest volume. The power piston **11** is at its innermost position so that the compression space **14** between it and the regenerator is at a minimum. Such a position is illustrated in FIG. 1A.

At this time the working fluid (except for a small amount in the permeable regenerator) is all in the colder compression space **16.** During this portion of the cycle the gaseous working fluid has its lowest temperature and hence lower pressure. From this point the displacer piston **12** moves toward the regenerator, compressing the working fluid in the compression space. Since the temperature of a gas rises as the gas is compressed, heat is extracted from the working fluid to the heat sink **18** to maintain the temperature of the working fluid substantially constant. The end of the compression cycle is indicated in FIG. 1B, as the displacer piston **12** approaches the regenerator **13.**

During the next stage of the Stirling cycle both the power piston and displacer piston move synchronously and the working fluid passes through the porous regenerator **13** and into the expansion space **14.** Such a constant volume or isochoric regenerative transfer of the working fluid is indicated in the transition from FIGS. 1B to 1C.

As the working fluid passes through the porous regenerator it absorbs heat therefrom. (The heat is stored in the regenerator from a previous cycle of operation of the engine.) The heat causes the temperature of the working fluid to rise and results in an increase in working fluid pressure.

Next, the working fluid in the expansion space expands, forcing the power piston **11** towards its outermost position as illustrated in FIG. 1D, and giving a power output. During this expansion the pressure of the working fluid decreases with a consequent potential reduction in temperature. In order to maintain the temperature of the working fluid in the expansion space at a constant level, heat is supplied by way of the heat source **17.**

At the end of the power stroke the two pistons again move simultaneously back to the original positions illustrated in FIG. 1A. This results in a constant volume transfer of the working fluid back through the regenerator to the compression space. As the working fluid, which has been heated in the expansion space, passes through the regenerator it gives up heat to this temporary reservoir, which heat is subsequently available for reheating the compressed gas in the next cycle of the engine. As the heat is given up, the temperature of the working fluid decreases from that of the expansion space to that of the compression space, resulting in a decrease of working fluid pressure to the original level.

Thus, it will be seen that the idealized Stirling cycle consists of isothermal compression, isochoric heating, isothermal expansion and isochoric cooling. Obviously, in any practical system these conditions are not met, but they can be approached without great difficulty.

FIG. 2 illustrates a typical thermodynamic cycle for a Stirling engine in the pressure-volume plane. Thus, in a typical Stirling engine cycle the working fluid at point

A corresponding to FIG. 1A has a pressure of 268 psi and for purposes of comparison a specific volume of 1.0. As the working fluid is isothermally compressed with a compression ratio of 3:1 the pressure rises to about 800 psi as represented by point B. It will be recognized that the working fluid does not move along the simplified straight line A–B but along a curved line between these points. Since idealized performance is not obtained in any practical heat engine the straight line makes a reasonable approximation of the thermodynamic cycle for purposes of illustration.

After compression there is isochoric transfer of the fluid from the compression space to the expansion space. The consequent heating of the working fluid in the regenerator raises the pressure to over 1,900 psi without change in specific volume as illustrated by point C. The gas is then expanded isothermally with addition of heat from the heat source. Pressure drops to about 640 psi and the specific volume returns to its original value. Thereafter, the gas is passed through the regenerator again to give up its heat and the thermodynamic cycle is closed by return to point A. The area within the curve ABCD represents the power available from the heat engine.

In practice of this invention the working fluid in the Stirling cycle engine is a mixture of components subject to reversible chemical reaction. A number of materials are suitable as working fluids, however, for purposes of illustration the reaction of cyclohexane, benzene, and hydrogen is considered as typical. Under suitable conditions cyclohexane is dehydrogenated endothermically to produce benzene and hydrogen; that is, during the dehydrogenation reaction heat must be supplied. Conversely, at lower temperatures benzene can be hydrogenated exothermically to produce cyclohexane. The cyclohexane to benzene and hydrogen reaction is reversible and in the presence of suitable catalysts proceeds at a relatively rapid rate.

Thus, for example, in the range of about 400° to 1,000°F in the presence of a conventional platinum dehydrogenation catalyst, cyclohexane is endothermically decomposed to form 1 mole of benzene and 3 moles of hydrogen for every mole of cyclohexane. At lower temperatures and in the presence of a conventional hydrogenation catalyst such as nickel the benzene reacts exothermically with hydrogen to reform cyclohexane. A mixture of cyclohexane, benzene, and hydrogen is suitable for a working fluid in a Stirling cycle engine.

The regenerator **13** in the improved Stirling engine using such a working fluid is formed in two catalytic sections **21** and **22.** In the higher temperature portion **21** of the regenerator, the gas contacting surfaces are coated with a dehydrogenation catalyst such as sputtered platinum. In the relatively cooler portion **22** of the regenerator the surfaces are provided with a hydrogenation catalyst such as sputtered nickel. Either a metal, ceramic, or carbon substrate may be employed and other catalytic surfaces may be suitable. In some cases with other working fluid combinations both catalytic portions may have the same catalyst surfaces, platinium, for example, being suitable for enhancing the rate of many reactions in either direction.

Once the Stirling cycle engine has been started and warmed up, the cyclohexane and benzene components of the working fluid are vaporized and vapor only is present in the cylinder **10.** Referring again to FIG. 1 at the initiation of the compression portion of the cycle as illustrated in FIG. 1A the compression space contains a working fluid that is primarily cyclohexane. The cyclohexane is compressed and during the second portion of the cycle heat is transferred to the vapor as it is passed through the regenerator.

As the cyclohexane vapor passes over the dehydrogenation catalyst in the warmer portion **21** of the regenerator, endothermic decomposition to benzene and hydrogen occurs. The heat stored in the regenerator partially serves to provide sensible heat for raising the temperature of the working fluid and partially serves to supply the heat for the endothermic reaction. The resultant working fluid in the expansion space is principally benzene and hydrogen at a higher temperature and pressure. This working fluid expands during the power stroke, taking heat from the heat source as in a standard Stirling cycle.

Thereafter the working fluid is transferred back through the regenerator to the compression space. As it passes back through the regenerator, the benzene and hydrogen pass over the hydrogenation catalyst in the cooler portion **22** of the regenerator. The exothermic half of the reversible reaction occurs, reconverting the principal portion of the working fluid to cyclohexane in the compression space.

The advantage of using the working fluid with constituents subject to a reversible reaction and a catalytic regenerator comes about from the different molal quantities of working fluid in the compression space and expansion space. Each mole of cyclohexane being compressed produces 4 moles of benzene and hydrogen for expansion in the power stroke. The work available from the increased volume of working fluid, and the reduced quantity of working fluid subject to compressional heating increase the thermal efficiency of the Stirling engine.

Referring again to FIG. **2** initial pressure in the Stirling engine with a working fluid consisting of cyclohexane vapor alone in the compression space may be as low as about 85 psi as represented by point E. Compression of this working fluid raises the pressure to about 250 psi as represented by point F. As the working fluid flows through the regenerator and is heated and dehydrogenated to benzene and hydrogen, the pressure rises again to point C. The power stroke again returns the working fluid to point D. The hot expanded working fluid is then passed back through the regenerator where its sensible heat is removed and heat of the exothermic hydrogenation of the benzene to cyclohexane is also removed. This restores the working fluid to point E in FIG. **2**.

It is immediately apparent that the area of the *PV* figure EFCD in FIG. **2** is appreciably larger than the area of the *PV* figure ABCD. This increased area represents an enhanced efficiency of a Stirling cycle engine using a working fluid subject to a reversible reaction and a catalytic regenerator. It appears that with a cyclohexane-benzene working fluid, a thermal efficiency increase of almost 50 percent is theoretically achievable. Practical considerations may make this figure either higher or lower for such an engine as compared with a conventional Stirling cycle engine. The reason that direct comparisons are difficult is that the operating temperatures and pressures may also be varied to accommodate the differences in properties of the working fluids and a somewhat larger regenerator is required to accommodate the additional heat temporarily stored in this reservoir. Aerodynamic losses during fluid transfer will also vary.

Another factor to consider in estimating efficiency is that the reversible reaction ordinarily will not proceed to completion even in the presence of the catalytic surfaces. Thus the working fluid in the compression space is primarily cyclohexane but certain quantities of benzene vapor and hydrogen are also present. Conversely, certain proportions of cyclohexane appear in the expansion space. A permanently gaseous component (such as an excess of hydrogen or an inert gas) is also desirable in the working fluid since cyclohexane and benzene condense into liquid at normal ambient temperatures. The presence of some gas in the Stirling engine cylinder is, therefore, important to provide an ability to start the engine at temperatures below the condensation point of the working fluid. This enables warm-up of the engine with limited power until temperatures are reached to assure presence of cyclohexane and benzene vapors.

The hydrogenation-dehydrogenation reaction between benzene and cyclohexane is representative of reactions suitable for use in a Stirling cycle engine.

The following are additional examples of reactions suitable for the practice of this invention. It will be understood that the reactions set forth below are not intended to limit those suitable for use but are merely illustrative.

C_n paraffins = Olefin + H_2
where n = 3 or more

$$iso(CH_3)_2CHOH = CH_3COCH_3+H_2$$

$$CH_3OH = CO+2H_2$$

$$CH_4+H_2O = CO+3H_2$$

$$2NH_3 = N_2+3H_2$$

$$C_6H_5C_2H_5 = C_6H_6+C_2H_4$$

$$C_2H_5OH = C_2H_4+H_2O$$

$$COCl_2 = CO+Cl_2$$

$$N_2O_4 = 2NO_2$$

Examples of paraffins suitable according to this invention are propane, butane, pentane and hexane and isomers of these compounds. In the following table there are provided data corresponding to the number of each reaction. These data show a temperature at which each reaction will proceed in one direction designated as T_n, and a temperature at which each reaction is reversed designated as T_r. Furthermore, where such is required, suitable catalysts for increasing the rate of the forward reaction, designated as C_n, and suitable catalysts for increasing the rate of the reverse reaction, designated as C_r are shown. The values of ΔH in the table are illustrative of the amount of heat absorbed in kilogram-calories per gram-mol of reactant at a temperature at which the reaction is endothermic.

No. of Reaction	T_n - °C.	T_r - °C.	ΔH	C_n	C_r
(2)	750(n=3)	460	29.7	Pt;$Cr_2O_3+Al_2O_3$	Pt;Ni
	750(n=4)	460	30.1	Pt;$Cr_2O_3+Al_2O_3$	Pt;Ni
	650(n=5)	410	30.1	Pt;$Cr_2O_3+Al_2O_3$	Pt;Ni
	630(n=6)	380	30.0	Pt;$Cr_2O_3+Al_2O_3$	Pt;Ni

–Continued

No. of Reaction	T_u - °C.	T_r - °C.	ΔH	C_u	C_r
(3)	300	25	12	Cu	Pt
(4)	350	250	24	$Cu+Cr_2O_3$	$Cu+Cr_2O_3$
(5)	800	300	52	Ni	Ni
(6)	700	400	24	Fe	Fe
(7)	550	150	25	$SiO_2+Al_2O_3$	$SiO_2+Al_2O_3$
(8)	450	100	11	Al_2+O_3	H_3PO_4
(9)	400	0–100	27	None	Charcoal
(10)	140	0	14	None	None

It is to be understood that the temperatures set forth in the table are not necessarily the optimum temperatures at which either the forward reaction or reverse reaction is carried out. The temperatures are temperatures at which these reactions respectively occur with significant conversion of reactant to reaction products according to the appropriate reaction. Furthermore, the pressures at which the reactions set forth above occur are not necessarily in the best temperature range for an automobile Stirling engine but may be suitable for other Stirling engine applications. In some reactions, as, for example, the dissociation of ammonia, reaction (6), or the dehydrogenation of methanol, reaction (4), high temperatures and high pressures are required in order that the reaction proceed at a suitable rate.

It will be recognized that since the number of moles of reaction product reaching the expansion space is greater than the number of moles leaving the compression space and since the pressure increases, there is a condition tending to suppress the chemical reaction, that is, the tendency is to urge the reaction towards the direction having a smaller number of moles of gas. The reaction is, however, biased in the direction of the larger number of moles by the increased temperature and it may be desirable to maintain a higher temperature in the expansion space than would be present in the conventional Stirling engine to assure more complete reaction. The equilibrium condition for the reactant and products under various temperature and pressure conditions can be readily determined by those skilled in the art. Equilibrium and rate considerations of a number of reactions having different molal quantities on opposite sides of the reaction are set forth in U.S. Pat. No. 3,225,538 by Reginald B. Bland and Frederick J. Ewing.

It might be noted that under some circumstances the same catalytic surfaces can cause a reaction to proceed in either direction depending on the pressure and the temperature conditions prevailing in the regenerator. In such a situation the regenerator may not have separate catalytic regions for enhancing the rate of reaction in each of the two directions. A single catalytic region may suffice with the direction and rate of reaction determined by the prevailing temperature and pressure conditions. Similarly, separate regions may be present, but with the same catalytic surfaces.

Some of the catalytic surfaces suitable for dehydrogenation reaction may also induce cracking of certain hydrocarbons at elevated temperatures. It may, therefore, be desirable to provide for cooling of the working fluid prior to contact with the catalytic portion of the regenerator. FIG. **3** illustrates in a fragmentary schematic view a suitable regenerator. As illustrated in this embodiment the Stirling engine cylinder **23** has a conventional noncatalytic regenerator portion **24** nearer the hot end of the engine. Nearer the cold end there is a permeable regenerator **26** wherein the surfaces have a hydrogenation catalyst. Intermediate between these portions is a third regenerator portion **27** the surfaces of which have a conventional dehydrogenation catalyst.

When a Stirling engine having such a regenerator is used, the hotter gases first lose sensible heat to the noncatalytic regenerator portion **24** and then pass through the portions of the regenerator having catalytic surfaces. Since the working fluid has given up some of its sensible heat it is cooler when it reaches the catalytic surfaces and cracking is avoided. The heat of reaction and a portion of the sensible heat is temporarily stored in the catalytic portions of the regenerator to be picked up by the cooler working fluid during mass transfer after the compression portion of the cycle.

Since the Stirling engine having a catalytic regenerator and a working fluid subject to reversible chemical reaction has a higher thermal efficiency than a corresponding engine without these features, the quantity of heat that must be rejected by the cooling system is decreased. In theory using a working fluid consisting of cyclohexane, benzene and hydrogen the heat to be dissipated by way of the cooling system is only about 38 percent of the heat load from a conventional 40 horsepower engine. In a practical 40 horsepower engine the cooling requirements appear to be only about 65 percent of those for a conventional Stirling engine. Such dramatic reductions in cooling requirements substantially alleviate the problems of high rate cooling for practical Stirling cycle engines.

Although the principles of the Stirling engine having catalytic regenerator and a working fluid subject to reversible chemical reaction have been described and illustrated in a schematic arrangement herein, many adaptations, modifications and variations will be apparent to one skilled in the art. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. In a Stirling engine having an expansion space; a compression space; a working fluid in said spaces; means for periodically transferring working fluid between the expansion space and the compression space; a heat source for adding heat to the working fluid adjacent the expansion space; a heat sink for removing heat from the working fluid adjacent the compression space; and a regenerator in the fluid flow path between the expansion space and the compression space, the improvement comprising:

a working fluid having components susceptible to reversible chemical reaction under the temperature and pressure conditions in the engine, said reaction having a greater number of moles of fluid when the reaction proceeds in its higher temperature direction than when it proceeds in its lower temperature direction; and

a catalyst in the regenerator for enhancing the rate of the chemical reaction.

2. In a Stirling cycle engine as defined in claim **1** the further improvement wherein the reaction is exothermic in one direction and endothermic in the other direction.

3. In a Stirling cycle engine as defined in claim **1** the further improvement wherein the components of the working fluid comprise hydrogen and hydrocarbons subject to reversible hydrogenation and dehydrogenation at temperatures and pressures prevailing in the Stirling cycle engine; and the catalyst in the regenerator enhances the dehydrogenation reaction nearer the expansion space and enhances the hydrogenation reaction nearer the compression space.

4. In a Stirling cycle engine as defined in claim **3** the further improvement wherein the working fluid is selected from the group consisting of hydrogen, cyclohexane, and benzene paraffins having three or more carbon atoms, and their corresponding olefins, said paraffins and olefins being in the vapor state at temperatures and pressures prevailing during operation of the Stirling cycle engine.

5. In a Stirling cycle engine as defined in claim **3** the further improvement wherein the working fluid comprises cyclohexane, benzene and hydrogen.

6. In a Stirling cycle engine as defined in claim **1** the further improvement comprising a second catalyst in the regenerator, the catalyst nearer the expansion space enhancing reaction in the greater molal direction and the catalyst nearer the compression space enhancing reaction in the lesser molal direction.

7. In a Stirling cycle engine as defined in claim **6** the further improvement comprising a noncatalytic regenerator portion between the expansion space and the catalyst.

8. In a Stirling cycle engine as defined in claim **1** the further improvement comprising a noncatalytic regenerator portion between the expansion space and the catalyst.

9. In a Stirling engine having an expansion space; a compression space; a working fluid in said spaces; means for periodically transferring working fluid between the expansion space and the compression space; a heat source for adding heat to the working fluid adjacent the expansion space; a heat sink for removing heat from the working fluid adjacent the compression space; and a regenerator in the fluid flow path between the expansion space and the compression space, the improvement comprising:

a working fluid having components susceptible to reversible chemical reaction under the temperature and pressure conditions in the engine, said reaction producing a number of moles of working fluid that is greater in the expansion space than the number of moles of working fluid in the compression space; and

a catalyst in the regenerator for enhancing the rate of the chemical reaction.

10. In a Stirling engine having an expansion space; a compression space; a working fluid in said space; means for periodically transferring working fluid between the expansion space and the compression space; a heat source for adding heat to the working fluid adjacent the expansion space; a heat sink for removing heat from the working fluid adjacent the compression space; and a regenerator in the fluid flow path between the expansion space and the compression space, the improvement comprising:

a working fluid having components susceptible to reversible chemical reaction under the temperature and pressure conditions in the engine, said reaction having a reactant that is more stable at a relatively lower temperature and reaction products more stable at a relatively higher temperature, the molal volume of the reaction products being greater than the molal volume of the reactant; and

a catalyst in the regenerator for enhancing the rate of the chemical reaction.

11. A method of operating a Stirling cycle engine comprising the cyclic steps of:

compressing a working fluid including a chemically reactive fluid;

heating the working fluid to a temperature sufficient for reaction to products having a greater number of moles than the reactive fluid;

expanding the reaction products;

cooling the expanded reaction products to a sufficiently low temperature for reversing the reaction and producing the original reactive fluid; and

temporarily storing the heat from the cooling step for transfer to the reactive fluid in the heating step, said stored heat including sensible heat of the working fluid and any heat of reaction.

12. A method as defined in claim **11** further comprising catalytically promoting the reversible reaction between the compressing and expanding steps.

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