KRYPTON BASED ADSORPTION TYPE CRYOGENIC REFRIGERATOR

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Field of Search .......................... 62/18, 22, 48, 467

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ABSTRACT

Krypton and a monolithic porous carbon such as Saran carbon are used respectively as the sorbate and sorbent of an adsorption type refrigerator to improve refrigeration efficiency and operational longevity.

13 Claims, 2 Drawing Sheets
Fig. 1
KRYPTON BASED ADSORPTION TYPE CRYOGENIC REFRIGERATOR

ORIGIN OF THE INVENTION

The invention described herein was made within the scope of work under a NASA contract and subject to the provisions of Public Law 96-517 (35 USC 202) in which the Contractor has elected to retain title.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is directed generally to cryogenic refrigerators and more specifically to adsorption type refrigeration systems in which a low pressure refrigeration fluid is adsorbed by the surface of a sorbent material and then pressurized by heating the sorbent material.

2. Description of the Prior Art

Adsorption type refrigerators can pressurize a refrigeration fluid such as methane gas (CH₄) without using a reciprocating piston or other moving compression means. Because fewer moving parts are required for such refrigeration systems, the systems exhibit relatively long lifetimes (e.g., ten years or more) and usually operate with little or no mechanical vibration. The lack of mechanical vibration is particularly advantageous when sensitive transducers need to be cooled without being disturbed by vibrations.

The operation of an adsorption type refrigerator can be summarized as follows. A refrigeration fluid is precooled and adsorbed onto the cavity walls of a porous adsorption material, at a first temperature. Charcoal (carbon) such as saran carbon type A (the inert pyrolysis product of essentially 100% polyvinylidene chloride, PVDC) and, each having respective inlet and outlet check valves, 12b and 12c. The outlet valves 12c are connected to a first side 15a of a first heat exchanger 15 by means of a passive heat radiating pipe 14. The first heat exchanger side 15a couples as shown to a thermoelectric cooler (TEC) 16 and, thereafter, in series to a first side 17a of a second heat exchanger 17 and the high pressure side 18a of a Joule-Thompson (J-T) valve 18. The low pressure side 18b of the J-T valve 18 is connected in series back to the bank of adsorption chambers 12 through a liquid/gas transition chamber 20, a second side 17b of the second heat exchanger 17, and a second side 15b of the first heat exchanger 15. Numerous structures can be employed for forming the first and second heat exchangers. The preferred embodiment presently comprises two tubes joined together with a bimetallic TEC being formed at a central portion of the high pressure tube.

A refrigeration fluid 30 which includes a substantial amount of krypton (Kr), and which more preferably consists essentially of krypton, flows through the system 10 in the following manner. At the inlet valves 12b of the adsorption chambers 12, the fluid 30 is maintained at a first temperature T₁ of for example, approximately 275 K and a first pressure P₁ of for example, approximately 4 atmospheres. A substantial portion 30a of the fluid 30 (preferably all of it) is in the gaseous phase at this point. The inlet valves 12b, of a preselected one 12b of the adsorption chambers 12 is opened to let the fluid 30 into the selected chamber 12b. The corresponding outlet valve 12c of that selected chamber is closed at this time. The fluid 30 is adsorbed by the sorbent material 12a of the selected chamber 12b and a substantial portion of the fluid adheres onto the surface area of the sorbent material either by physisorption or chemisorption. (Physisorption is believed to be the primary mech-
anism for the adherence of krypton to carbon based surfaces.)

After a predetermined length of time and/or a predetermined amount of the fluid is adsorbed, the inlet valve \(12_b\) is closed. The temperature of the newly-filled chamber \(12_a\) is raised to a second temperature \(T_2\) of approximately 575 K by introducing a first amount of heat \(Q_1\) into the chamber \(12_a\). The heat \(Q_1\) can be generated by passing an electric current \(I_1\) through an electric heating rod \(R_1\) disposed centrally within the chamber \(12_a\) as shown or by any other suitable means. One contemplated method is to use the resistivity of the sorbent material as a direct means for heating the adsorbed fluid. The electrical current \(I_1\) is conducted directly through the sorbent material to generate heat. Another method is to use the sorbent material \(12_a\) (preferably a monolithic carbon) as a heat conducting matrix for transferring heat from an external source to the sorbed working fluid 30. The temperature increase due to heating drives off the working fluid from the sorbent surface and raises the pressure of the fluid 30 (sorbate) from the first pressure \(P_1\) (of approximately 4 atm) to a higher second pressure \(P_2\) of for example, 36.8 atmospheres. As the fluid \(Q_1\) is pressurized, the fluid releases on, is then repeated.

The chambers \(12_a\) are preferably cooled to a temperature substantially below \(T_2\) (e.g. well below 575 K) after the pressurized fluid leaves the chambers by removing a residual heat \(Q_0\) therefrom with a suitable cooling means (not shown). One simple method for doing this is to pass the fluid \(Q_0\) through a heat exchanger \(15\) (e.g. a simple water radiator) and thus to cool the fluid \(Q_0\) for the purpose of removing residual heat from the fluid. The fluid undergoes this initial cooling in heat exchanger \(15\) and is then passed through a thermoelectric cooler \(16\) which further reduces the temperature of the fluid \(Q_0\) to below approximately 200 K. A second amount of heat \(Q_2\) thereby causing the temperature of the fluid 30 to drop to an above-critical second temperature \(T_3\) of for example approximately 275 K (this temperature being selected to be above the critical temperature of krypton). In the first heat exchanger \(15\), the fluid 30 gives up a third quantity of heat \(Q_3\) to the second side \(15_b\) of the first heat exchanger. The third heat \(Q_3\) recuperatively warms fluid in the second side \(15_b\) to approximately 275 K as will be explained later.

The thermoelectric cooler \(16\) is supplied with a TEC driving electric current \(I_2\) to drive the temperature of the fluid 30 to a below-critical fourth temperature \(T_4\) of, for example, approximately 195 K by extracting a fourth quantity of heat \(Q_4\) from the fluid. The fourth temperature \(T_4\) is preferably preselected to be between 190 K and 209 K; and more preferably centered around or above 200 K. This TEC heat extraction step changes the krypton in the fluid 30 from a gaseous phase \(30_a\) to a liquid phase \(30_b\). As will be noted later, the selection of the fourth temperature \(T_4\) is a key role in determining the energy efficiency of the TEC and the system 10 as a whole. The critical temperature for krypton at 36.8 atm is roughly 209.4 K.

A fifth quantity of heat \(Q_5\) is removed from the fluid 30 when the liquid flows through the first side \(17_a\) of the second heat exchanger 17. The latter heat extraction step preferably brings the fluid down to a subcritical fifth temperature, \(T_5\) of approximately 120 K–209 K and more preferably to about 140 K–190 K.

When the fluid 30 reaches the high-pressure side \(18\) of the J-T valve 18, its pressure is still at approximately 36.8 atmospheres \(P_2\). As the fluid 30 passes through the orifice of the J-T valve 18, its pressure drops to a low pressure level \(P_{low}\), for example, approximately 4 atmospheres and its temperature preferably drops to a low temperature \(T_{low}\) of approximately 120–160 K, and more preferably 140 K, being a preferred temperature for precooling an oxygen chemisorption refrigerator. A substantial amount of the krypton component of the fluid 30 should be primarily in the liquid phase \(30_b\) at this low temperature although some of the fluid 30 becomes gassified as a result of passing through the J-T valve. The liquefied component \(30_b\) is collected into the liquid/gas transition chamber 20 (e.g., a dewar flask having a heat inlet portion). A sixth quantity of heat \(Q_6\) is absorbed by the transition chamber \(20\) causing the liquefied component \(30_b\) to begin reverting back to the gaseous phase \(30_a\). The rate at which the sixth heat quantity \(Q_6\) can be absorbed from a to-be-cooled heat source (refrigeration load) determines the cooling power \(P_{inlet}\) of the refrigeration system 10. The complimentary input power \(P_{inlet}\) of the system is determined primarily by the energy requirements of the adsorption chamber heaters \(R\) and the TEC (input currents \(I_1\) and \(I_2\)).

After leaving the transition chamber \(20\), the temperature of the fluid 30 is then raised from the low temperature \(T_{low}\) of approximately 140 K to the first temperature \(T_1\) of approximately 275 K by passing the fluid 30 through the second sides, \(17_b\) and \(15_b\), of the second and first heat exchangers, respectively. By the time the fluid 30 reaches the adsorption chambers \(12\), the fluid is substantially gassified and therefore readily able to flow into pores or surface cavities of the sorbent material \(12\). The fluid is adsorbed onto the surfaces of the sorbent material in one of the chambers \(12\) and the cycle of heating the filled chamber to pressurize the fluid, and so on, is then repeated.

The plural adsorption/pressurizing chambers \(12\) are preferably operated in staggered fashion so that, while a first of the chambers \(12\) is taking in a first amount of precooled low-pressure fluid 30 through its respective inlet valve, \(12_a\), a second of the chambers \(12\) can be outputting a second amount of pressurized fluid from its corresponding outlet valve \(12_b\) and a third of the chambers \(12\) can be absorbing the first heat \(Q_1\) to raise the temperature and pressure of the refrigeration fluid 30 contained therein. As such, a generally continuous flow of fluid 30 can be maintained through the system 10 to thereby provide a generally constant refrigeration capacity.

The comparison of one refrigeration system to the next is a difficult task because a large number of param-
ters can come into play. Some of the parameters usually considered are: cost, size, operating temperatures, energy efficiency, absolute cooling power, mean time between maintenance (MTBM), and potential interactions with other systems in the operating environment of the refrigeration system. Typically, energy efficiency is used as a rudimentary comparison tool for evaluating systems of different configurations. Energy efficiency can be expressed as a specific power factor, \( S_p = \frac{P_{in}}{P_{out}} \), which indicates how much power needs to be pumped into the system (e.g. system 10 of FIG. 1) to obtain one comparable unit of cooling power (e.g. Watts in/Watts out). Systems having higher specific power factors can be said to be less energy efficient than those with lower specific power factors. If one takes into balance cost factors such as the MTBM and the danger of a destructive explosion occuring, the importance of the specific power factor may become significantly diminished. This is particularly the case for remote cooling applications such as cryogenic freezing on board a space satellite.

Comparative experiments were conducted with a number of refrigerants, including methane and krypton. A number of different adsorbent materials, including granular charcoal and monolithic porous carbons such as saran carbon, were also studied to determine which configuration was best suited for an environment requiring a high MTBM and a relatively low specific power \( S_p \). The particular environment in mind is that of the precooling stage for an oxygen based chemisorption refrigerator on board a space satellite. The oxygen stage is desirably precooled to 120–160 K and more preferably to a temperature substantially below the 150 K critical point of oxygen. A temperature of approximately 140 K has been found well suited for liquefying oxygen before moving it to subsequent parts of the chemisorption refrigerator.

A first study was conducted to find potential refrigerants other than methane which will not solidify in the range 120–160 K and which can provide efficient cooling in that temperature range. A second study was conducted to find optimal adsorption materials for these refrigerants.

Table 1 (below) shows the results of the latter study wherein computer modelling was used to calculate comparative specific powers for different sorbents. The working fluid wa in all instances selected to be methane (CH\(_4\)), the refrigeration system was computer modelled to the configuration shown in FIG. 1, the J-T low pressure side 18b was set to have a low temperature \( T_{J-1} \) of 50 K, and the TEC temperature, \( T_4 \) was set at 190 K in order to assure that the methane working fluid will be cooled to below its critical temperature of 190.7 K as it enters the J-T valve. Those skilled in the art will appreciate that a significant amount of energy efficiency is lost by operating the TEC below roughly 200 K. Bimetallic thermoelectric converters usually operate with better efficiency at or above 200 K in comparison to their efficiency at 190 K as a result of a basic thermodynamic characteristic common to known metals. The critical temperature of methane is unfortunately below 200 K and the TEC has to be consequently operated in the less efficient temperature range of 190 K or below to assure that the methane is liquefied.

The computer modelling study was based on measured pressure (PSIA) versus adsorption density (grams sorbate/grams sorbent) isotherms for various working fluids and adsorption materials. The adsorption density isotherm curves for the adsorption of krypton on saran carbon is provided as an example in FIG. 2.

In order of their listings, the sorbents of Table 1 are: (a) Amoco GX-31 which is a commercially available granular charcoal having a relatively high adsorption surface area but a relatively large void volume and a relatively poor thermoconductivity in comparison to other materials listed in Table 1; (b) Saran carbon A which is the inert pyrolysis product of a pressurized block of homopolymeric polyvinylidene chloride (PVDC), the latter material being an organic polymer designated by Dow Chemical Company as Saran A; (c) Mycarta charcoal which is the pyrolysis product of a compressed, spirally wound (laminated) phenolic resin; and (d) (AX-21)\(_{20}\) (Saran)\(_{20}\) which is the pyrolysis product of a compressed mixture of 20% powdered Saran A and 80% granulated Amoco/Anderson AX-21, the latter being a commercially available charcoal.

After pyrolysis, sorbents (b), (c) and (d) can be characterized as monolithic carbon matrices having substantially monolithic macro and microstructures dominated by a large micropore volume (pore diameters of less than 3 nanometers) uniformly distributed throughout and relatively small macropore and void volumes. Because of their monolithic structure, these sorbents can act as efficient thermal conductors for transferring heat between an external heat source and an adsorbed fluid. Saran carbon is relatively expensive to manufacture. It requires approximately 4–5 weeks for production in an inert gas or vacuum at a temperature of approximately 700°C and a compression pressure prior to pyrolysis of roughly 15000 psi. A description of Saran carbons B and D which are copolymeric cousins of Saran carbon A can be found in HIGH PRESSURE ADSORPTION OF METHANE ON POROUS CARBONS by S. S. Barton, J. R. Dacezy and D. F. Quinn which paper is printed in Fundamentals of Adsorption, edited by Myers and Belfort, Engineering Foundation Press, 345 East 47th Street N.Y, N.Y. 10017. The 80/20 mix of AX-21 and Saran carbon A, (sorbent (d)) is much less expensive because it can be produced in about a week. The Mycarta charcoal typically can be made in one day.

The results of the computer modeling studies are as follows:

<table>
<thead>
<tr>
<th>TABLE 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPECIFIC POWER</td>
</tr>
<tr>
<td>(Watts in per each watt of cooling)</td>
</tr>
<tr>
<td>COMMENTS</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>(a) Amoco GX-31</td>
</tr>
<tr>
<td>Poor thermoconductivity</td>
</tr>
<tr>
<td>Large void volume</td>
</tr>
<tr>
<td>(b) Saran carbon</td>
</tr>
<tr>
<td>Good thermoconductivity</td>
</tr>
<tr>
<td>Large micro pore volume and surface area</td>
</tr>
<tr>
<td>4-5 weeks to produce</td>
</tr>
<tr>
<td>(c) Mycarta charcoal</td>
</tr>
<tr>
<td>Porous matrix</td>
</tr>
<tr>
<td>Approx. 1 day to produce</td>
</tr>
<tr>
<td>(d) (AX-21)(<em>{20}) (Saran)(</em>{20})</td>
</tr>
<tr>
<td>Porous matrix</td>
</tr>
<tr>
<td>Approx. 1</td>
</tr>
</tbody>
</table>
the working fluid, adverse reactions between the krypton, the other contaminants, and the cryogenic system as a whole are either of an insignificant level or unlikely to occur at all. As such, multiple advantages including improved energy efficiency and system longevity are derived from the utilization of krypton. The scope of the present invention should not be limited to the above detailed description but should rather be defined more broadly in light of its spirit, the accompanying claims and equivalents thereof.

We claim:

1. In a physical adsorption type refrigeration system having a sorbent material, a sorbate fluid capable of being adsorbed onto said sorbent material predominantly by physical adsorption, means for heating said sorbent material to cause the sorbate fluid to be desorbed from said sorbent material, and means for directing the desorbed sorbate fluid away from said sorbent material through an expansion valve, the improvement comprising a sorbate fluid which includes a substantial percentage of krypton.

2. The refrigeration system of claim 1 wherein the sorbate fluid essentially consists of krypton.

3. An adsorption type refrigeration system according to claim 1, wherein the sorbent material comprises a monolithic porous carbon.

4. The refrigeration system of claim 3 wherein the monolithic porous carbon is selected from the group consisting of saran carbon, mycarta charcoal and the pyrolysis product of a mixture of polyvinylidene chloride and granulated charcoal.

5. The refrigeration system of claim 3 wherein said means for heating comprises an electric heater, coupled to pass an electric current directly through the sorbent material to thereby heat the sorbent material.

6. An adsorption type refrigeration system according to claim 1 further comprising a thermoelectric cooler, operatively coupled to a flow path of the sorbate fluid, wherein the thermoelectric cooler operates at a temperature greater than 190.7 degrees Kelvin and less than 209.4 degrees Kelvin.

7. A refrigeration system according to claim 6 further comprising a pressurization chamber enclosing the sorbent material, and pressure control means, coupled to the chamber, for intaking the sorbate fluid into the pressurization chamber at a first pressure level and wherein said means for directing includes means for outletting the sorbate fluid out of the pressurization chamber at a higher second pressure level.

8. The system of claim 7 wherein said pressure control means are either of an insignificant level or unlikely to occur at all. As such, multiple advantages including improved energy efficiency and system longevity are derived from the utilization of krypton. The scope of the present invention should not be limited to the above detailed description but should rather be defined more broadly in light of its spirit, the accompanying claims and equivalents thereof.

We claim:

9. In a physical adsorption type refrigeration system having a sorbent material, a sorbate fluid capable of being adsorbed onto said sorbent material predominantly by physical adsorption, means for heating said sorbent material to cause the sorbate fluid to be desorbed from said sorbent material, and means for directing the desorbed sorbate fluid away from said sorbent material through an expansion valve, the improvement comprising a sorbate fluid which includes a substantial percentage of krypton.

10. The refrigeration system of claim 9 wherein the sorbate fluid essentially consists of krypton.
providing the sorbate fluid to said sorbent material such that said sorbate fluid is adsorbed onto said sorbent material; heating the adsorbed sorbate fluid to a temperature above 209 K to thereby gassify the krypton and pressurize the sorbate fluid; and liquefying the sorbate fluid at a temperature above 190 K.

12. The method of claim 11 wherein the heating step includes heating the sorbate fluid to a temperature of approximately 575 K.

13. A two stage cryogenic refrigeration system, comprising:
   an upper stage physical adsorption cryogenic refrigeration system, comprising:
   a first sorbent material;
   a first sorbate fluid capable of being adsorbed onto said first sorbent material, said first sorbate fluid including a substantial percentage of krypton;
   means for desorbing the first sorbate fluid from said first sorbent material; and
   means for controlling the flow of the first sorbate fluid away from said first sorbent material to provide expansion and cooling of said desorbed first sorbate fluid; and
   a lower stage chemisorption cryogenic refrigeration system, comprising:
   a second sorbent material capable of reversibly chemically reacting with oxygen;
   a second sorbate fluid substantially comprised of oxygen;
   means for desorbing the oxygen from said second sorbent material; and
   means for controlling the flow of said desorbed second sorbate fluid away from said second sorbent material so as to provide expansion and cooling of said desorbed second sorbate fluid.

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