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Sherwood

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(54) **HYDROFLUOROETHERS AS LOW TEMPERATURE REFRIGERANTS**

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- (22) Filed: **Jan. 24, 2000**

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- (51) **Int. Cl.⁷** **C09K 5/04**
- (52) **U.S. Cl.** **62/114; 252/67**
- (58) **Field of Search** **62/114; 252/67**

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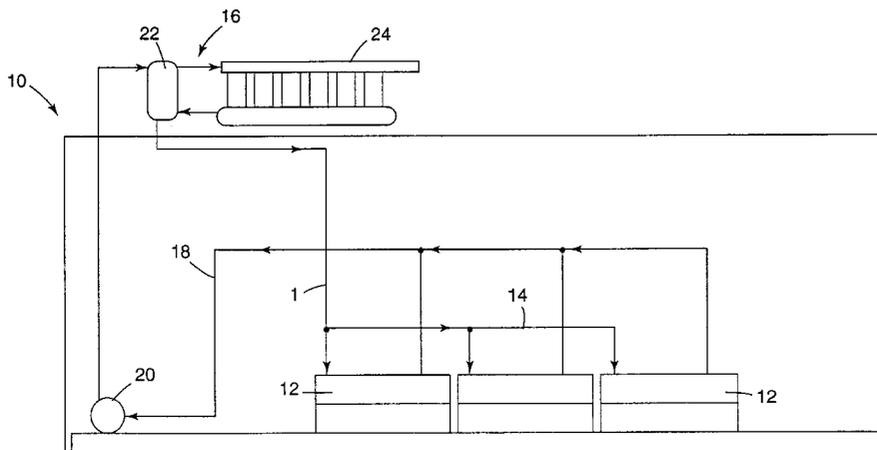
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(57) **ABSTRACT**

A method and apparatus are provided for using certain hydrofluoroethers (HFEs) as low temperature heat transfer media in secondary loop refrigeration systems. These materials exhibit a low, somewhat linear Temperature Difference Factor over the temperature range of -15° C. to -65° C., making them ideal for use as low temperature heat transfer media. The HFEs of the present invention are nonflammable, nontoxic, environmentally benign, and have a high heat transfer capacity and low viscosity over the required operating temperatures. Furthermore, since these materials have high boiling points and low freezing points, they are not prone to phase changes over the required operating temperatures, and do not require pressurized systems.

31 Claims, 10 Drawing Sheets



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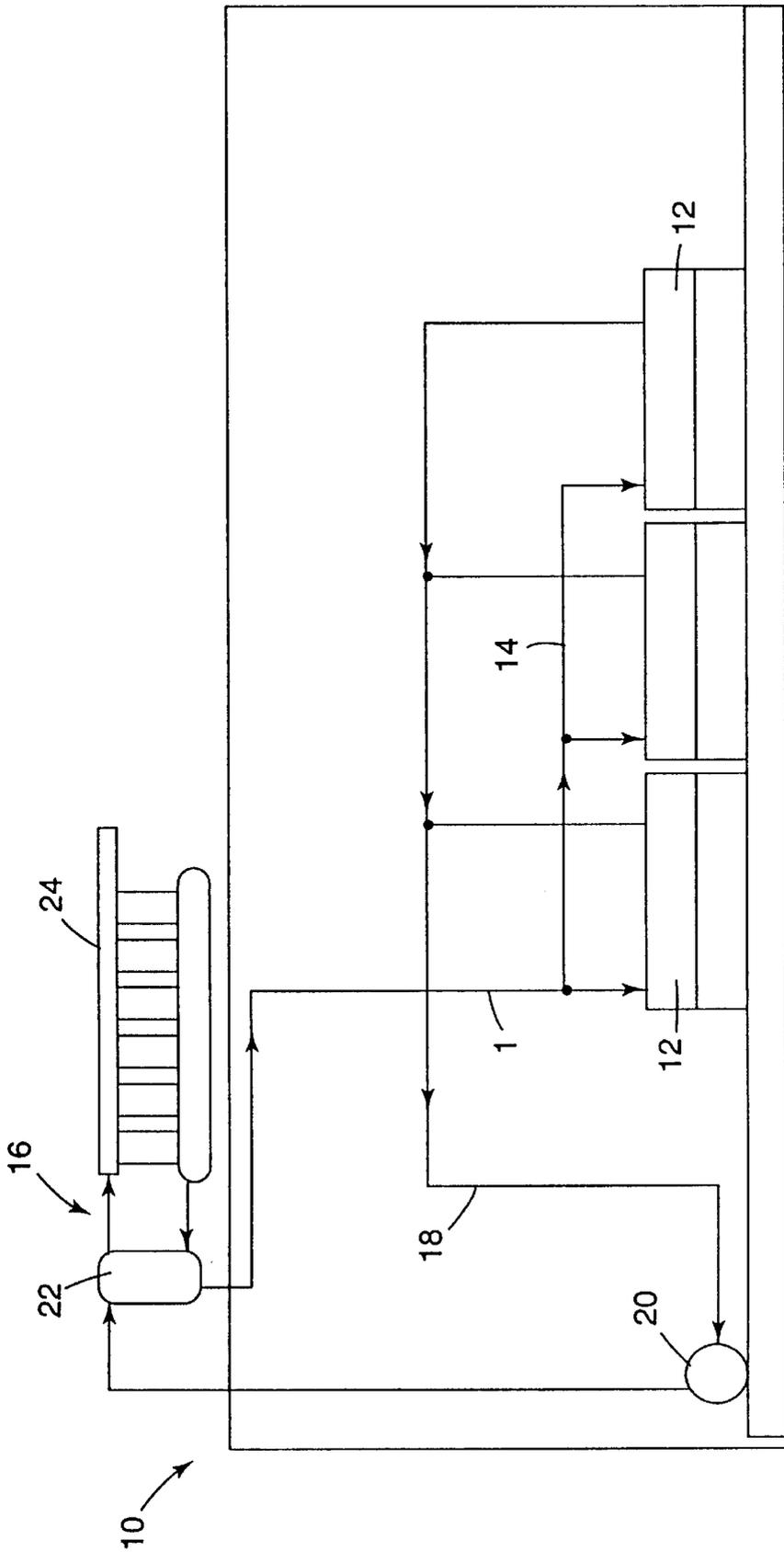


Fig.1

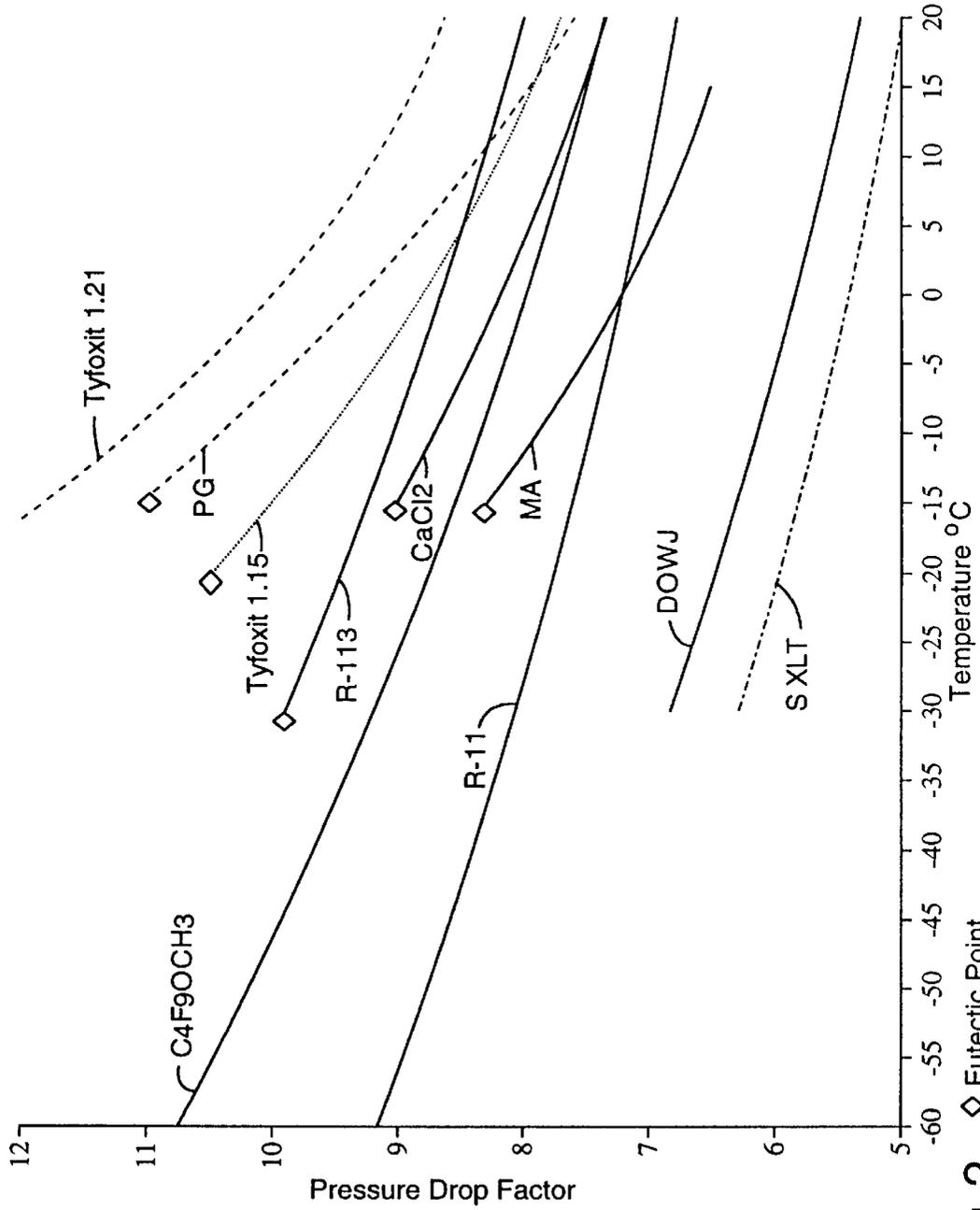


Fig.2
◇ Eutectic Point

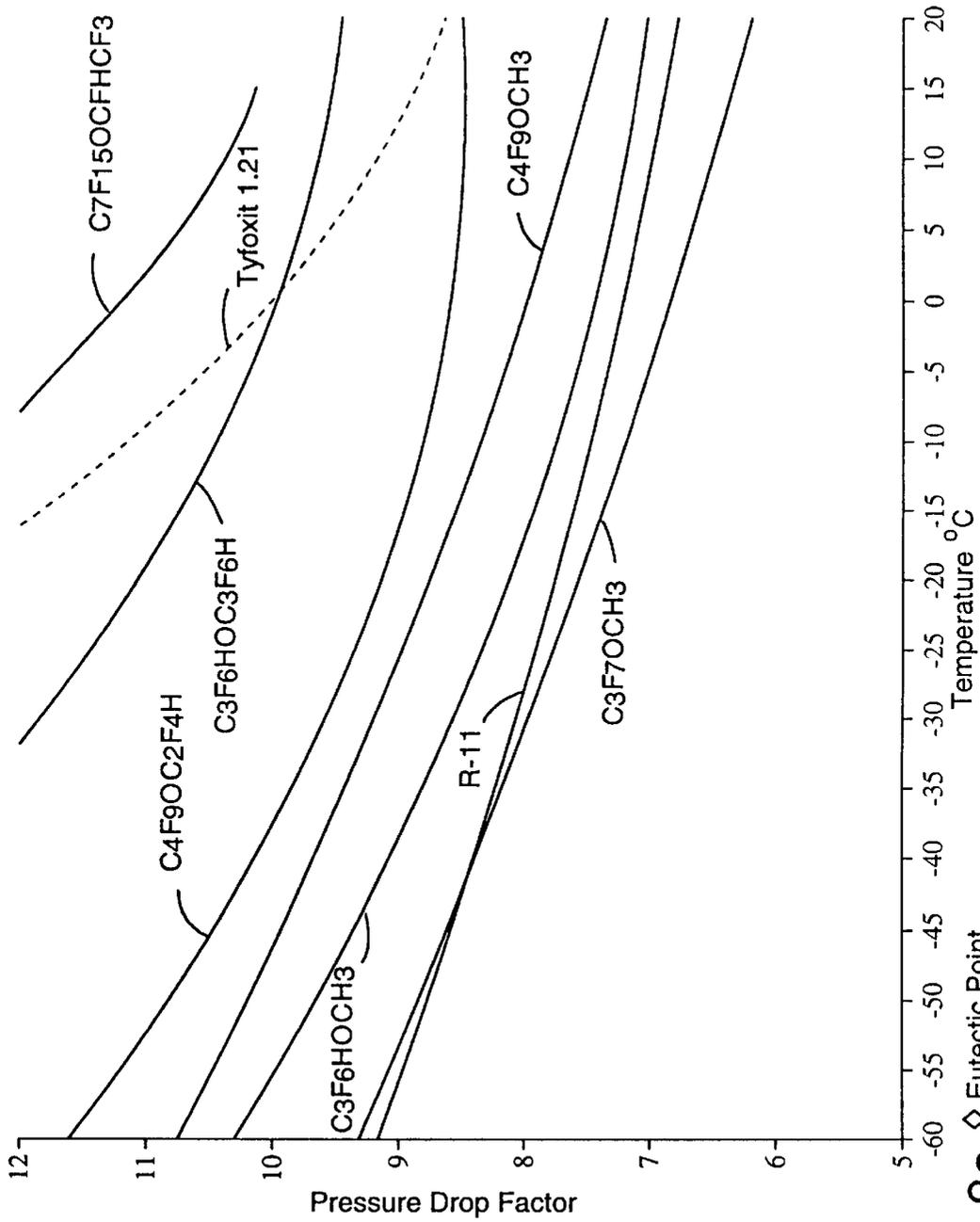


Fig.2a \diamond Eutectic Point

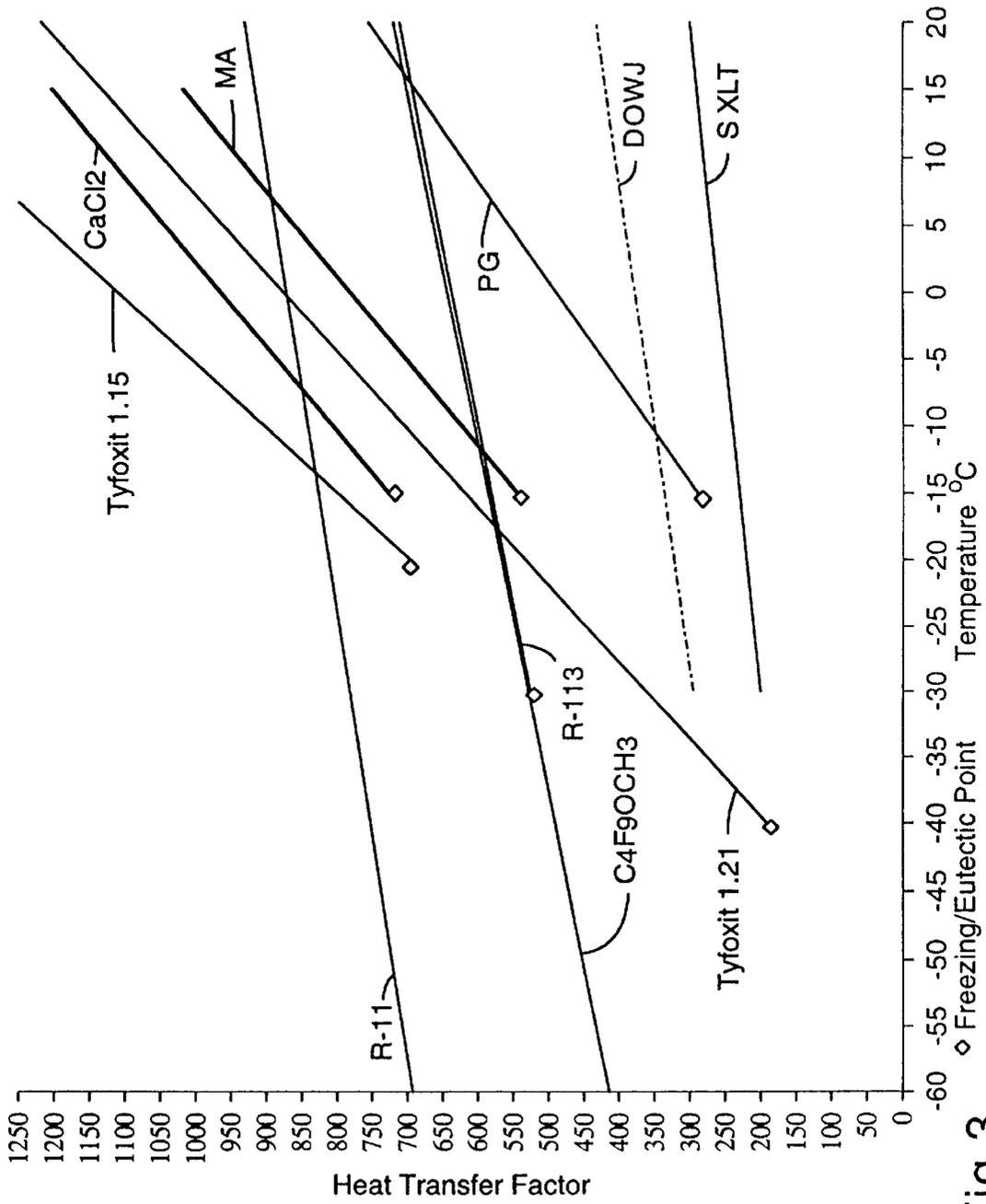


Fig. 3

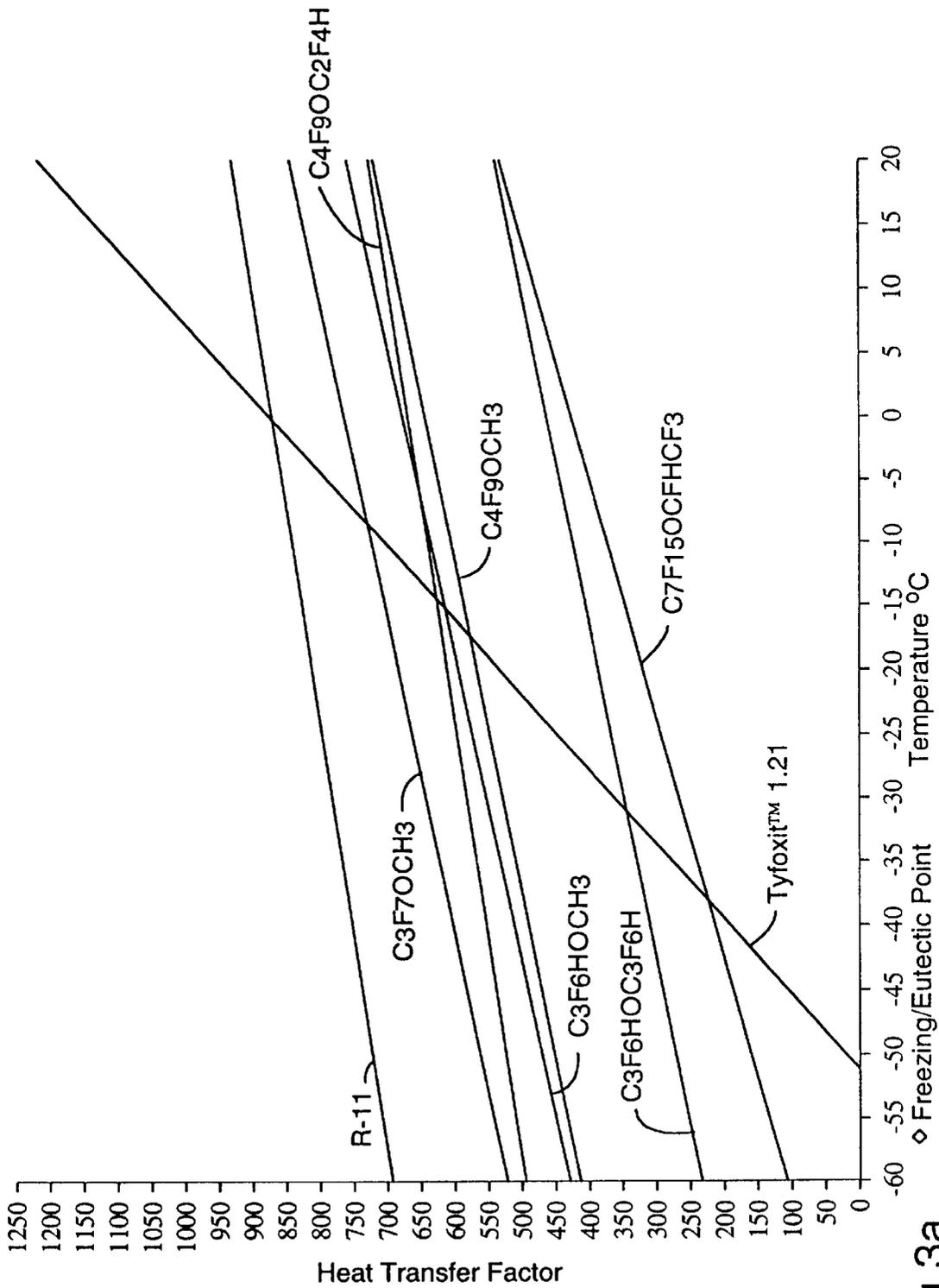


Fig.3a

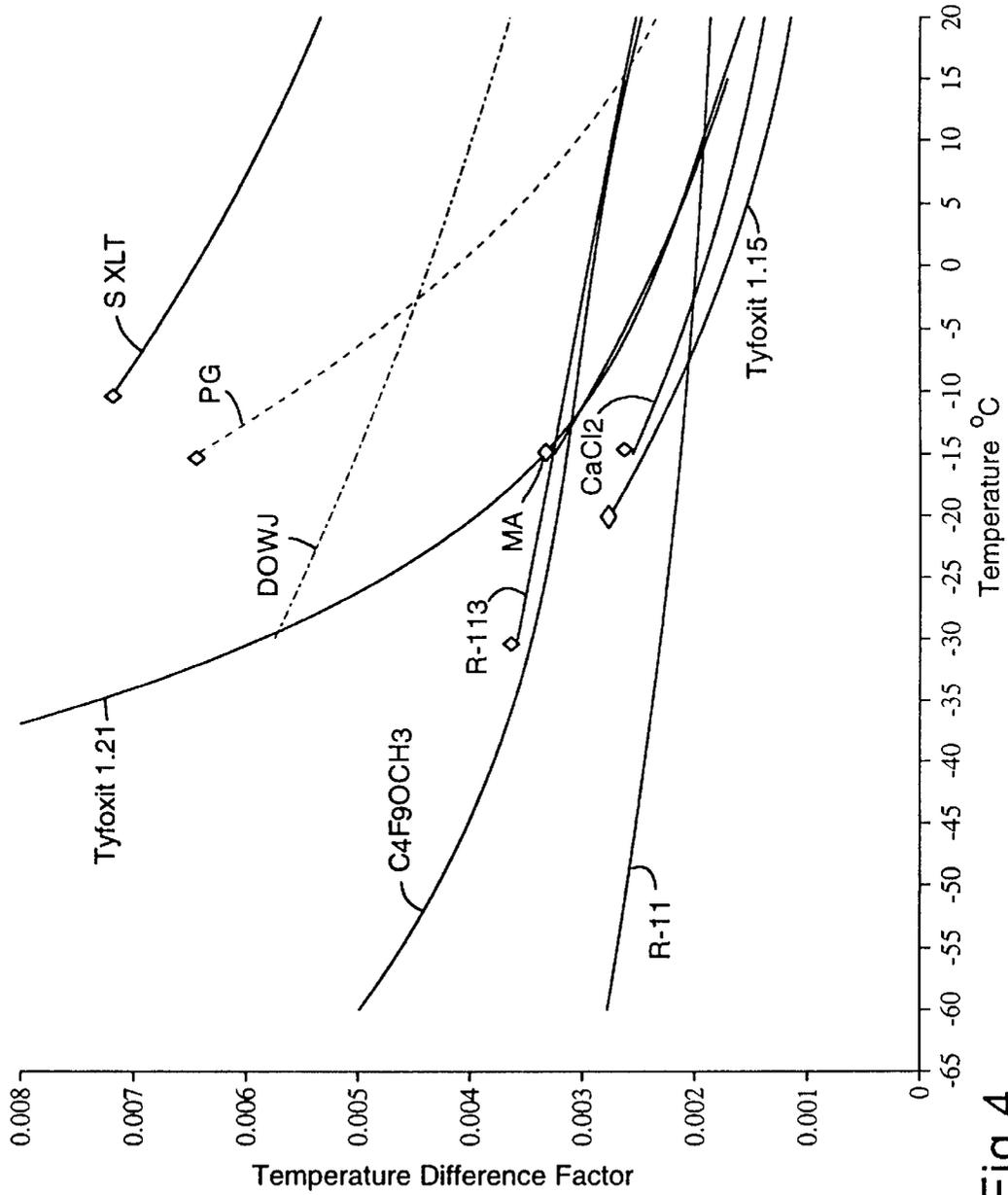


Fig.4

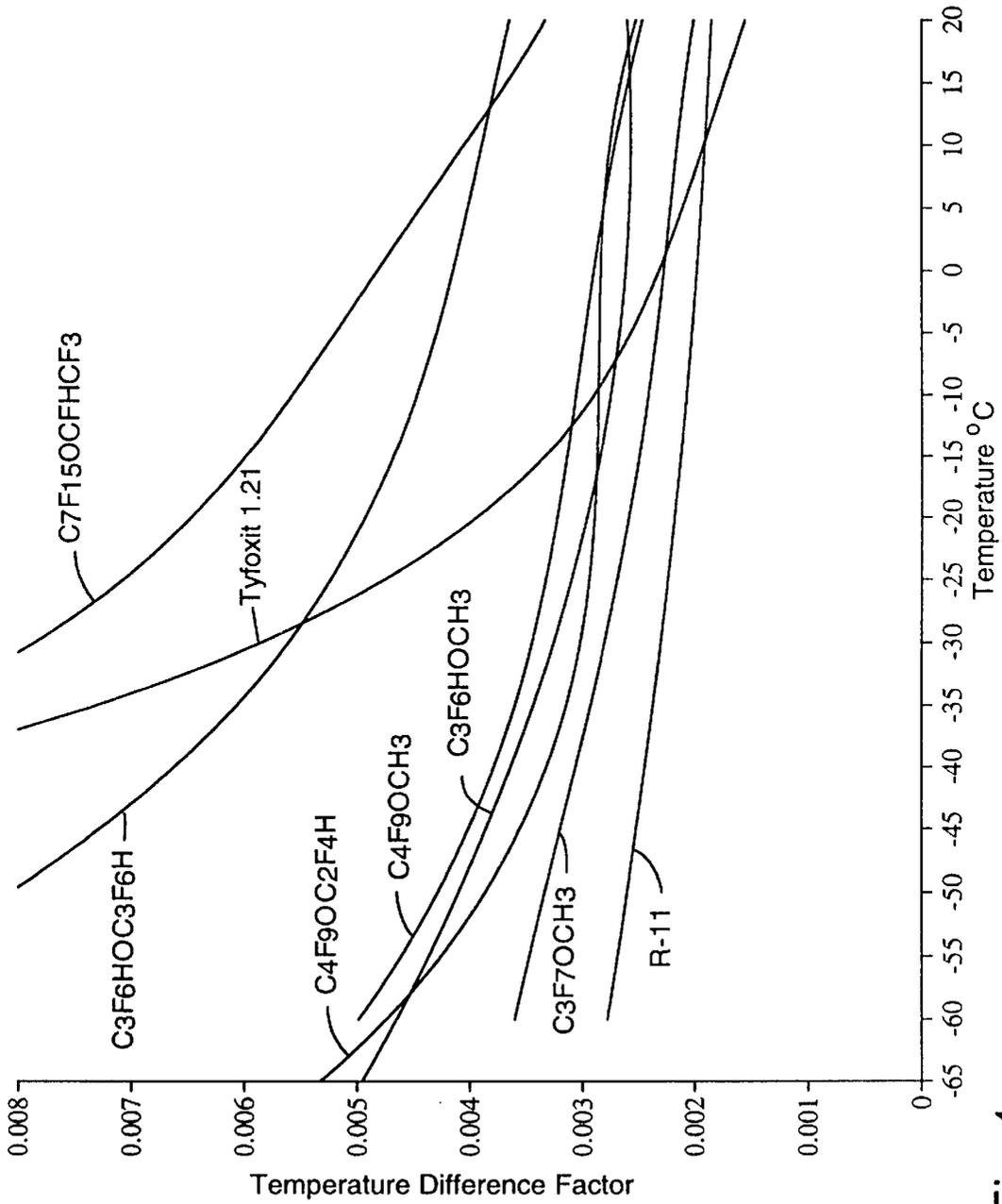


Fig.4a

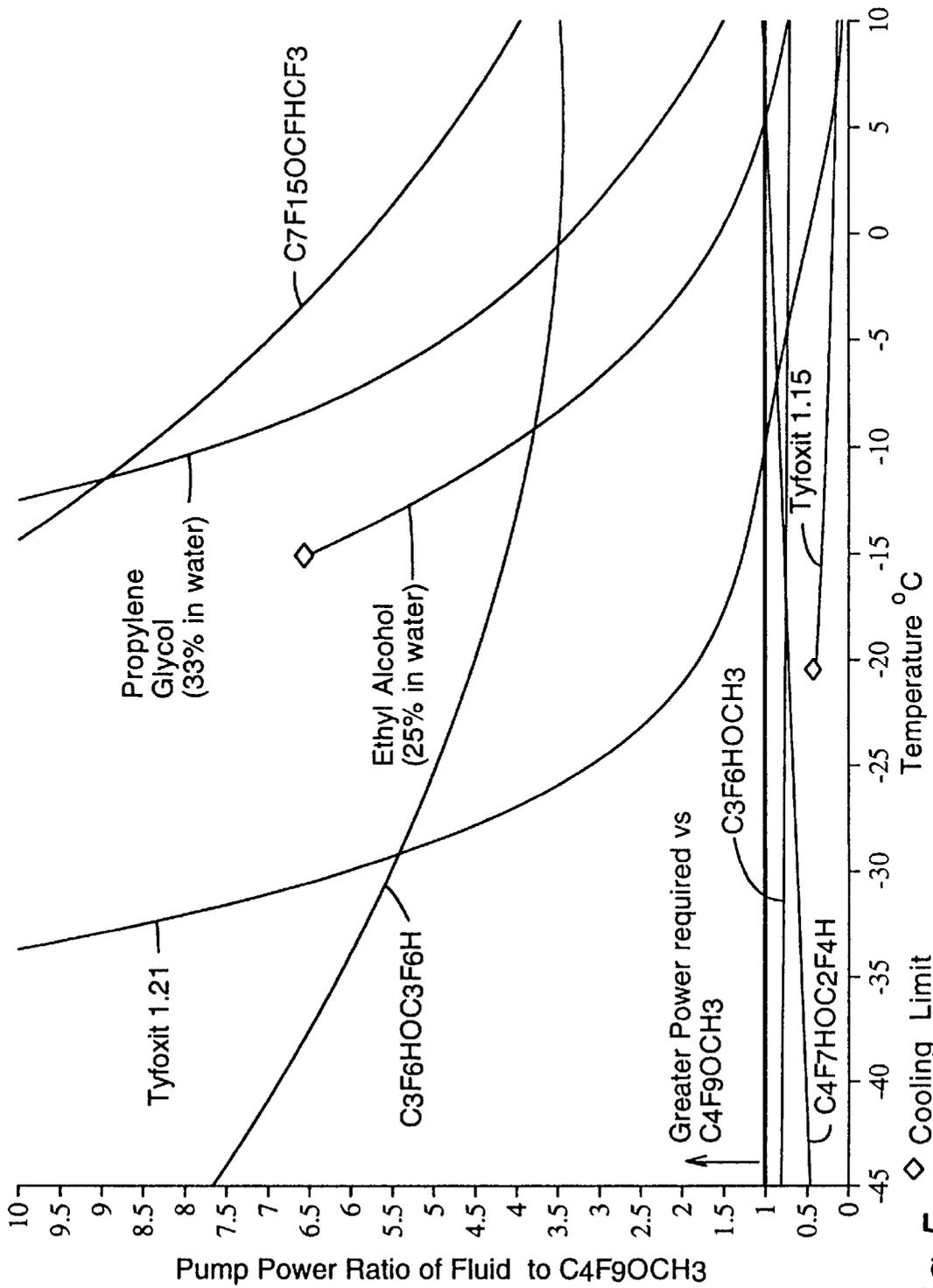


Fig.5

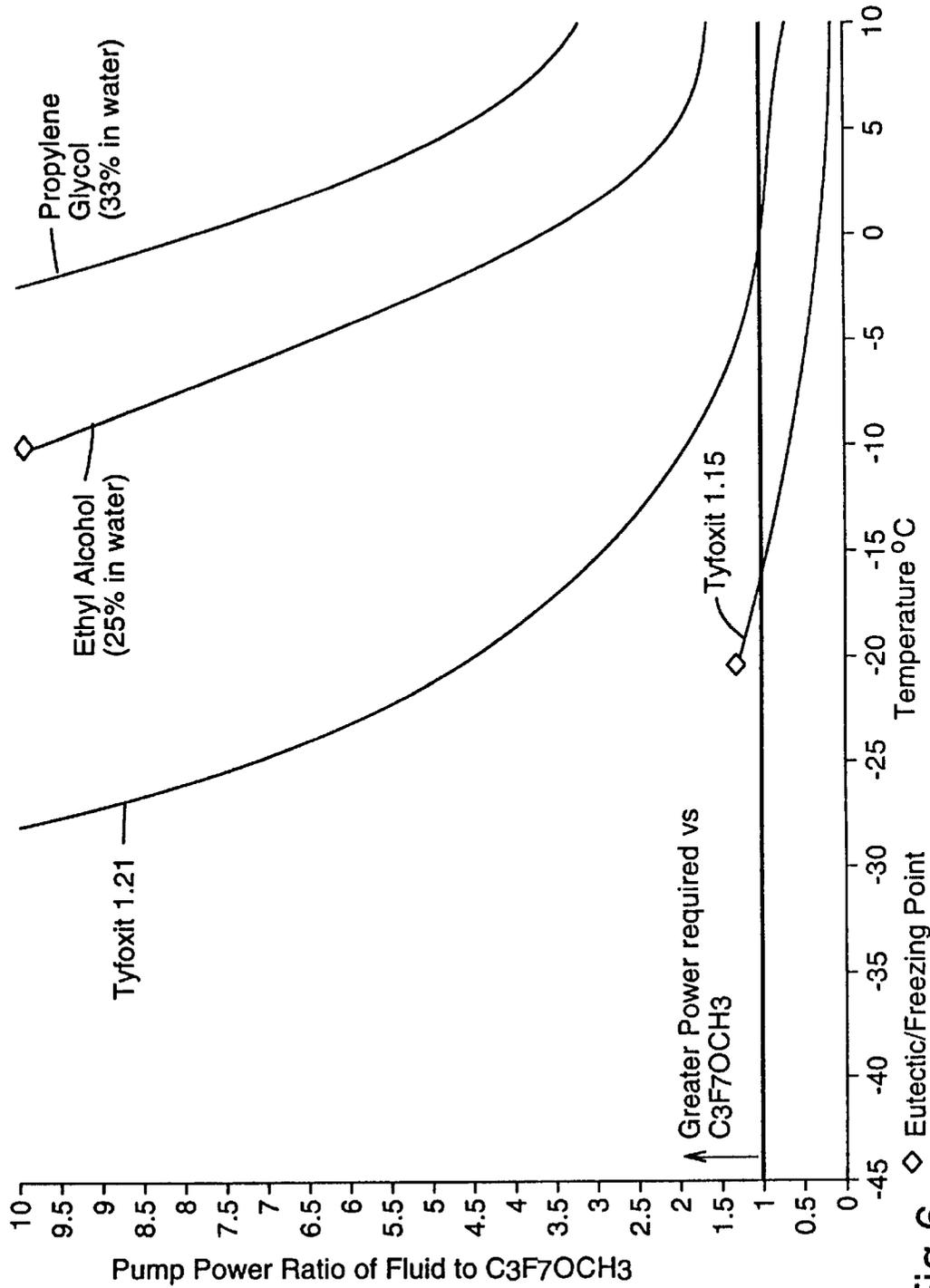


Fig.6

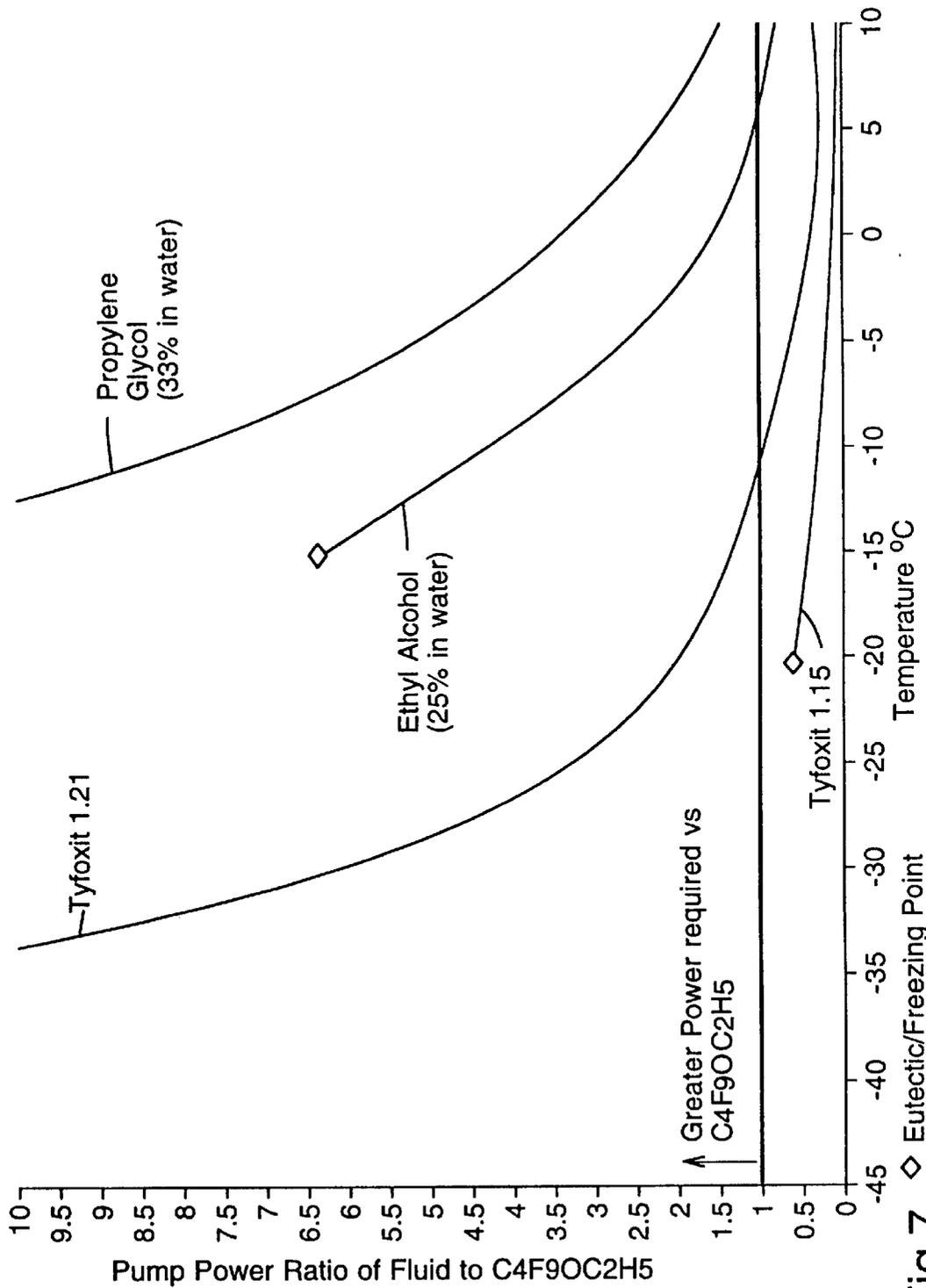


Fig.7

HYDROFLUOROETHERS AS LOW TEMPERATURE REFRIGERANTS

Matter enclosed in heavy brackets [] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to U.S. provisional patent application No. 60/005711, filed Oct. 20, 1995.

FIELD OF THE INVENTION

The present invention relates to heat transfer media, and in particular to the use of hydrofluoroethers (HFEs) as low temperature heat transfer media.

BACKGROUND OF THE INVENTION

Various materials are known to the art which can be used as heat transfer media in refrigeration systems. These materials include water, aqueous brines, alcohols, glycols, ammonia, hydrocarbons, ethers, and various halogen derivatives of these materials. While many of these materials are effective as heat transfer media under certain conditions, practical considerations eliminate many of them from use in key commercial settings, such as in refrigeration systems in grocery stores. In these applications, only a fraction of the class of known heat transfer agents are of commercial significance.

One factor that eliminates many heat transfer media from consideration is their environmental impact. Many known heat transfer media are being phased out because of their environmental persistence, or because they have been implicated in depletion of the ozone layer. An example of the former are the perfluoroalkanes, whose chemical inertness prevents them from being degraded by the natural processes that cleanse the atmosphere. As a result, perfluoroalkanes can have atmospheric half lives of several decades. An example of the latter are the chlorofluorocarbons, which are currently being banned in most countries. See, e.g., P. S. Zurer, "Looming Ban on Production of CFCs, Halons Spurs Switch to Substitutes," *Chemical & Engineering News*, page 12, Nov. 15, 1993.

Another factor that removes many heat transfer agents from consideration is their toxicity. This is the case, for example, with ammonia and with many of the ethylene glycols. The toxicity of these materials, by ingestion, inhalation, or transdermal absorption, makes them dangerous to handle and unsuitable for commercial food handling environments.

Still other heat transfer agents are disfavored because of their flammability. This is the case, for example, with most ethers and hydrocarbons. The risk of flammability is particularly great where the heat transfer agent is subject to large positive pressures within the refrigeration cycle.

Other heat transfer agents are disfavored because they are gases at normal operating temperatures. An example of this type of refrigerants is ammonia. Gaseous heat transfer media require special high pressure equipment, such as pressure regulators and reinforced tubing, that are not required for refrigerants that remain in a liquid state through most or all of the operating cycle. Furthermore, high pressure systems are prone to leakage. Thus, it has been estimated that annual refrigerant losses to the atmosphere from high pressure systems fall within the range of 10 to 20% of the full charge per year.

Still other heat transfer media are not preferred because of their corrosive nature. Many of the aqueous brines fall into this category. Like gaseous media, corrosive agents require special handling provisions, such as Teflon®-lined conduits and interfaces, which add significantly to the overall cost of the system. Furthermore, restrictions on the selection of materials usable with corrosive agents decreases the overall efficiency of these systems.

Recently, a new type of refrigeration system has emerged that has placed even greater demands on the already narrow class of commercially viable refrigeration. This type of system, known as a secondary loop refrigeration system, has many advantages over conventional refrigeration systems, one of the most important being a significant improvement in energy efficiency. Currently, 20% of the refrigerants sold in the United States are installed in conventional high pressure supermarket systems. These systems consume about 4% of the electrical energy output in the United States each year (see Hrnjak, EPA grant application AEERL 5-22, 3/25/95). Hence, the total energy savings offered by secondary loop refrigeration systems in the supermarket sector alone is enormous.

In addition to being more energy efficient, secondary loop systems are also more compact in design, can be factory built, and are capable of operating with an extremely small charge of refrigerant. Furthermore, in secondary loop systems, the vapor compression process of the refrigeration cycle is centralized, and can be operated from a remote location. Thus, the compressor in a secondary loop system can be placed on a rooftop, in a ventilated machine room, or in any other convenient location where it will not occupy valuable floor space or contribute to background noise, and where the effects of refrigerant leakage are minimized. Also, since the primary loop running through the compressor is segregated from the secondary loop used to cool the goods being refrigerated, the primary loop may utilize ammonia and other high efficiency refrigerants that are unsuitable for use as direct refrigerants in many applications.

While secondary loop systems have many clear advantages over conventional refrigeration systems, the commercial use of secondary loop systems has been limited by the unavailability of suitable secondary refrigerants. For a secondary loop system to function most efficiently, the heat transfer media within the secondary loop must be cooled to a low temperature, typically at least -15° C., and more preferably lower than about -25° C. While refrigeration systems are known that cool to temperatures of -30° to -40° C., such systems typically require the use of high pressure refrigerants to achieve these temperatures. The disadvantages of high pressure systems have already been noted.

Unfortunately, absent a high positive pressure, most refrigerants that perform suitably at normal temperatures no longer perform well at the low temperatures required by secondary loop systems. See, e.g., E. Granryd, A. Melinder, "Secondary Refrigerants for Indirect Refrigeration and Heat Pump Systems", ScanRef 14-20 (April 1994), which considers a variety of secondary refrigerants, but concludes that it is difficult to nominate good candidates for low temperature applications. At low temperatures, the viscosities of many refrigerants increase to the point where a large amount of energy is required to circulate the refrigerant through the secondary cooling loop. Propylene glycol exhibits this phenomenon. Other refrigerants, such as silicone oils and hydrocarbon based fluids, have a poor heat transfer capacity at low temperatures. As a result, systems utilizing these refrigerants suffer a marked decrease in energy efficiency at lower temperatures. Often, the drop off in performance of

refrigerants at lower temperatures is precipitous. Thus, the efficiency with which Tyfoxit® 1.15 transfers heat decreases by more than 15% between -10°C . and -15°C . When one considers that many conventional refrigerants undergo phase changes at temperatures above about -20°C ., the choices of heat transfer media for secondary loop systems are few indeed.

There thus remains a need in the art for a heat transfer medium that is suitable for low temperature applications, and for secondary loop refrigeration systems in particular, and which is nontoxic, nonflammable, environmentally friendly, and does not require the use of a high positive pressure. These and other needs are answered by the present invention, as hereinafter disclosed.

SUMMARY OF THE INVENTION

The present invention provides a method and apparatus for using certain hydrofluoroethers (HFEs) as low temperature heat transfer media in secondary loop refrigeration systems. Surprisingly, these materials exhibit a low, somewhat linear Temperature Difference Factor over the temperature range of -15°C . to -65°C ., making them ideal for use as low temperature heat transfer media. The HFEs of the present invention are nonflammable, nontoxic, environmentally benign, and have a high heat transfer capacity and low viscosity over the required operating temperatures. Furthermore, since these materials have high boiling points and low freezing points, they are not prone to phase changes over the required operating temperatures, and do not require pressurized systems.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic drawing of a secondary loop refrigeration system suitable for installation in a supermarket;

FIGS. 2 and 2a are graphs depicting the pressure drop factor as a function of temperature for some embodiments of the present invention as well as several prior art heat transfer fluids;

FIGS. 3 and 3a are graphs depicting the heat transfer factor as a function of temperature for some embodiments of the present invention as well as several prior art heat transfer fluids;

FIGS. 4 and 4a are graphs depicting the temperature difference factor as a function of temperature for some embodiments of the present invention as well as several prior art heat transfer fluids; and

FIGS. 5-7 are graphs depicting the theoretical specific pump power requirements of several conventional secondary cooling fluids compared with $\text{C}_4\text{F}_9\text{OCH}_3$, $\text{C}_3\text{F}_7\text{OCH}_3$ and $\text{C}_4\text{F}_9\text{OC}_2\text{H}_5$ respectively.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

As used herein, the term "secondary loop refrigeration system" refers to a system in which a heat transfer medium is used to transport energy from a heat source to a primary refrigeration system.

The term "secondary loop" refers to the path over which the heat transfer medium travels while it is being cycled between the heat source and the primary refrigeration system.

The term "secondary refrigerant" refers to the heat transfer medium in the secondary loop.

The term "primary refrigeration system" refers to that portion of a secondary loop refrigeration system where heat is transferred to the external environment by way of a compressor.

The term "primary refrigerant" refers to the heat transfer medium used in the primary refrigeration system.

FIG. 1 illustrates the configuration of a typical secondary loop refrigeration system 10 suitable for installation in a grocery store. The goods to be refrigerated are arranged in a series of display cases 12 located throughout the store. Each display case is fitted with one or more refrigeration coils that are in open communication with a network of liquid feedlines 14 which convey the secondary refrigerant from the primary refrigeration system 16 to the display cases.

In operation, energy enters the display cases in the form of ambient heat, and is transferred to the secondary refrigerant by way of the refrigerant coils. The transfer of heat to the secondary refrigerant is typically facilitated by the use of fans, which circulate air around the goods in the display case and over the surfaces of the refrigeration coils. The warmed secondary refrigerant is then withdrawn from the display cases through the liquid return lines 18 by means of a circulation pump 20 and is fed into a primary-to-secondary heat exchanger 22, where the heat from the warmed secondary cooling medium is transferred to the primary refrigerant. The cooled secondary medium is then returned to the display cases by means of the liquid feed lines.

The warmed primary refrigerant is circulated through a rooftop compressor 24. In the compressor, heat is extracted from the primary refrigerant and expelled to the environment. In the process, the primary refrigerant is liquefied and cooled. The primary refrigerant is then expanded and returned to the primary-to-secondary heat exchanger.

To date, several criteria have been used in the art for selecting refrigerants for particular applications. However, for the purposes of the present invention, it was desirable to find a single factor that would summarize the overall performance of a refrigerant as a function of temperature, and that could be used to compare the performance of any two refrigerants independent of system specific variables. In order to accurately reflect the performance of a heat transfer medium in a secondary loop refrigeration system, such a factor would have to take into account the energy required to pump the medium through the secondary loop as temperature decreases, and the ability of the medium to transfer heat at lower temperatures.

The factor selected for this purpose is the Temperature Difference Factor (F_{θ}), which has been described by Granryd and Melinder, SCANREF International, pp. 15-20 (April 1994). The Temperature Difference Factor describes the performance of a fluid over a broad temperature range by characterizing the temperature difference on the fluid flow side of a heat exchanger under turbulent flow conditions, at a given heat flux, q , and at a given specific pumping power, E/Q . The Temperature Difference Factor can be determined from four system independent transport variables; density, thermal conductivity, specific heat, and kinematic viscosity. Consequently, the Temperature Difference Factor allows for direct comparison of performance for both aqueous and non-aqueous secondary cooling fluids over their entire operating ranges by showing the temperature rise of a given fluid as it passes through a heat exchanger under predetermined conditions of heat flux, load, pump power, pump efficiency and tube diameter. In evaluating heat transfer fluids, a low value of F_{θ} indicates a low temperature rise, and therefore high heat transfer efficiency.

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The Temperature Difference Factor (F_θ) is calculated from the equation

$$\theta = F_\theta \times (q^{5/7} \cdot d^{1/7}) / (4\eta_p \cdot E_p / Q)^{2/7} \quad \text{(Equation 1)}$$

where q is the heat flux, d is the diameter of the tube, η_p is the pump efficiency, E_p is the pump power, Q is the load and θ is the temperature difference between the fluids in the heat exchanger. The equation can be solved for pump power, E_p , and the ratio of pump powers for any two fluids can be determined. This ratio provides a comparative factor for the relative pump power requirements of two different fluids under a given set of fixed conditions of heat flux, load and tube diameter, and is given by the equation

$$E_{1p} / E_{2p} = (F_{1\theta})^{7/2} / (F_{2\theta})^{7/2} \quad \text{(Equation 2)}$$

For example, a first fluid having $F_{1\theta} = 0.006$ and a second fluid having a $F_{2\theta} = 0.004 \text{ Kg}^{2/7} \text{ m}^2 \text{ S}^{1/3} / \text{J}$ would have a pump power ratio of 4.1. This demonstrates that the power required to pump the first fluid is 4.1 times greater than the second fluid.

Equation 1 may be simplified to

$$F_\theta = (F_p^{2/7}) / F_\alpha \quad \text{(Equation 3)}$$

where F_p is the Pressure Drop Factor and F_α is the Heat Transfer Factor. The Pressure Drop Factor is an estimate of the pressure drop, or loss due to friction, as a fluid flows through a tube. As such, it is a function of both fluid properties and system properties. This factor separates fluid-dependent variables from system-dependent variables and, when plotted as a function of temperature, allows different fluids to be compared, independent of system specific variables. The Pressure Drop Factor is calculated by the equation

$$F_p = 0.092 \rho v^{0.2} \quad \text{(Equation 4)}$$

where ρ is density of the fluid and v is the kinematic viscosity of the fluid at a specified temperature.

The Heat Transfer Factor is proportional to the heat transfer of a fluid under turbulent flow conditions. Heat transfer is a function of both fluid properties and the geometry of the heat transfer surface. As with the Pressure Drop Factor, the fluid-dependent variables may be separated from the system-dependent variables and the former may be plotted as a function of temperature. The Heat Transfer Factor (F_α) may be calculated by the equation

$$F_\alpha = 0.023 \cdot \lambda^{(6/5)} \cdot (\rho \cdot c_p)^{1/3} \cdot v^{-1/2} \quad \text{(Equation 5)}$$

where λ is the thermal conductivity, ρ is the density, c_p is the specific heat, and v is the kinematic viscosity.

The heat transfer media useful in the present invention comprise fluorinated ethers of the formula



where R_1 and R_2 are the same or different and are selected from the group consisting of substituted and nonsubstituted alkyl, aryl, and alkylaryl groups and their derivatives. At least one of R_1 and R_2 contains at least one fluorine atom, and at least one of R_1 and R_2 contains at least one hydrogen

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atom. Optionally, one or both of R_1 and R_2 may contain one or more catenary or noncatenary heteroatoms, such as nitrogen, oxygen, or sulfur, and/or one or more halogen atoms, including chlorine, bromine, or iodine. R_1 and R_2 may also optionally contain one or more functional groups, including carbonyl, carboxyl, thio, amino, amide, ester, ether, hydroxy, and mercaptan groups, R_1 and R_2 may also be linear, branched, or cyclic alkyl groups, and may contain one or more unsaturated carbon-carbon bonds.

Preferably, the heat transfer media of the present invention comprise fluorinated ethers of the formula



where R_f and R are defined as above for R_1 and R_2 , except that R_f contains at least one fluorine atom, and R contains no fluorine atoms. More preferably, R is a noncyclic branched or straight chain alkyl group, such as methyl, ethyl, n-propyl, iso-propyl, n-butyl, iso-butyl, or t-butyl, and R_f is a fluorinated derivative of such a group.

In the most preferred embodiment, R_1 and R_2 or R_f and R are chosen so that the compound has at least three carbon atoms, and the total number of hydrogen atoms in the compound is most equal to the number of fluorine atoms. Compounds of this type tend to be nonflammable. Specific examples of preferred heat transfer media for use in the present invention include $C_3F_7OCH_3$, $C_3F_7OC_2H_5$, $C_4F_9OCH_3$, and $C_4F_9OC_2H_5$.

The heat transfer media of the present invention may be used alone or in conjunction with one or more other heat transfer media of the invention or with one or more other heat transfer media as are known to the art. The heat transfer media of the present invention may be used as a pure compound, or as a blend, solution, or mixture (azeotropic or otherwise) with one or more other materials. Such other materials may include other heat transfer media, either of the present invention or as are known to the art, or one or more substances used to induce a freezing point depression or boiling point elevation.

Examples 1-4 illustrate the improved performance characteristics of the heat transfer media of the present invention, compared to prior art heat transfer media.

EXAMPLE 1

The thermal conductivities of $C_4F_9OC_2H_5$, $C_4F_9OCH_3$, $C_3F_7OCH_3$, and C_6F_{14} were determined using a transient hot-wire thermal conductivity cell over the temperature range of -50°C . to $+50^\circ \text{C}$., according to ASTM D 2717-86. A platinum wire was used in the measurements. The wire was 20 cm in length, 0.17 mm in diameter, and had a resistance of 120 Ω at 20°C . The thermal conductivities are set forth in Tables 1-4.

EXAMPLE 2

The densities of the fluids of Example 1 were determined from 0°C . to $+50^\circ \text{C}$. using a using a Mettler-Parr Model DMA45 densitometer. For temperatures below 0°C ., densities were determined by extrapolation of the measured densities with a linear curve fit. The densities are set forth in Tables 1-4.

EXAMPLE 3

The kinematic viscosity of the fluids of Example 1 were measured according to ASTM D 4486-85 over the temperature range of -60°C . to 25°C . The results were curve fit to

five data points. The resulting kinematic viscosities are set forth in Tables 1-4.

EXAMPLE 4

The specific heats of the fluids of Example 1 were measured by differential scanning calorimetry according to ASTM E 1269-90 over a temperature range of -30° to 58° C. For temperatures below -30° C., specific heats were determined by extrapolation of the measured specific heats with a linear curve fit. The specific heats are shown in Tables 1-4.

TABLE 1

Fluid Property Data for C ₄ F ₉ OC ₂ H ₅				
Temperature (° C.)	Specific Heat (J/Kg ° C.)	Density (Kg/m ³)	Thermal Conductivity (Watt/m ° C.)	Kinematic Viscosity (m ² /sec × 10 ⁻⁷)
-60	1053	1601	.0850	18.1
-55	1063	1590	.0838	15.6
-50	1073	1579	.0827	13.6
-45	1083	1568	.0816	11.9
-40	1093	1557	.0805	10.7
-35	1103	1546	.0795	9.6
-30	1113	1535	.0784	8.8
-25	1123	1524	.0774	8.2
-20	1133	1513	.0764	7.6
-15	1143	1502	.0754	7.2
-10	1153	1491	.0745	6.8
-5	1163	1480	.0735	6.4
0	1173	1469	.0726	6.0
5	1183	1458	.0718	5.6
10	1193	1447	.0709	5.2
15	1203	1436	.0700	4.7
20	1213	1425	.0692	4.3
25	1223	1414	.0684	3.9
30	1233	1403	.0676	3.5
35	1243	1392	.0669	3.2
40	1253	1381	.0661	2.9
45	1263	1370	.0654	2.9

TABLE 2

Fluid Property Data for C ₄ R ₆ OCH ₃				
Temperature (° C.)	Specific Heat (J/Kg ° C.)	Density (Kg/m ³)	Thermal Conductivity (Watt/m ° C.)	Kinematic Viscosity (m ² /sec × 10 ⁻⁷)
-60	1013	1672	.085	18.1
-55	1023	1661	.084	15.6
-50	1033	1650	.083	13.6
-45	1043	1639	.083	11.9
-40	1053	1629	.082	10.7
-35	1063	1618	.081	9.6
-30	1073	1607	.080	8.8
-25	1083	1597	.079	8.2
-20	1093	1586	.078	7.6
-15	1103	1575	.077	7.2
-10	1113	1564	.076	6.8
-5	1123	1554	.075	6.4
0	1133	1543	.074	6.0
5	1143	1532	.073	5.6
10	1153	1522	.072	5.2
15	1163	1511	.071	4.7
20	1173	1500	.070	4.3
25	1183	1489	.069	3.9
30	1193	1479	.068	3.5
35	1203	1468	.067	3.2
40	1213	1457	.066	2.9
45	1223	1447	.065	2.9

TABLE 3

Fluid Property Data for C ₃ F ₇ OCH ₃				
Temperature (° C.)	Specific Heat (J/Kg ° C.)	Density (Kg/m ³)	Thermal Conductivity (Watt/m ° C.)	Kinematic Viscosity (m ² /sec × 10 ⁻⁷)
-60	1013	1606	.085	9.90
-55	1023	1591	.084	9.22
-50	1033	1576	.083	8.54
-45	1043	1561	.083	7.86
-40	1053	1546	.082	7.22
-35	1063	1531	.081	6.61
-30	1073	1516	.080	6.05
-25	1083	1501	.079	5.54
-20	1093	1486	.078	5.10
-15	1103	1471	.077	4.71
-10	1113	1456	.076	4.38
-5	1123	1441	.075	4.10
0	1133	1426	.074	3.86
5	1143	1411	.073	3.65
10	1153	1396	.072	3.45
15	1163	1381	.071	3.25
20	1173	1366	.070	3.02
25	1183	1351	.069	2.74
30	1193	1336	.068	2.38
35	1203	1321	.067	1.91
40	1213	1306	.066	1.29
45	1223	1291	.065	

TABLE 4

Fluid Property Data for C ₆ F ₁₄ (Comparative)				
Temperature (° C.)	Specific Heat (J/Kg ° C.)	Density (Kg/m ³)	Thermal Conductivity (Watt/m ° C.)	Kinematic Viscosity (m ² /sec × 10 ⁻⁷)
-60	921	1897	.070	20.50
-55	928	1884	.069	17.50
-50	936	1871	.068	15.10
-45	944	1857	.068	13.20
-40	951	1844	.067	11.70
-35	960	1831	.066	10.40
-30	967	1818	.066	9.32
-25	975	1805	.065	8.41
-20	982	1792	.064	7.64
-15	991	1779	.063	6.96
-10	998	1766	.063	6.38
-5	1006	1753	.062	5.87
0	1014	1740	.061	5.42
5	1022	1727	.061	5.03
10	1029	1714	.060	4.67
15	1037	1701	.059	4.36
20	1045	1688	.059	4.08
25	1053	1675	.058	3.83
30	1061	1662	.057	3.60
35	1068	1649	.057	3.40
40	1072	1636	.056	3.22
45	1084	1623	.055	3.05
50	1092	1610	.055	2.90
55	1099	1596	.054	2.77

EXAMPLE 5

The values of the Pressure Drop Factor, the Heat Transfer Factor and the Temperature Difference Factor were calculated using Equations 1, 3, 4, and 5 for the temperature range 20° C. to -60° C. for each of the compounds of Example 1, based on the data in Table 1-4. For the purposes of these calculations, the specific heats and thermal conductivities for the compound C₃F₇OCH₃ were assumed to be the same as for C₄F₉OCH₃. For comparison, corresponding data was collected for C₆F₁₄, and the Pressure Drop Factor, Heat Transfer Factor, and Temperature Difference Factor were

determined for this compound as well. These results are plotted in FIGS. 2-4. For further comparison, the Pressure Drop Factor, Heat Transfer Factor, and Temperature Difference Factor for several conventional refrigerants, as obtained from Grarnyd and Melinder, supra, is also shown. The units for the Heat Transfer Factor are $J/(s^{1/3}m^{8/30}C.)$. The units for the Pressure Drop Factor are $Kg/(m^{1.3/5}s^{1/5})$. The units for the Temperature Difference Factor are $(Kg^{2/7}m^{2}s^{1/3})/J$.

The above Examples, as summarized in FIGS. 2-4, illustrate the unexpected advantages of the heat transfer media of the present invention over other refrigerants in low temperature applications.

FIGS. 2 and 2a depict the Pressure Drop Factor as a function of temperature for several heat transfer media. The viscosity of a fluid has the greatest influence on the Pressure Drop Factor. A low viscosity indicates that the fluid enters turbulent flow sooner given the same fluid velocity. The frictional forces from the tube walls are translated into the fluid, forcing it to churn and mix. As the viscosity increases with reduced temperature, the frictional forces also increase, as does the Pressure Drop Factor.

The relative energy transfer losses that occur due to friction are readily apparent from FIGS. 2 and 2a. All of the aqueous solutions follow a nonlinear plot as the temperature drops. The fluids with the least pressure drop are the Dowtherm® (a mixture of alkylated aromatic isomers, available from Dow Corning Corp., Midland, Mich.) and Syltherm® (a silicone polymer available from Dow Corning Corp., Midland, Mich.) heat transfer fluids, primarily due to their combined low viscosity and low density. Below $-15^{\circ}C.$, $C_4F_9OCH_3$ is surpassed only by these two fluids.

With reference to FIGS. 3 and 3a, the Heat Transfer Factor curves are essentially linear for all of the fluids of interest, although the slopes & these curves vary significantly. The aqueous solutions generally follow the same slope, but are shifted along the ordinate by the different freezing point depressants added to the water. Relative to the non-aqueous fluids, the slopes of the curves for the aqueous solutions are quite steep, and indicates that their ability to transfer heat drops off rapidly as the operating temperatures of secondary systems is approached. Below $-20^{\circ}C.$, $C_4F_9OCH_3$ holds the highest value of the Heat Transfer Factor.

The value of the Pressure Drop Factor is generally less significant than the value of the Temperature Difference Factor. As noted in Equation 3, the Pressure Drop Factor is required to calculate the Temperature Difference Factor, but its value is reduced by raising it to the power of $2/3$ during this calculation. The Temperature Difference Factor is very important for these calculations because it relates the ability of the fluid to transfer heat to the cost of pumping the fluid through the loop. Since the pump power requirements are determined by the temperature difference factor raised to the $1/2$ power (see Equation 2), a small difference in the Temperature Difference Factor between two fluids can mean a large difference in pump power requirements.

EXAMPLES 6-8

To illustrate the magnitude of the shift in power requirements brought about by small differences in the Temperature Difference Factor, the Pump Power Ratio (E_{p1}/E_{p2}) was determined as a function of temperature in accordance with Equation 2 for Tyfoxit® 1.15. Tyfoxit® 1.21 (inhibited

alkali ethanate solutions commercially available from Tyforop Chemic GmbH, Hamburg, Germany), an aqueous solution of 25% by weight ethyl alcohol, and an aqueous solution of 33% by weight of propylene glycol. The reference medium used was $C_4F_9OCH_3$ as shown in FIG. 5, $C_3F_7OCH_3$ as shown in FIG. 6, and $C_4F_9OC_2H_5$ as shown in FIG. 7.

As indicated in FIGS. 5-7, the Pump Power Ratio of all but one of the known heat transfer media surpasses unity at temperatures below about $-10^{\circ}C.$ Below about $-20^{\circ}C.$, the freezing point of Tyfoxit® 1.15, $C_4F_9OCH_3$ stands alone. When evaluating the Pump Power Ratio, the compound $C_3F_7OCH_3$ is especially effective as a secondary heat transfer medium.

Water mixed with a freezing point depressant tends to follow the same slope and curve function. Whether the depressant is alcohol, glycol, or salt, the slope and form of the curves tend to be very similar. The ability of these fluids to transfer heat drops off rapidly as temperatures approach $-20^{\circ}C.$ The power required to circulate these water mixtures also climbs at a rapid pace, reducing the feasibility of the secondary heat transfer loop as an economic alternative to direct expansion systems. By contrast, $C_4F_9OCH_3$ has excellent low temperature heat transfer abilities that result in a much reduced pump power requirement for circulation in a secondary system.

EXAMPLE 9

The fluorinated ethers $C_4F_9OCH_3$, $C_4F_9OC_2H_5$, and $c-C_6F_{11}OCH_3$ were tested for flash point by the standard method defined by ASTM D3278-89. Each compound was determined to have no flash point.

The environmental impact of several of the fluorinated ethers of the present invention was assessed by determination of the atmospheric lifetime (τ_{sample}) and the global warming potential (GWP) of certain compounds, as described in Examples 10-11 below.

EXAMPLE 10

The atmospheric lifetime (τ_{sample}) of various sample compounds was calculated by the technique described in Y. Tang, *Atmospheric Fate of Various Fluorocarbons*, M. S. Thesis, Massachusetts Institute of Technology (1993). According to this technique, an ultraviolet (UV) gas cell was charged with a sample compound, a reference compound (either CH_4 or CH_3Cl), ozone, and water vapor. Hydroxyl radicals were then generated by photolytic decomposition of the ozone in the presence of the water vapor and an inert buffer gas, i.e., helium. As the sample compounds and reference compounds reacted with the hydroxyl radicals in the gas phase, their concentrations were measured by Fourier transform infrared spectroscopy (FTIR). The rate constant for reaction of the sample compound (k_{sample}) with hydroxyl radical was measured relative to the rate constant for a reference compound (k_{ref}), and the atmospheric lifetime was then calculated using the following formula (where τ_{CH_4} and k_{CH_4} are known values):

$$\tau_{sample} = \frac{\tau_{CH_4}}{\left(\frac{k_{sample}}{k_{ref}}\right)\left(\frac{k_{ref}}{k_{CH_4}}\right)}$$

The rate constant for each sample compound was measured (using CH_4 as the reference compound and again using

CH₃Cl) at 298 K. and the atmospheric lifetime values were calculated and then averaged. The results of these measurements are shown in Table 5. For comparison, the atmospheric lifetime for several hydrofluorocarbons is also shown in Table 5.

Atmospheric lifetime was also estimated from a correlation developed between the highest occupied molecular orbital (HOMO) energy and the known atmospheric lifetimes of hydrofluorocarbons and hydrofluorocarbon ethers, in a manner similar to that described by Cooper et al. in Atmos. Environ. 26A, 7, 1331 (1992). The correlation differed from that found in Cooper et al. in the following respects: the correlation was developed using a larger data set; lifetimes for the correlations were determined by relative hydroxyl reactivity of the sample to CH₃CCl₃ at 277 K. as described by Zhang et al. in J. Phys. Chem. 98(16), 4312 (1994); HOMO energy was calculated using MOPAC/PM3, a semi-empirical molecular orbital package; and the number of hydrogen atoms present in the sample was included in the correlation. The results are reported in Table 5.

EXAMPLE 11

Global warming potential (GWP) was determined for some of the heat transfer media of the present invention using the values for atmospheric lifetime calculated in Example 7 and experimentally determined infrared absorbance data integrated over the spectral region of interest, typically 500 to 2500 cm⁻¹. The calculations were based on the definition of GWP set forth by the Intergovernmental Panel in Climate Change in *Climate Change: The IPCC Scientific Assessment*, Cambridge University Press (1990). According to the Panel, GWP is the integrated potential warming due to the release of 1 kilogram of sample compound relative to the warming due to 1 kilogram of CO₂ over a specified integration time horizon (ITH) using the following equation:

$$\text{GWP}_{\text{sample}} = \frac{\int_0^{\text{ITH}} \Delta T_x C_{\text{ex}} e^{-\alpha \tau_x t} dt}{\int_0^{\text{ITH}} \Delta T_{\text{CO}_2} C_{\text{CO}_2} dt}$$

where ΔT is the calculated change in temperature at the earth's surface due to the presence of a particular compound in the atmosphere [calculated using a spreadsheet model (using parameters described by Fisher et al. in Nature 344, 513 (1990)) derived from Atmospheric and Environmental Research, Inc.'s more complete one-dimensional radiative-convective model (described by Wang et al. in J. Atmos. Sci. 38, 1167 (1981) and J. Geophys. Res. 90, 12971 (1985)], C is the atmospheric concentration of the compound, τ is the atmospheric lifetime of the compound (the calculated value described above), and x designates the compound of interest. Upon integration, the formula is as follows:

wherein $A_1=0.30036$, $A_2=0.34278$, $A_3=0.35686$, $\tau_1=6.993$, $\tau_2=71.108$, and $\tau_3=815.73$ in the Siegenthaler (1983) coupled ocean-atmosphere CO₂ model. The results of these calculations are set forth in Table 5.

$$\text{GWP}_{\text{sample}} = \frac{\Delta T_x C_{\text{ex}} \tau_x \left[e^{-\text{ITH}/\tau_x} \right]}{\Delta T_{\text{CO}_2} (1.3 \times 10^{-30}) \left[A_1 \tau_1 (1 - e^{-\text{ITH}/\tau_1}) + A_2 \tau_2 (1 - e^{-\text{ITH}/\tau_2}) + A_3 \tau_3 (1 - e^{-\text{ITH}/\tau_3}) \right]}$$

TABLE 5

Compound	Estimated Atmospheric Lifetime (years)	Atmospheric Lifetime (years)	Global Warming Potential (100 year ITH)
CF ₃ -CH ₃	62.2		
CF ₃ -O-CH ₃	1.6		
C ₂ F ₅ -CH ₃	12.6		
C ₂ F ₅ -O-CH ₃	1.6		
C ₃ F ₇ -CH ₃	9.6		
C ₃ F ₇ -O-CH ₃	1.9		
C ₄ F ₉ -CH ₃	7.0		
C ₄ F ₉ -O-CH ₃	1.9	5.5	330
C ₄ F ₉ -C ₂ H ₅	2.0		
C ₄ F ₉ -O-C ₂ H ₅	0.5	1.2	70
c-C ₆ F ₁₁ -CH ₃	13.7		
c-C ₆ F ₁₁ -O-CH ₃	1.8	3.8	170
CF ₃ CFHCFHCF ₂ C ₃	23*		1000

*A. M. Schmoltner et al., J. Phys. Chem. 97, 8976 (1993)

As indicated by the data in Table 5, each of the fluorinated ethers of the present invention has an unexpectedly lower atmospheric lifetime than the corresponding hydrofluorocarbon, i.e., the hydrofluorocarbon having the same carbon number. The fluorinated ethers of the present invention are thus more environmentally acceptable than the hydrofluorocarbons (which have previously been proposed as chlorofluorocarbon replacements).

The physical properties of C₄F₉OCH₃, determined in accordance with the above described methods, are set forth in Table 6.

TABLE 6

Physical Properties of C ₄ F ₉ OCH ₃		
Boiling Point (° C.)		60
Freezing Point (° C.)		-135
Flash Point (° C.)		None
Solubility for water (ppm)		95
Solubility in water (ppm)		<10
Thermal Transport Properties of C ₄ F ₉ OCH ₃		
	@ 0° C.	@ -40° C.
Density (gm/ml)	1.54	1.63
Specific Heat	1133	1053
Viscosity (cSt)	.60	1.07
Thermal Conductivity (W/m ° C.)	.074	.082
Environmental Properties of C ₄ F ₉ OCH ₃		
Ozone Depletion Potential (ODP)	0	(CPC11 = 1)
Volatile Organic Compound (VOC)	No	
Atmospheric Lifetime	4.0 years	
GWP (IPCC 1994)	480	(CO ₂ = 1, 100th year)
HGWP	0.09	(CPC11 = 1)

EXAMPLE 12

The following example illustrates the effectiveness of hydrofluoroethers over other refrigerants in secondary refrigeration systems.

A secondary refrigeration system was needed for large events at stadiums and arenas. In order to meet customer demands, the system had to be capable of chilling several cases of plastic bottles of soda from room temperature (85° F.) to serving temperature (34° F.) in less than 15 minutes. The proposed system was rejected as being unfeasible by several refrigeration companies in the U.S. and in Europe.

In one design proposed by a refrigeration manufacturer, a traditional refrigeration system was used to cool a large

reservoir of liquid. The chilled liquid was then pumped from the reservoir to a coil in a blast cooler. Air in the cooler was then circulated at high velocity to remove thermal energy from the bottles and transfer it to the cooled coil. In this design, the large reservoir of liquid served as a "Thermal flywheel" capable of absorbing a large amount of energy. Upon completion of the blast cycle, the thermal energy is removed from the reservoir at a lower rate with the refrigeration system to prepare for another cycle.

An initial test was performed using a propylene glycol/water mixture (a common secondary refrigerant) in this system. Using the propylene glycol mixture, it took 75 minutes to achieve the required drop in temperature from 85° F. to 34° F., well above the 15 minute period specified.

A second test was performed which was identical to the initial test, except that C₄F₉OCH₃ was substituted for the propylene glycol/water mixture. This time, the system required only 12 minutes to achieve the required temperature drop.

The above description is intended to be illustrative of the present invention, and is not intended to be limiting. Therefore, the scope of the invention should be construed solely by reference to the appended claims.

What is claimed is:

1. A method for transferring heat, comprising the steps of: providing a heat source; providing a heat sink; and transferring heat between the heat source and the heat sink through the use of a heat transfer medium comprising a fluorinated ether; wherein the heat sink is cooled to a temperature of less than about -15° C.

2. The method of claim 1, wherein the fluorinated ether is a compound of the formula



wherein R₁ and R₂ are the same or different and together contain at least three carbon atoms, wherein at least one of R₁ and R₂ contains at least one fluorine atom, and wherein the total number of hydrogen atoms in the compound is at most equal to the number of fluorine atoms.

3. The method of claim 2, wherein R₁ and R₂ are the same or different and are selected from the group consisting of alkyl, aryl, or alkylaryl moieties.]

4. The method of claim 1, wherein the fluorinated ether is a compound of the formula



wherein R₁ is a moiety containing at least one partially fluorinated alkyl, aryl, or alkylaryl group, and wherein R₂ is a moiety containing at least one non-fluorinated alkyl, aryl, or alkyl aryl group.

5. The method of claim 4, wherein R₁ is a partially fluorinated alkyl group, and wherein R₂ is a non-fluorinated alkyl group.

6. The method of claim 1, wherein the fluorinated ether contains only carbon, hydrogen, oxygen, and fluorine.

7. The method of claim 1, wherein the fluorinated ether is a compound of the formula



wherein R_f is a perfluorinated alkyl, aryl, or alkylaryl group, and wherein R is a nonfluorinated alkyl, aryl, or alkylaryl group.

8. The method of claim 7, wherein R_f is a perfluorinated alkyl group and R [are] is a non-fluorinated alkyl group[s].

9. The method of claim 1, wherein the fluorinated ether is selected from the group consisting of C₃F₇OCH₃, C₄F₉OCH₃, and C₄F₉OC₂H₅.

10. The method of claim 1, wherein the heat transfer medium is cooled to less than about -15° C.

11. The method of claim 1, wherein the heat transfer medium is cooled to less than about -25° C.

12. The method of claim 1, wherein the heat transfer medium has a temperature difference factor of less than about 0.00375 Kg^{2/7}m²s^{1/3} at -25° C.

13. The method of claim 1, wherein the temperature difference factor of the heat transfer medium shows a substantially linear dependence on temperature over the temperature range of -15° C. to -45° C.

14. The method of claim 1, wherein the temperature difference factor of the heat transfer medium shows an substantially linear dependence on temperature over the temperature range of 30° C. to -60° C.

15. The method of claim 13, wherein the first derivative of the temperature difference factor with respect to temperature over the temperature range of -15° C. to -45° C. is within the range of about 0 to about -1.6x10⁻⁴Kg^{2/7}m²s^{1/3}/J+C.

16. The method of claim 12, wherein the second derivative of the temperature difference factor with respect to temperature over the temperature range of -15° C. to -45° C. is about 0.

17. The method of claim 1, wherein the fluorinated ether has no flash point.

18. The method of claim 1, wherein the heat transfer factor of the fluorinated ether is less than about 650 J/(s^{1/3}am^{8/3}C.) at -35° C.

19. The method of claim 1, wherein the pressure drop factor of the fluorinated ether is less than about 9.75 kg/(m^{1.3/5}s^{1/5}) at temperatures greater than about -40° C.

20. The method of claim 1, wherein the ratio of the pump power of the fluorinated ether to the pump power of C₄F₉OCH₃ is less than about 1 at -25° C.

21. The method of claim 1, wherein the ratio of the pump power of the fluorinated ether to the pump power of C₄F₉OCH₃ is less than about 3 at temperatures between -25° C. and -45° C.

22. The method of claim 1, wherein the heat sink is a primary refrigeration system.

23. A method for transferring heat between a heat source and a heat sink, comprising the steps of:

transferring heat from the heat source to a fluorinated ether; and

transferring heat from the fluorinated ether to the heat sink;

wherein the heat sink is cooled to less than about -15° C., and wherein the fluorinated ether is a compound selected from the group consisting of C₃F₇OCH₃, C₄F₉OCH₃, and C₄F₉OC₂H₅.

24. A method for transferring heat, comprising the steps of:

providing a heat source;

providing a heat sink; and

transferring heat between the heat source and the heat sink through the use of a heat transfer medium comprising a material having a Temperature Difference Factor of less than about 0.00375 (Kg^{2/7}m²s^{1/3})/J at -25° C;

wherein the heat sink is cooled to a temperature of less than about -15° C.

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25. A heat transfer system, comprising:
 a heat source;
 a heat sink; and
 heat transfer means for transferring heat between said heat source and said heat sink;
 wherein said heat transfer means comprises a fluorinated ether, and wherein said heat sink is cooled to less than about -15° C.
26. The system of claim 25, wherein said heat transfer means is a secondary loop refrigeration system.
27. A refrigeration system, comprising:
 a [first] *second* refrigeration loop for transferring heat from a heat source to a [first] *second* heat transfer medium; and
 a [second] *first* refrigeration loop for transferring heat from said [first] *second* heat transfer medium to a [second] *first* heat transfer medium;
 wherein said [first] *second* heat transfer medium comprises a fluorinated ether and is cooled to less than about -15° C. by said [second] *first* refrigeration loop.
28. The refrigeration system of claim 27, further comprising: accelerating means for accelerating the rate at which heat is transferred from said heat source to said *second* heat transfer medium.
29. The refrigeration system of claim 28, wherein said accelerating means induces a turbulent flow in the atmo-

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- sphere between said heat source and said [first] *second* refrigeration loop.
30. The refrigeration system of claim 28, wherein said accelerating means is a high velocity fan.
31. A method for transferring heat from a heat source to a heat sink, comprising the steps of:
 providing a heat source, a first heat transfer medium, and a second heat transfer medium comprising a fluorinated ether which is cooled to less than about -15° C.;
 transferring heat from the heat source to the [first] *second* heat transfer medium; and
 transferring heat from the [first] *second* heat transfer medium to the [second] *first* heat transfer medium.
32. The method of claim 31, wherein the first and second heat transfer media are disposed in separate refrigeration coils.
33. The method of claim 31, wherein the transfer of heat from the first heat transfer medium to the second heat transfer medium heats the second heat transfer medium to above -15° C.]
34. The method of claim 33, further comprising the step of:
 cooling the second heat transfer medium down to less than about -15° C.]

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : RE 37,119 E
DATED : April 3, 2001
INVENTOR(S) : Sherwood, Gregory J.

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 6,

Line 57, please delete the second occurrence of the phrase "using a".

Column 7,

Table 2, please delete the equation " $C_4R_9CH_3$ " and insert in place thereof -- $C_4F_9OCH_3$ --.

Column 9,

Line 7, please delete the equation " $Kg/(m^{1.3/5}S^{1/5})$ " and insert in place thereof -- $Kg/(m^{13/5}S^{1/5})$ --.

Line 36, please delete the ampersand (i.e., "&") and insert in place thereof -- of --.

Column 12,

Line 44, Table 6, after the words "Specific Heat" please insert -- (J/Kg °C.) --.

Column 13,

Line 31, please delete the word "other" and insert in place thereof -- ether --.

Line 55, after the word "wherein" please delete the word "is".

Column 14,

Line 18, please delete the word "an" and insert in place thereof -- a --.

Line 25, please delete the plus sign (i.e., "+") and insert in place thereof the degree sign (i.e., -- ° --).

Lines 36-37, please delete the equation " $9.75 kg/(m^{1.3/5}S^{1/5})$ " and insert in place thereof -- $9.75 Kg/(m^{13/5}S^{1/5})$ --.

Signed and Sealed this

Sixteenth Day of July, 2002

Attest:



Attesting Officer

JAMES E. ROGAN
Director of the United States Patent and Trademark Office