United States Patent [19]

Daniels

[11] **3,862,546**

[45] **Jan. 28, 1975**

[54] **VUILLEUMIER REFRIGERATOR**

[75] Inventor: **Alexander Daniels**, Briarcliff Manor, N.Y.

[73] Assignee: **North American Philips Corporation**, New York, N.Y.

[22] Filed: **June 19, 1972**

[21] Appl. No.: **264,036**

[52] **U.S. Cl.** **62/6,** 62/86

[51] **Int. Cl.** **F25b 9/00**

[58] **Field of Search** 62/6; 1/86

[56] **References Cited**

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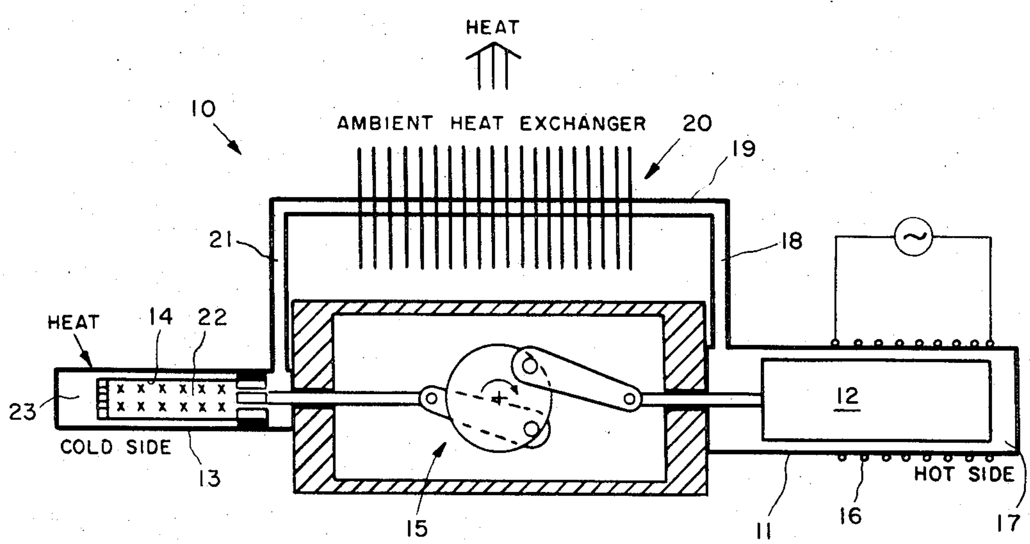
Primary Examiner—William J. Wye
Attorney, Agent, or Firm—Frank R. Trifari

[57] **ABSTRACT**

A Vuilleumier-cycle apparatus for producing refrigeration receives heat energy through its hot side via a positive temperature co-efficient semi-conductor thermistor which provides very rapid and high heat energy initially, and subsequently at or about a specific high temperature automatically prevents further heating.

5 Claims, 6 Drawing Figures



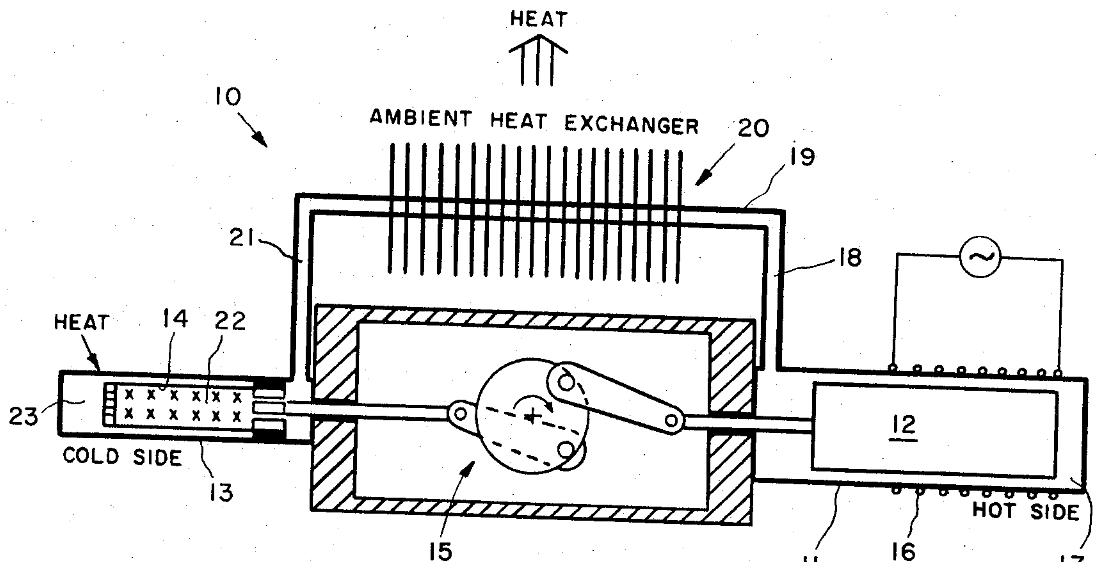

HEAT
AMBIENT HEAT EXCHANGER
10
20
19
21
18
HEAT
14
22
23
COLD SIDE
13
12
HOT SIDE
15
11
16
17

Fig. 1

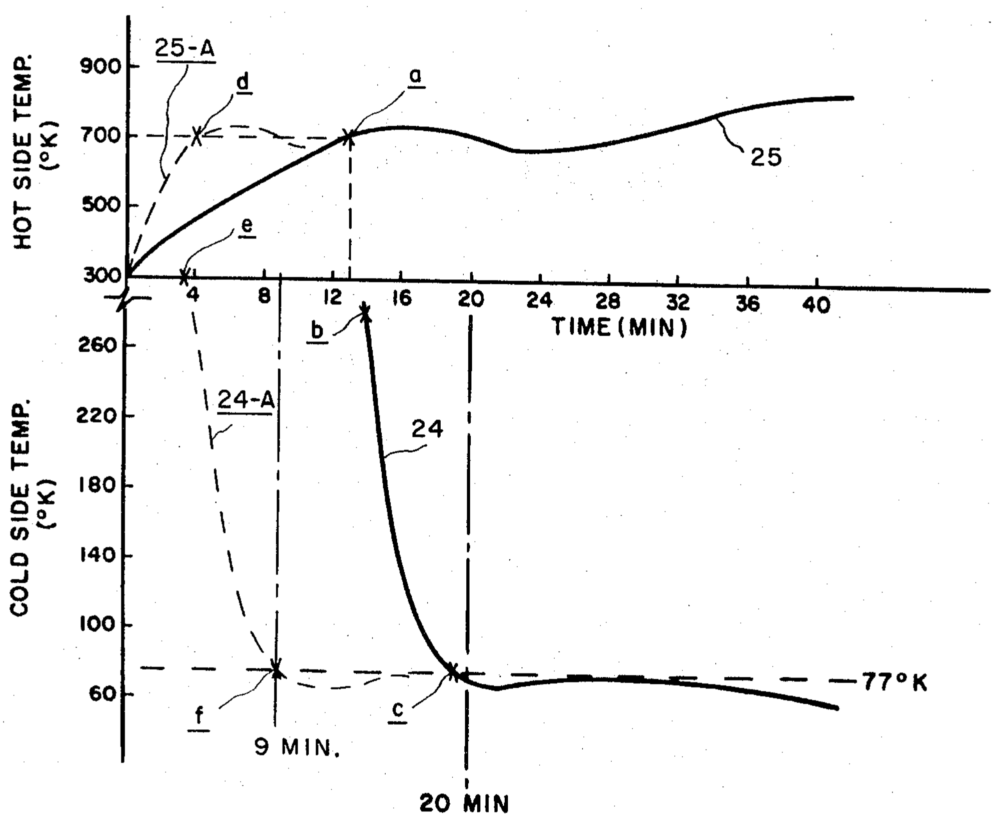

HOT SIDE TEMP. (°K)
900
700
500
300
25-A
d
a
25
e
TIME (MIN)
4
8
12
16
20
24
28
32
36
40
COLD SIDE TEMP. (°K)
260
220
180
140
100
60
b
24-A
24
f
c
77°K
9 MIN.
20 MIN

Fig. 2

PATENTED JAN 28 1975

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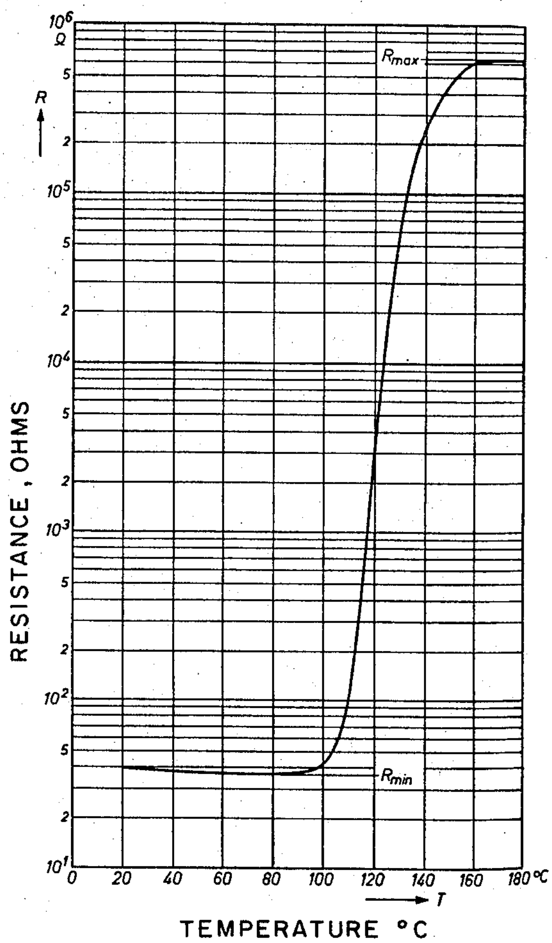

Fig. 3

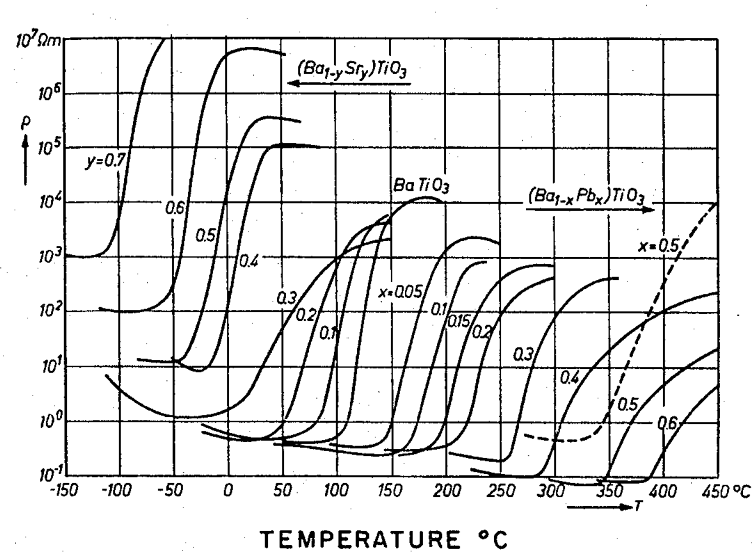

Fig. 4

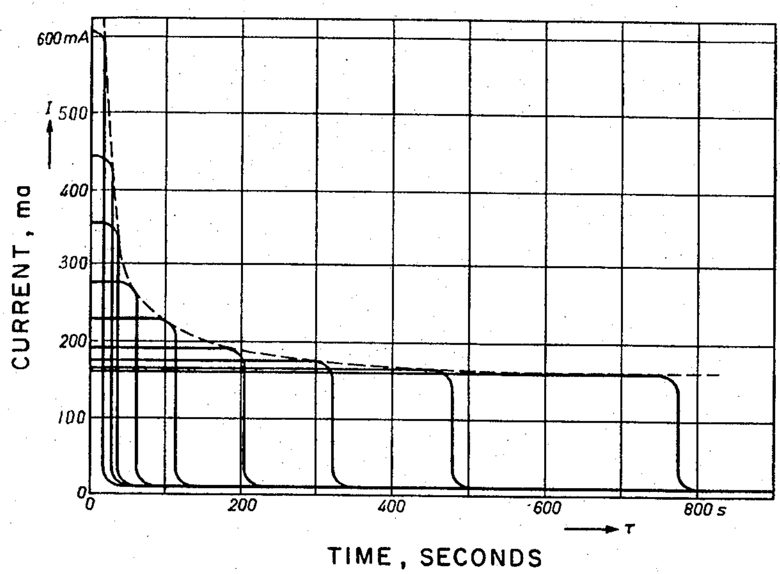
600 mA
I
500
400
300
200
100
0
CURRENT, ma
0
200
400
600
800 s
τ
TIME, SECONDS

Fig. 5

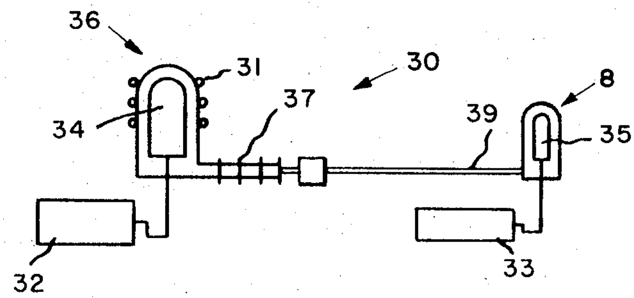
36
31
30
8
37
34
39
35
32
33

Fig. 6

VUILLEUMIER REFRIGERATOR

BACKGROUND OF THE INVENTION

The invention relates to apparatus for producing refrigeration at cryogenic temperatures, and particularly to a refrigerator operating according to the Voilleumier or V-M thermodynamic cycle. The basic concepts of V-M refrigerators may be understood from certain publications which include U.S. Pat. Nos. 1,275,507 and 3,630,041, and an article entitled "Miniature Vuilleumier Cycle Refrigerator" by G. K. Pitcher and F. K. duPre which appeared in Advances in Cryogenic Engineering, Volume 15, "Proceedings of the 1969 Cryogenic Engineering Conference", published by Plenum Press, New York, 1970.

In summary, the Vuilleumier cycle cryogenic refrigerator is a closed-cycle, regenerative type apparatus having a hot side cylinder and piston where a working gas such as helium, becomes compressed, and a cold side cylinder and displacer where this gas is expanded to produce refrigeration, with the displacer operating at the same speed but 90° out-of-phase from the compression piston. Increased pressure and resulting compression of the gas occurs as a consequence of heat input to the gas within the hot side cylinder, which thus functions as a thermal compressor. The pressure variations in the cold volume of this Vuilleumier device are produced by the motion of the hot displacer in the following way. If the hot displacer is "down", much of the helium is in the hot area, the average helium temperature will be high, and the pressure will be high everywhere in the working space. On the other hand, if the displacer is "up", very little of the helium is in the hot area, the average helium temperature will be low, and the pressure will be low. Therefore, as long as the hot displacer moves up and down in the correct phase relationship to the motion of the cold displacer, the required pressure and volume variations are produced in the cold expansion space, and cold is produced according to the equation of $Q=\int pdV$; this equation defines cold production per period in the various thermodynamic cycles, with the same cold produced in a given expansion volume no matter how the pressure variation is produced. A further characteristic of the Vuilleumier refrigerator is that the power required to drive the displacers may be small, since the only forces on the displacers are those due to the small pressure drop of the helium flowing through them, and to the nominal mechanical friction.

Various factors affect the effeiciency of a V-M refrigerator, including the design of the cold-end displacer, the regenerators, the heat exchanger, and the drive unit, most of which have been examined and considered in other documents. Another parameter by which the efficiency of this machine is established is the temperature difference between the hot and cold sides, which is partially controlled by the heat input, namely the quantity and rate of heat transferred into the working gas in the hot side, until an "operating" hot-side temperature is reached.

This input heat may be selected from various sources including external combustion or electrical heating elements, by chemical, nuclear, or other energy. For numerous applications, including the V-M refrigerator, which require heating at very high temperatures and use electric current to produce the heat energy, it is well established design-procedure to use high resistance, nichrome wires as heating elements: nichrome is essentially the only practical material because of its unusually good stability against deterioration at high temperatures and because it will eventually provide adequate heat. However, due to the very high electrical resistance of this wire, there is a considerable power loss and consequent loss in overall efficiency; also there is a considerable time requirement for the conversion of electrical to thermal energy, which delayed heat-up time causes a corresponding delay in achieving a temperature differential with the cold end, and thus delayed production of refrigeration. Consequently the cool-down time for the cold end to reach its operating temperature is not rapid enough for certain applications.

Another common problem with V-M refrigerators is the control of the heat energy transmitted into the hot-side cylinder. To do this generally requires a sensor to determine the temperature of the working gas inside the compression chamber and to determine whether more or less current is needed to alter the heater temperature; a relay device then controls the electrical energy flowing to the heater wires. The temperature sensing mechanism is typically a thermocouple in combination with an amplifier, which results in an expensive and complicated device whose reliability is diminished by the number and complexity of its components. An alternative to such electrical control, requires a valve for releasing working gas pressure in the compression chamber of the hot-side and bleeding the gas to the expansion chamber, when the pressure differential between the hot and cold sides become excessive. Certain of the above-described problems and undesirable features of known Vuilleumier refrigerators are overcome by the invention presented below.

SUMMARY OF THE NEW INVENTION

The new Vuilleumier refrigerator of this invention utilizes a PTC thermistor for providing heat energy directly to the hot-side cylinder. The PTC wire has numerous characteristics which initially do not appear to be particularly relevant or useful for V-M refrigerators, but which have been discovered to provide a number of advantages over nichrome wire heat-elements in regard to the heat input and temperature control problems discussed above.

The first V-M refrigerator problem to be considered is the cool-down time, which means the time required for the cold side of the refrigerator to reach its operating temperature of approximately minus 277°K. It is generally desirable that this cool-down time be reduced to a minimum, and according to the operation of this thermodynamic cycle operation, this can be accomplished by reducing to a minimum the time required to heat up the hot-side to its operating temperature of about 800°K. Since power (P) in watts for heating the hot side, can be computed as I^2R, the electrical power input (and correspondingly the heat energy available for output from the wire) will be maximized when the current (I) is maximized.

As is now known, the PTC wire has extremely low resistance (R) at low temperature, and thus will permit a large current to flow from an electric supply with a given voltage. Furthermore, according to the equation, power, $P=I^2R$, the input power quantity will be greatly (exponentially) increased since the (I) factor is squared. It follows therefore, with a characteristic PTC wire, that at the low temperature range of about 0° to 100°C, the resistance is so low, it is almost negligible; initial current flow will be great with very rapid and great production of heat. Then at operating temperatures above 120°C, the resistance in the PTC wire increases by a factor of from ten to a thousand, such that the high resistance effectively and automatically and almost totally eliminates the current flow. This control of current flow and heat is automatic at selected high temperatures by merely choosing PTC wire that has the appropriate characteristics.

In accordance with the teachings of this new invention, a Vuilleumier refrigerator operable with an electric current input power, has a hot-side cylinder and compression piston reciprocally movable therein. The working gas in the hot side is heated by PTC thermistor wire in heat-transfer contact with the cylinder. This wire could be secured around the outer surface of the cylinder in an economical arrangement, or embedded within the cylinder walls, or even positioned internally. Communicating with the hot-side space is the cold-finger formed of a cylindrical part and a displacer reciprocally movable therein, defining an expansion space where the working gas expands to the cryogenic temperatures for refrigerative purposes. This PTC heater concept is applicable to V-M refrigerators comprising both (a) an integrated housing wherein the hot and cold sides are physically connected, and the hot and cold displacers or pistons are driven in phased relationship by a single power source, and (b) a two-part housing with the hot and cold sides physically separated, and their pistons driven by separate motors. The invention will now be described with reference to drawings of a preferred embodiment of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic view of a Vuilleumier engine, including the new PTC heater at the hot end.

FIG. **2** is a graph of the time-required for hot and cold ends of this engine to reach their respective hot and cold operating temperatures.

FIG. **3** is a graph for a typical PTC thermistor, showing the change in electrical resistance corresponding to temperature change. FIG. **4** is a graph of characteristic for different PTC thermistors.

FIG. **5** is a graph for a typical PTC thermistor, showing the time to reach operating temperature with corresponding high resistance and current drop, relative to the amount of "initial" current flow in the wire.

FIG. **6** is a schematic view of a second embodiment of a V-M refrigerator, including a PTC heater at the hot end.

DESCRIPTION OF THE PREFERRED EMBODIMENT

A refrigerator **10** operative according to the Vuilleumier thermodynamic cycle is shown in FIG. **1**, with the hot side cylinder **11** and piston or compression displacer **12** situated opposite the cold-finger cylinder **13** and displacer **14**. The two displacers are driven by respective rods of a crank mechanism **15** that is driven by a single motor; it is thus ensured that the two displacers will be driven synchronously, though in and out-of-phase relationship.

Associated with the hot side is a heat input element **16** formed of PTC thermistor wire which is a resistor made of semiconducting materials having large positive temperature coefficients. The technology for manufacturing such thermistors is adequately described in the publication, "Philips Technical Review", Vol. 30, page 170, in an article by Mr. E. Andrich. Working gas, preferably helium, is heated in the hot side space **17** which constitutes a thermal compressor with a resulting increase in the temperature and pressure of the gas. Movement of the displacer **12** toward the right drives this working gas through duct **18** to the intermediate space **19** where a heat exchanger **20** can extract a portion of the heat of compression from this gas. Next the working gas passes via duct **21** to the cold finger where it traverses the regenerator **22** within displacer **14** to the expansion space **23** where the lowest-temperature refrigeration is produced.

As discussed earlier, the efficiency of this refrigerator in producing cold, and particularly the speed of reaching cold-side operating temperature, is dependent upon numerous factors. FIG. **2** shows a graph of the time required, with a typical V-M refrigerator, for the hot and cold sides to reach their operating temperatures. Note that the cold side temperature curve **24** does even not begin to descend, until the hot side temperature curve **25** nears or reaches it operating temperature of about 700°K at the point of *a*. Thus, although the cold side curve **24** drops relatively quickly from point *b* to the desired 77°K level at point *c*, this descent does not begin for about fourteen minutes, during which time the hot-side curve **25** rises relatively slowly from 300° to 700°K. This slow rise is characteristic of the nichrome heating-element wire, whereby considerable time and electrical power are consumed before operating temperature and heat production are reached.

The graph in FIG. **3** shows a curve of resistance in ohms plotted against temperature in degrees C. For the particular PTC wire plotted, the resistance is about forty ohms in the temperature range of 20° to 100°C. Then as the temperature rises by 10° to 110°C resistance increases to 100 ohms; with further temperature and resistance changes shown by the chart below:

CHART I

TEMPERATURE	RESISTANCE
20 – 100°C	40 ohms
110°C	100 ohms
118°C	1,000 ohms
122°C	10,000 ohms
132°C	100,000 ohms
160°C	1,000.000 ohms

Consequently, for this particular wire, a temperature rise of only 8°C from 100° to 118°C produces a resistance increase from 40 to 1000, or a further temperature rises from 118°C to 122°C produces resistance of 10,000 ohms which effectively stops further current flow through the wire, and thus stops further heating of the hot end.

FIG. **4** discloses the temperature-resistance curves for a variety of PTC wires made of selected compositions of $BaTiO_3$, $SrTiO_3$, and $PbTiO_3$ with 0.3 mol percent added to make these substances semiconducting. Another ususual characteristic of a representative PTC wire is shown in FIG. **5** which charts time in seconds for the current flow in the wire to drop from its initial rate to zero. Accordingly, if the initial rate is 160ma, there will be a time lapse of 750 seconds or 12.5 minutes until the wire heats sufficiently that the current flow is reduced to zero. at 190 ma, the time lapse is only 200 seconds or 3.3 minutes, with further data as follows:

CHART II

INITIAL CURRENT IN A	TIME LAPSE			
160	750	sec.	= 12.5	min.
190	200	do.	= 3.3	do.
230	115	do.	= 1.9	do.
275	60	do.	= 1.	min.
350	35	do.	=	
450	27	do.		
610	20	do.		

Now, reconsider the equation that expresses the conversion of electrical power to input heat at the hot end, $P = I^2R$; with a fixed resistance R, the power is related to the current squared. Thus if we double current from 230 to 460, power should be quadrupled: i.e., heat input is quadrupled, so that the time to reach operating temperature and current cut off would be reduced to 25 percent. Actually the drop shown above was from 115 seconds to about 27 seconds, or $27/115 = 23.5$ percent. Where current tripled from 200 ma to 600 ma, and then the current factor was squared according to the $P = I^2R$ equation, the power would be increased by a factor of 9; the corresponding time factor should be the inverse, namely 1/9, and in fact the time factor was reduced to 1/10, according to the chart where the time element was reduced to 20 sec. from 200 sec.

Because of the unusual characteristics of the PTC wire discussed above, very high current flow is possible at low temperature, with high heat production in a very small time period. This capability permits performance figures totally unexpected, in view of the long accepted usuage of nichrome and comparable resistance wire for heating purposes.

A typical V-M regrigerator has a hot side operating temperature of about 450°C (720°K). By using a PTC heater wire having a resistance change curve operable in the 450°C region, the resulting device will not only reach its operating temperature of 450°C on the hot side, but will automatically cease further heating, unless the temperature should drop below 450°C, at which time resistance would drop, and current flow and heat would again develop. With this PTC heater arrangement, temperature sensors, relays, and other thermostat system components are all unnecessary.

FIG. 6 shows schematically another embodiment **30** of a V-M refrigerator including PTC heater **31**, but this device has two separate electric motors **32, 33** driving the hot and cold pistons **34, 35** respectively. The hot end **36** operates as a thermal compressor with heat rejected through heat exchanger **37**, and refrigeration is produced in cold finger **38.** Duct **39** permits the hot and cold ends and their motors to be physically separate, yet the device functions as an integral system. As distinguished from FIG. **1**, the cold finger here is isolated from the heat and vibration associated with the hot end; also the motors are separated, but can be electrically synchronized, or easily varied in speed and phase, with all the benefits of the new PTC heater still available at the hot end.

In practicing the Vuilleumier apparatus of this application the heater component and hot-end cylinder would, according to FIGS. **1** and **6** and the corresponding Chart II above, reach operating temperature in a very brief time period that would be under three minutes. Furthermore, the curve representing temperature rise would be relatively steep, as shown by line **25-A** in FIG. **2** reaching the 700°K operating temperature at point *d* on the curve; at approximately the same time the heat-up curve **25-A** reached point *d*, the cool-down curve **24-A** could begin its descent at point *e*, and reach the low operating temperature at point *f* in under 10 minutes which is less than half the time required by a conventional Vuilleumier refrigerator.

The new Vuilleumier heating system described above, operable in various selected temperature ranges, (including a 1000°K hot-end) makes possible successful refrigeration with greatly improved performance and efficiency, compared to all previous related methods.

I claim:

1. A Vuilleumier refrigerator operable with a source of electric current and including a hot-side cylinder and reciprocating compression piston defining a working space and a quantity of compressible working gas therein, first means for introducing heat into said working space and gas therein comprising a semi-conductor, positive temperature coefficient material formed as wire and positioned in physical contact with said cylinder, said material having variable electrical resistance that increases by at least 10% per degree C in a selected temperature range, and second means for connecting said current source to said first means.

2. In a Vuilleumier refrigeration apparatus operable with an electric current source, and including a hot-side cylinder with a compression piston reciprocally movable therein, and a working gas in the cylinder cyclically heated for compression and transfer to an expansion chamber in the cold finger of the apparatus, the improvement in combination therewith of first means for heating said working gas in said hot-side cylinder comprising positive temperature coefficient thermistor semiconductor material in thermal communication with said hot-side cylinder, and second means for connecting said electrical current source to said first means, said first means characterized in having electrical resistance that increases at least 10 percent per degree centigrade in the temperature range of −150°C to +300°C.

3. In apparatus according to claim **2** wherein said first means comprises a thermistor made of at least one titanate material selected from the group consisting of $BaTiO_3$, $SrTiO_8$, $PbTiO_3$, and $LaTiO_3$.

4. In apparatus according to claim **3** wherein said hot-side cylinder has an outer surface, and said first means formed as wire is positioned in intimate physical contact with said outside surface and coiled therearound.

5. In apparatus according to claim **1**, wherein said first means has an electrical resistance increase of at least 20 percent per °C in the temperature range of −160° to 300°C.

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