Secondary Heat Transfer Systems and the Application of a New Hydrofluoroether

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A great deal of effort has been focused recently on alternative refrigeration systems that can provide the required cooling for food storage and retailing, and also reduce the impact on the environment. Refrigeration systems that cool to temperatures of -30 to -40°C are very common and require the use of high pressure refrigerants. High pressure refrigeration systems are prone to leakage, with annual refrigerant losses to the atmosphere in the range of 5 to 15% of the full charge per year. A proposed solution to this problem lies in centralizing the vapor compression process of the refrigeration cycle, thus reducing the volume of refrigerant that is pressurized. The energy removed from the storage or display areas is carried to the centralized system by means of a secondary heat transfer liquid. This secondary system involves mechanically pumping the liquid to heat exchangers or coils located in the storage or display cases. Air that is circulated in these cases removes energy from the food and transfers it to the coil, which then transfers it to the liquid. The liquid emerges from the coils at a higher temperature and is returned to the refrigeration system.

The secondary heat transfer concept is simple, but the selection of fluid for such a system can be challenging. Efforts have focused on developing a fluid that can effectively transfer energy from the heat source to the refrigeration system without the burden of a large amount of energy input at the circulation pump. Ideally, the energy consumption of the combined refrigeration and secondary loop would be less than that of present systems.

This paper presents the properties of a new fluid that appears to fill the need for a secondary heat transfer system. Compared to traditional and newly-developed liquids — this material has several advantages including low viscosity, excellent low temperature heat transfer characteristics, and modest pumping power requirements even for low temperature heat transfer.

Background

The application of a heat transfer fluid to perform low temperature cooling is a very good idea in principle. The high pressure refrigeration system can be centralized and the refrigerant charge minimized. This also allows for use of more efficient refrigerants such as ammonia, as they can be isolated on roof tops or in ventilated machine rooms. The fluid system operates at much lower pressures. Combined with very little vapor pressure at these operating temperatures, fugitive material loss from the system would be substantially less.

Supermarket refrigeration is the most challenging application of secondary fluid loops. The varying loads and temperature requirements of such systems pose a difficult engineering problem. Yet,

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there are several motivating factors that drive the proposed solutions: twenty percent of the refrigerants sold in the United States are installed in high pressure supermarket systems; four percent of the electrical energy produced is consumed by these systems.[1] It is likely a secondary system that provides an energy benefit would be well received. Application beyond supermarket refrigeration, such as walk-in freezers and other large, low temperature storage systems, would be readily adapted to these types of secondary fluid loops.

Of the many fluids considered for secondary loop heat transfer, water is one of the best heat transfer fluids available. It is only natural to try to extend the use of water below its freezing temperature to take advantage of its thermal transport properties. This has been done for many years with the use of salts, methyl and ethyl alcohol, or glycol, and can be effective over a limited low temperature range. Silicone oils and hydrocarbon-based fluids have also been used as heat transfer fluids and have a large temperature range of operation but can have relatively low flash points. They also have relatively low thermal transport capabilities at low temperatures.

The new hydrofluoroethers (HFEs) have an excellent blend of thermal transport, safety, and environmental properties that make them excellent candidates for a secondary heat transfer system. A comparison of one HFE with many other fluids is made in the following text. A review of this material will reveal the advantages of this new fluid over all the other candidates and demonstrate the feasibility of secondary loop systems.

State-of-the-Art in Secondary Heat Transfer Fluids

As stated above, several fluids have been analyzed in a effort to develop a secondary system that fills all the refrigeration demands of supermarkets. A comparison of many fluids was performed by Granryd and Melinder of The Royal Institute of Technology in Stockholm, Sweden.[2] Several useful methods of comparing candidate fluids were presented, many of which have been employed in this study.

To analyze a heat transfer problem, one must account for the fluid’s temperature dependent transport properties and how the fluid interacts with the geometry of the object where the heat is being exchanged. There are four transport properties that are important for this analysis: density, thermal conductivity, specific heat, and kinematic viscosity. The geometric concerns are the hydraulic diameter and length of the flow channel, and are typically system dependent variables.

When comparing several different fluids to apply to a heat transfer problem, it is quite useful to separate the temperature sensitive transport properties from the system dependent variables. The fluid properties can be combined into “figures of merit” or “factors” that become a basis of comparison. These factors are created using forms of standard heat transfer correlations, and when plotted against temperature can be a very useful tool to compare fluids. The system-dependent variables are application or hardware specific and are included when quantitative values of heat transfer are desired.

Some materials can be mixed with water to get freezing points to -45°C. Many of these materials, known as freezing point depressants, are included in this paper. The salt solutions do maintain water's high level of thermal conductivity and specific heat. However, a major drawback is the corrosive nature of these solutions. Also, their ability to transfer heat drops dramatically as temperatures approach -30 or -40°C.

The alcohol/water solutions can have similar heat transfer characteristics to the salt solutions, yet there is a different risk of flammability of these mixtures, health risks with methyl alcohol, and high viscosity of ethyl alcohol.

Glycol solutions can be orally toxic, present an environmental pollution risk, and have high viscosity at low temperatures. A proprietary fluid, Tyfoxit™, that is blended with water to achieve a specific freezing point, is also included in this study.

Some non-aqueous heat transfer fluids are compared as well. Silicone based fluids such as Dowtherm™ J and Syltherm™ XLT have been used for many years in industrial processing, yet are limited for use as secondary coolants by their relatively low flash points or poor heat transfer characteristics when compared to other fluids.

A hydrofluoroether, listed in this paper under a 3M laboratory number L-13938, is a new liquid that has many benefits over other fluids proposed for this application. It is a single component material so there is no need to maintain proportions with another fluid in the system. It is non-corrosive and nonflammable. The HFE has a freezing point well below any of the other fluids and a low viscosity at very low temperatures. All these properties are complimented with positive environmental characteristics. A summary of these properties is listed below.

Typical Physical Properties of HFE L-13938

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 HFE L-13938

	@ 0°C	**@ -40°C**
Density (gm/ml)	1.54	1.63
Specific Heat (J/Kg °C)	1133	1053
Viscosity (cSt)	.60	1.07
Thermal Conductivity (W/m °C)	.074	.082

Environmental Properties of HFE L-13938

Ozone Depletion Potential (ODP)	**0**	(CFC11 = 1)
Volatile Organic Compound (VOC)	**No**	
Atmospheric Lifetime	**4.0 years**	
GWP (IPCC 1994)	**500**	(CO_2 = 1, 100th year)
HGWP	**0.09**	(CFC11 = 1)

Toxicological Properties of HFE L-13938

Oral	Practically non-toxic orally
Eye Irritation	No irritation
Skin Irritation	No Irritaiton
Skin Sensitization	Not a Skin Sensitizer
Inhalation	No observable effects at 10,000 ppm
ALC	>100,000 ppm (4hrs)
Chronic Toxicity	In Progress

Performance Comparisons

Heat transfer performance of these fluids can be predicted using several engineering correlations and the four thermal transport properties. By combining these properties into three different factors and then plotting them as a function of temperature, one can gain clear insight thermodynamically as to the appropriate fluid to use for the temperature of interest.

Pressure Drop Factor *Fp*

This factor is used in an equation to estimate the pressure drop or loss due to friction as the fluid flows through a tube. An accepted expression for this pressure drop is given by:

Pressure Drop (due to friction) = Friction Coefficient x Density x Velocity^2 x Length / Diameter (of the pipe or flow channel)

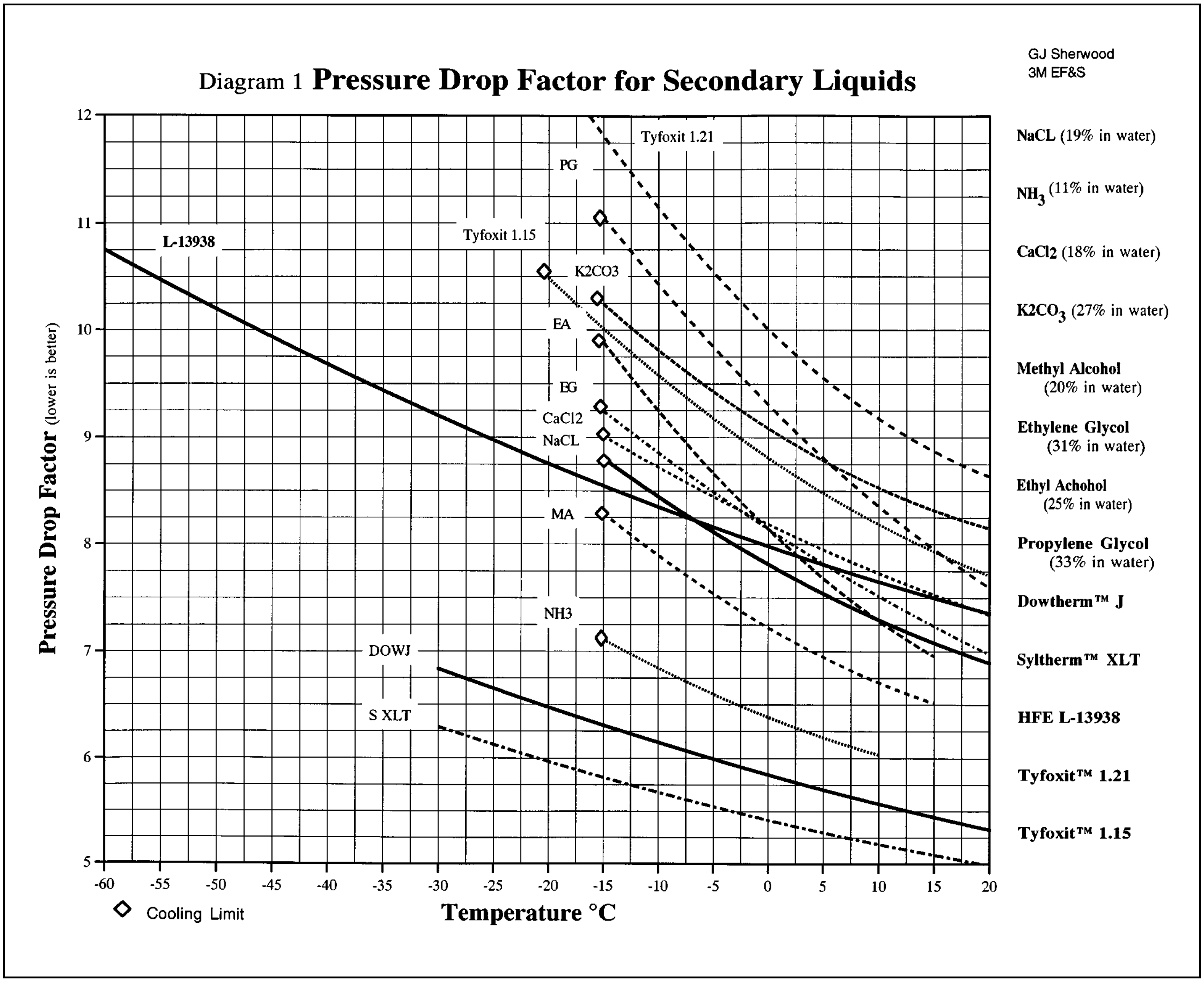
or $$\Delta p_f = f_1 \bullet \rho \bullet V^2 \bullet L \bullet d^{-1} \qquad (1)$$

The coefficient f_1 is calculated by the expression $f_1 = 0.092 \div Re^{0.2}$ where Re is the Reynolds number (Velocity • Diameter ÷ kinematic viscosity)[2]. Flow conditions where the Reynolds number is greater than about 2300 is considered turbulent flow and provides optimum heat transfer between the liquid and the tube wall.

When the pressure drop of several fluids are being compared, it is useful to separate the fluid dependent properties from this equation and combine them into a single factor. Hence, the dimensional information of the tube and the fluid velocity are separated from the fluid property information. The final form of this equation is

$$\Delta p_f = Fp \cdot V^{1.8} \cdot L \cdot d^{-1.2} \text{ where } Fp = 0.092 \cdot \rho \cdot \nu^{0.2} \quad (2)$$

The pressure drop factor, or *Fp,* is a function of the fluid density, ρ, and kinematic viscosity, ν, and is subject to change, as these properties do, with temperature. The pressure drop factor can be plotted against temperature for the fluids of interest to reveal relative differences between the fluids. A lower pressure drop factor relates to reduced frictional loses for the same fluid velocity and tube geometry. A plot of the pressure drop factor for potential secondary liquids is show in Diagram 1.



Heat Transfer Factor, *Fh*

By using the same logic as discussed in the pressure drop factor above, a heat transfer factor can be generated. Heat transfer is a function of the fluid properties and the geometry of the heat transfer surface. In many heat transfer devices, such as heat exchangers, the fluid of interest is flowing through a tube while the desired heat transfer is occurring. Given the fluid properties, tube dimensions, and desired temperature change of the fluid one can calculate the amount of heat that can be transferred into the fluid from the tube. To summarize this in an equation:

$$Q = h \cdot A \cdot \Delta T \quad (3)$$

where Q = Heat transferred
h = heat transfer coefficient
A = area of the heat exchange surface
ΔT = change in temperature of the fluid

The heat transfer coefficient, h, is defined as

$$h = Nu \cdot k \cdot d^{-1} \quad (4)$$

where k = fluid thermal conductivity
d = diameter of the tube
and Nu = the Nusselt number

The Nusselt number is, again, a combination of fluid properties and tube geometry. It can be shown using classic heat transfer relations that by algebraically separating the tube geometry and fluid velocity (assuming turbulent flow, Re > 2300) from the fluid properties, the heat transfer coefficient can be defined as:

$$h = Fh \cdot V^{0.8} \cdot d^{-0.2} \quad (5)$$

where V= fluid velocity
d = tube diameter

and *Fh* is defined as

$$Fh = 0.023 \cdot k^{0.66} \cdot (\rho \cdot c_p)^{0.33} \cdot \nu^{-0.5} \quad (6)$$

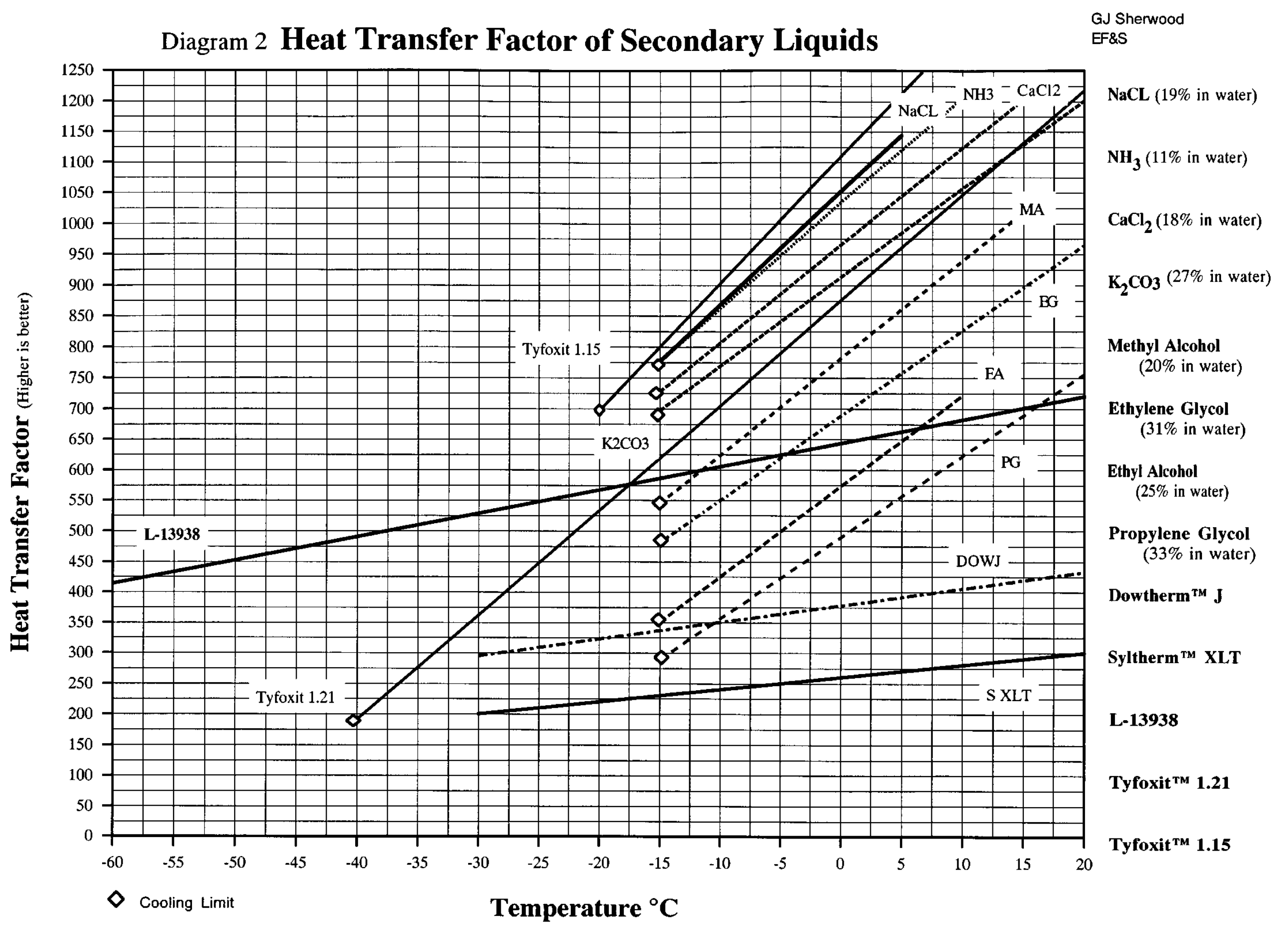
where k = thermal conductivity
ρ = density
c_p = specific heat
ν = kinematic viscosity

In comparing different fluids (given the same velocity, diameter of tube, and temperature change of the liquid during the heat transfer process) a fluid with twice the heat transfer factor of a second fluid can transfer twice the energy of the second fluid. A plot of the heat transfer factors for potential secondary candidates is shown in Diagram 2.

Temperature Difference Factor $F\theta$

The temperature difference factor is a combination of the two previous factors. From this relation, one can determine the temperature rise in the fluid as it passes through a heat exchanger with a specified set of conditions (i.e., a given heat flux, load, pump power, pump efficiency, and tube diameter). The temperature difference factor is multiplied by the given heat exchanger conditions (coupled together using heat transfer relations) to provide a prediction of the temperature difference between the fluid entering and leaving the heat exchanger. The equations are:

Diagram 2 **Heat Transfer Factor of Secondary Liquids**



$$\theta = F\theta \bullet \frac{q^{5/7} \bullet d^{1/7}}{(4 \bullet \eta_p \bullet E_p / Q)^{2/7}} \qquad (7)$$

where θ = Temp. change of the fluid
q = heat flux
d = diameter of tube
η_p = pump efficiency
E_p = pump power
Q = thermal load

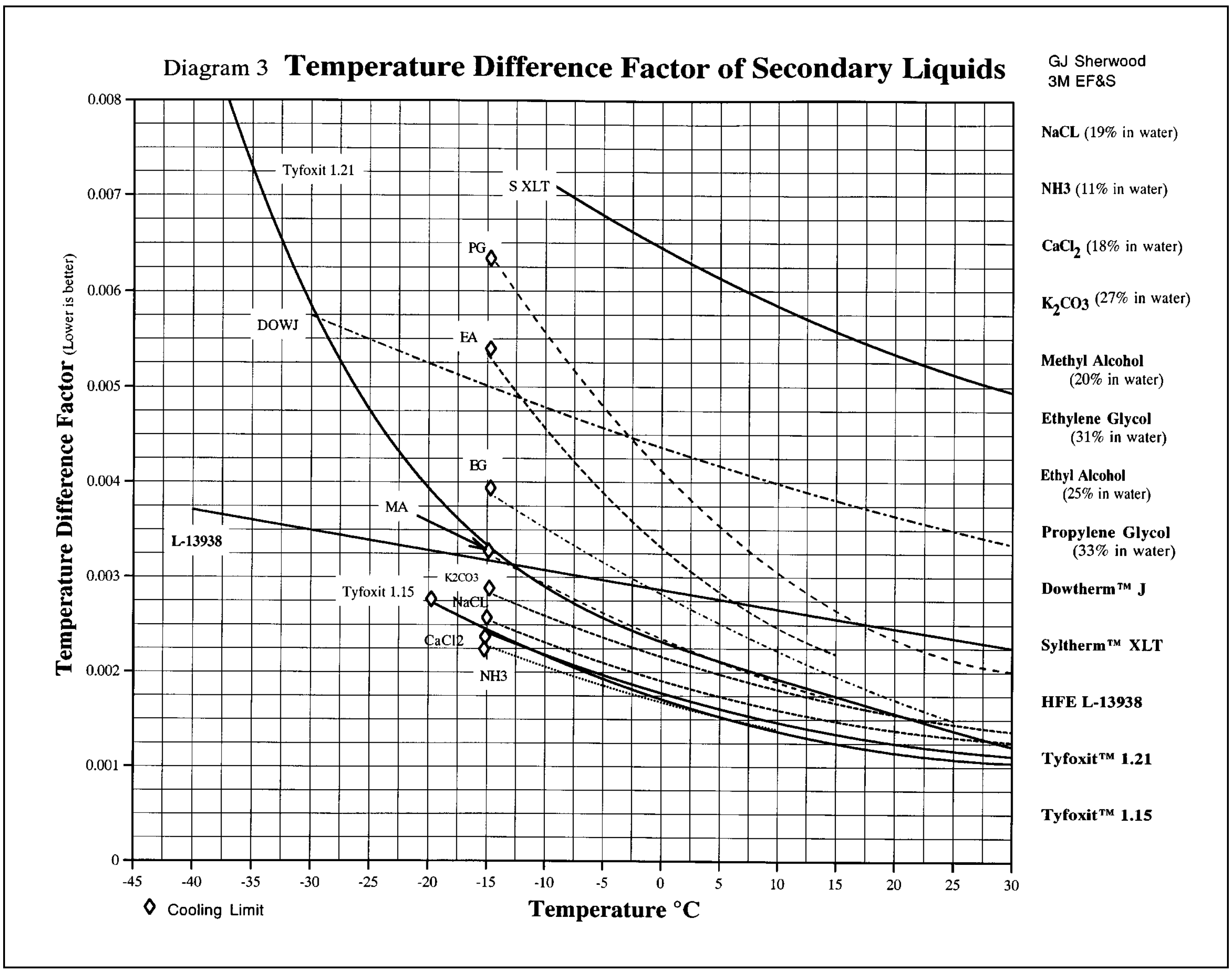
and the temperature difference factor can be shown to be defined as

$$F\theta = \frac{Fp^{2/7}}{Fh} = \frac{(\text{Pressure drop factor})^{2/7}}{\text{Heat transfer factor}} \qquad (8)$$

For secondary heat transfer liquids, it is best to minimize the temperature difference factor. An ideal fluid would have a low Fp (pressure drop factor) and a high Fh (heat transfer factor). Therefore, a lower value temperature difference factor relative to other fluids means the heat is being transferred more efficiently. In other words, for the same amount of energy expended by the pump, the fluid with a lower temperature difference factor transfers the same quantity of heat with a lower change in temperature of the fluid. A plot of the temperature difference factor is shown in Diagram 3.

Graphical Comparisons

The graphical representations of the three factors (Diagrams 1, 2, and 3) include information that is very useful. Starting with the pressure drop factor, one can see the relative losses that occur due to friction. The fluid property that has the greatest effect on this factor is the viscosity and its variation with temperature. A low viscosity means the fluid enters turbulent flow sooner given the same fluid velocity. The frictional forces from the tube wall are translated into the fluid, forcing it to churn and mix. As the viscosity increases with reduced temperature, the frictional forces increase and so does the pressure drop factor. All of the aqueous solutions follow a



nonlinear plot as the temperature drops. The fluids with the least pressure drop are the Dowtherm™ and Syltherm™ heat transfer fluids, primarily due to the combined low viscosity and low density. The HFE L-13938 is surpassed only by these two fluids below -15°C.

The heat transfer curves show a linear fit for all the fluids of interest. The aqueous solutions generally follow the same slope, being shifted by the different freezing point depressants added to the water. Relative to the non-aqueous fluids, the slope of these aqueous curves is quite steep and reveals that their ability to transfer heat drops off rapidly as the operating temperatures of secondary systems is approached. The HFE L-13938 fluid holds the highest value of the heat transfer factor from -20°C and cooler.

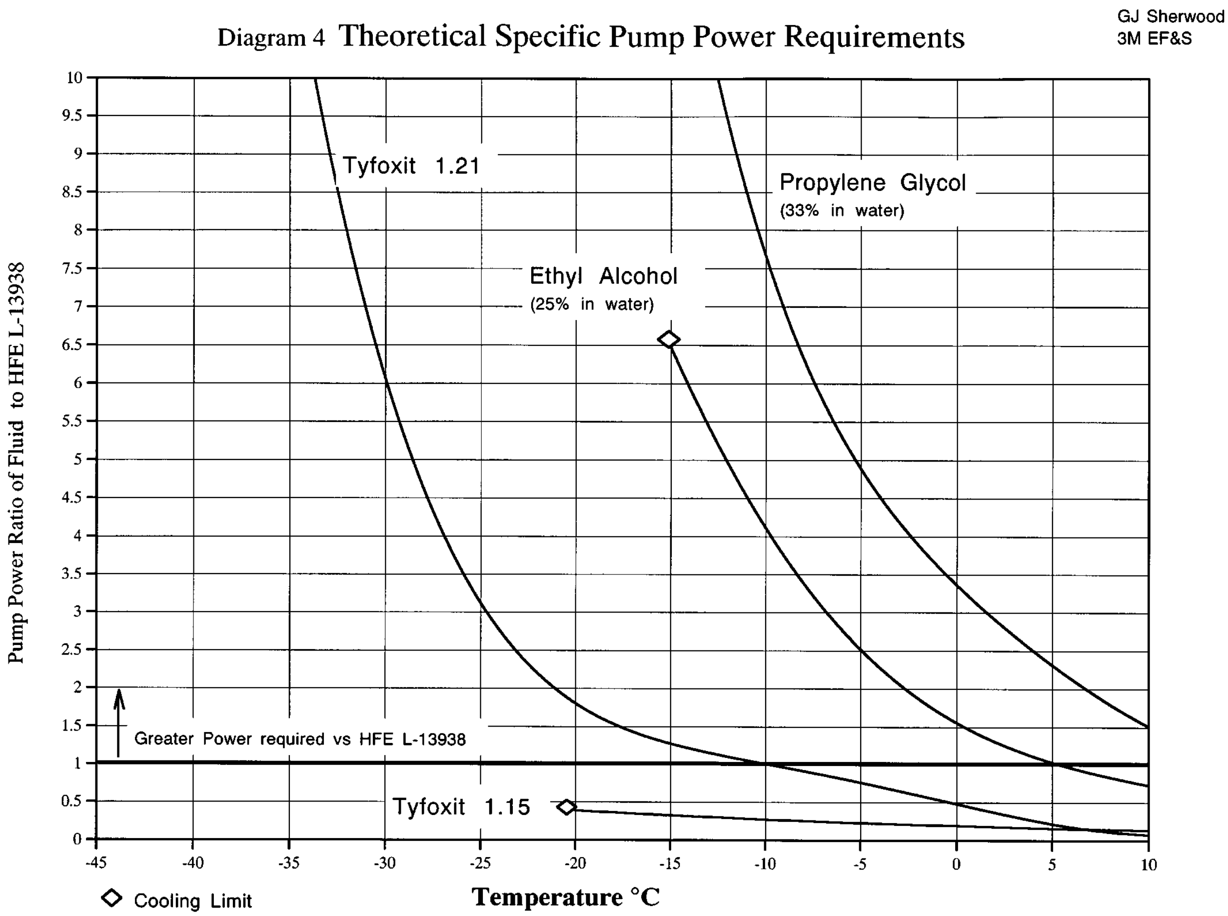
The value of the pressure drop factor is less important than the temperature difference factor. As noted in Equation 8, the pressure drop factor is required to calculate the temperature difference factor, but its value is reduced by raising it to the power of 2/7 during this calculation. The temperature 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. Further analysis of this factor shows that a small difference in the temperature difference factor between two fluids can mean a significant difference in power requirements.

A useful way to compare the performance of different secondary fluids is to solve the temperature difference equation (8) for the pump power, Ep. Then if this relation is used as a ratio for two different fluids, a comparative factor can be obtained for the relative pump power requirements for two different fluids given a fixed temperature rise through the exchanger, heat flux, load, and tube diameter. The result is:

Pump power ratio $$\frac{E_{p1}}{E_{P2}} = \frac{(F_1\vartheta)^{7/2}}{(F_2\vartheta)^{7/2}} \qquad (9)$$

For example, a value for F_1V f 0.006 for fluid 1 and a value for $F_2\vartheta$ of 0.004 for fluid 2 (both taken at the same temperature) yields a pump power ratio of 4.1. This implies that the power required to pump fluid 1 is 4.1 times that of fluid 2 through the specified heat exchanger to transfer the same amount of energy. This is a very useful comparison and brings to light the distinct advantage the HFE material offers. As the temperature difference graph illustrates, L-13938 stands alone as temperatures drop below -20°C.

Diagram 4 Theoretical Specific Pump Power Requirements



A graph of various pumping power ratios is included. A comparison is made between the HFE L-13938 and other selected fluids. Because the pump power requirements are determined by the temperature difference factor raised to the 7/2 power, a small difference between fluids becomes amplified.

Conclusion

Many candidate heat transfer fluids have been analyzed for use in low temperature secondary systems. To effectively compare these fluids, a method of using accepted heat transfer and fluid dynamic correlations has been employed. The resulting factors can be used to make a direct comparison of the expected performance of each of these fluids.

The results of this analysis are displayed on several graphs. Water mixed with a freezing point depressant in this study 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°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.

The hydrofluoroether presented has unique properties that set it apart from the other fluids. It has excellent low temperature heat transfer abilities that result in a much reduced pump power requirement for circulation in a secondary system. The hydrofluoroether is non-corrosive and nonflammable. It has very good toxicological and environmental properties as well, making it a safe, long term solution for secondary heat transfer systems.

Testing of this hydrofluoroether fluid is currently underway at a refrigeration system manufacturer's laboratory for application as a low temperature heat transfer fluid.

References

[1] "Secondary Loop Processes for use in Low Temperature Refrigeration for Supermarkets", Predrag Hrnjak, University of Illinois, 3/25/95

[2] "Secondary refrigerants for indirect refrigeration and heat pump systems", Eric Granryd and Ake Melender, SCANREF, April 1994, pp 14-20

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