UPDATE ON SECONDARY REFRIGERANTS FOR INDIRECT SYSTEMS

Å. Melinder
Dept. of Energy Technology, Div. of Applied Thermodynamics and Refrigeration
The Royal Institute of Technology (KTH), Stockholm, Sweden
E-mail: ake@thermo.kth.se

Abstract

Indirect systems with secondary refrigerants or coolants have in Sweden long been used for ice rinks and heat pumps and are today increasingly used by supermarket chains for cold storage, cooling cabinets and freezers. The secondary refrigerant is then used to transport energy from the cooling object to the evaporator. In an indirect system it is possible to design the primary refrigeration unit in a compact way and with an extremely small refrigerant charge. In order to choose a suitable fluid and for technical calculations of the system there is a need to know the thermophysical properties of the liquid secondary refrigerant. The liquid chosen should give enough freezing security, good transport capabilities, good heat transfer ability and low pressure drop giving small pumping power. This paper includes a comparison of liquids for cooling cabinets and freezers with indirect system in a supermarket. The comparison shows that salt solutions can perform quite well from a thermophysical aspect, also for freezer applications. When choosing secondary fluid, attention should also be given to material compatibility, toxicity, handling security and environmental pollution and we find that no secondary refrigerant is ideal for all types of applications. Much research is today also carried out with phase-changing secondary refrigerants, such as CO_2 and ice-slurry.

1. INTRODUCTION

1.1. Indirect systems

Indirect systems with liquid secondary refrigerants have in Sweden extensively been used for residential heat pumps and ice rinks, and are today increasingly used for cold storage, cooling cabinets of grocery stores and supermarket chains. The liquid secondary refrigerant is used to transport energy from cooling object to the evaporator. Indirect systems have lately found new applications in low temperature refrigeration, such as in freezers of supermarket chains due to the phasing out of CFC refrigerants and an increased awareness that the use of any primary refrigerant should be kept to a minimum.

Indirect systems have several advantages in comparison with direct systems. Factory built units can be used, local construction of primary refrigerant piping can be avoided and installation work can be made in a more simple way. In an indirect system it is possible to design the refrigeration unit in a compact way and with an extremely small refrigerant charge. The magazine "Kyla" reports on one example: A super market near Stockholm converted from direct to indirect system for its "dairy market", cooling cabinets and freezers. The amount of primary refrigerant could be reduced from 523 kg R22 installed in 1973 to 22 kg R404A in 1996 [Skaldeman, Kyla, No. 4, 1996].

An indirect system with a secondary refrigerant circuit introduces the added cost for pump and heat exchanger as well as an added temperature difference. However, as brought out in a recent article in Scan-Ref, in practice the total energy consumption over the year of a well-built indirect system is often lower than of a direct system. [Lindborg (2000)]. With indirect systems there is of course a need to find a suitable secondary fluid. All liquids used have some negative aspects as we will see later. The challenge becomes more difficult to handle with very low temperatures.

Some systems for supermarket chains use separate circuits for cooling cabinets and freezers. In other systems the main secondary refrigerant is used to cool the condenser of the freezer unit and a low-temperature liquid secondary refrigerant is used to keep the freezer cabinets at a right temperature [Arias, J., Lundqvist, P. [1999)].

1.2. Secondary refrigerants

Water solutions of ethylene and propylene glycol, ethyl alcohol and chloride salts have long been used as secondary refrigerants. A number of non-aqueous heat transfer liquids are also used. Some indirect systems today use water solutions of potassium acetate or potassium formate or a mixture of these organic salts. How do these newer products compare with those used for many years? What aspects must be considered when choosing secondary refrigerant?

There are several requirements that have to be fulfilled by an ideal secondary refrigerant. It should possess good thermophysical properties. High values of specific heat and thermal conductivity but low viscosity at the operating temperature are desirable, making it possible: 1st to transport a large refrigerating capacity with small volume flow and small temperature change, 2nd to get high heat transfer coefficients giving small temperature differences in heat exchangers and cooling object and 3rd to get small pressure drop for the system fluid flow so one can use a pump with little power consumption.

When determining which secondary refrigerant to use in a particular application, close attention should also be given to aspects such as corrosion, toxicity, flammability and cost. It is important that the fluid does not give cause to any material problems, is environmentally acceptable, and can be handled without danger. There is a need to examine carefully the product information and safety sheets available for the commercial products. A brief guideline will be given of these aspects for the various types of secondary refrigerants examined.

Much research is today carried out with phase-changing secondary refrigerants such as phase-changing CO_2 and ice-slurry and these technologies will no doubt develop further during the next few years. However, this research is reported on at other IIR-workshops.

1.3. IIR-publication

A publication entitled ”Thermophysical properties of liquid secondary refrigerants” [Melinder (1997)] was published simultaneously by IIR/IIF (English/French) and by the Swedish Society of Refrigeration (English/Swedish). It contains over 90 pages with charts and tables giving freezing point temperature and thermophysical property values such as density, specific heat, thermal conductivity and viscosity for ethylene and propylene glycol, ethyl and methyl alcohol, glycerol, ammonia, potassium carbonate, calcium, magnesium and sodium chloride and potassium acetate. A few non-aqueous heat transfer liquids with low viscosity at low temperatures are included as a comparison.

A number of property dependant ”factors” are introduced and presented in these charts and tables as a help to determine needed volume flow, Reynolds number as well as heat transfer and pressure drop for both turbulent and laminar flow. Property data from the basic tables have been converted into uniform polynom equations. Sets of coefficients, that can be put into computer programs and used for technical calculations of refrigeration systems, are listed in tables for each of the water solutions. (The English/Swedish version contains an Excel program where computer calculations can be made).

2. COMPARISON OF THERMOPHYSICAL ASPECTS

Basic thermophysical properties are introduced and equations are given to help determine refrigerating capacity, volume flow, Reynolds number as well as heat transfer and pressure drop for turbulent and laminar flow.

2.1. Basic thermophysical properties

For technical calculations of refrigeration and heat pump systems and for choice of secondary refrigerant we need to know the concentration and freezing point temperature (or cooling limit) as well as basic thermophysical properties of the liquid, such as density, specific heat, thermal conductivity and viscosity.

The freezing point temperature should be somewhat below the lowest operating temperature of the liquid secondary refrigerant. Water solutions do not freeze to solid ice even if the temperature is lower than the "freezing point" (at which ice crystals may begin to form), except near eutectic concentration. The risk for serious damage due to freezing up of a heat exchanger is therefore small with the aqueous solutions. The liquid used should have enough freezing security, yet not more than needed as a higher concentration of the freezing point depressant additive will mean less water and thereby poorer thermophysical properties (as can be seen by comparing the results from Examples 1 and 2 in 2.6).

The concentration of a certain known solution can be measured by checking the density. High values of specific heat and thermal conductivity are desirable as it contributes to good heat transfer and thereby decreases the temperature difference between liquid and tube wall.

The viscosity is of special importance, since it is inversely proportional to the Reynolds number and hence influences the type of flow that will occur in a heat exchanger, cooling object and also determines the pressure drop. A high viscosity makes it impossible to keep the flow turbulent in a conventional heat exchanger with a reasonable pumping power.

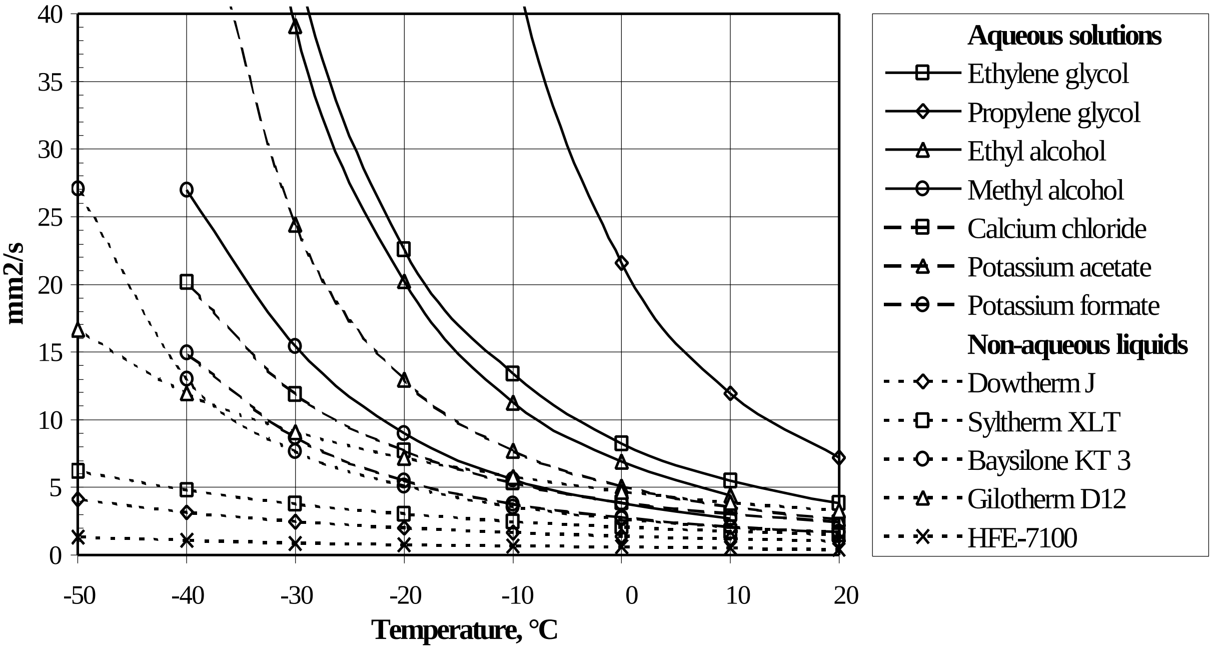

Fig. 1. Kinematic viscosity of a number of liquids (water solutions with t_{fr} = -40°C)

A comparison is in Fig. 1 made of the kinematic viscosity, ν, of the aqueous solutions with concentrations that give t_{fr} = -40°C and some non-aqueous commercial heat transfer liquids. Potassium formate has the lowest viscosity of the water solutions, followed by calcium chloride. But the best non-aqueous liquids have much lower viscosity. Water solutions of the glycols and ethyl alcohol (ethanol) have a very high viscosity at low temperatures, making it impossible to keep the flow turbulent in a conventional freezer cabinet and with some water solutions the flow may not even get turbulent in cooling cabinet applications.

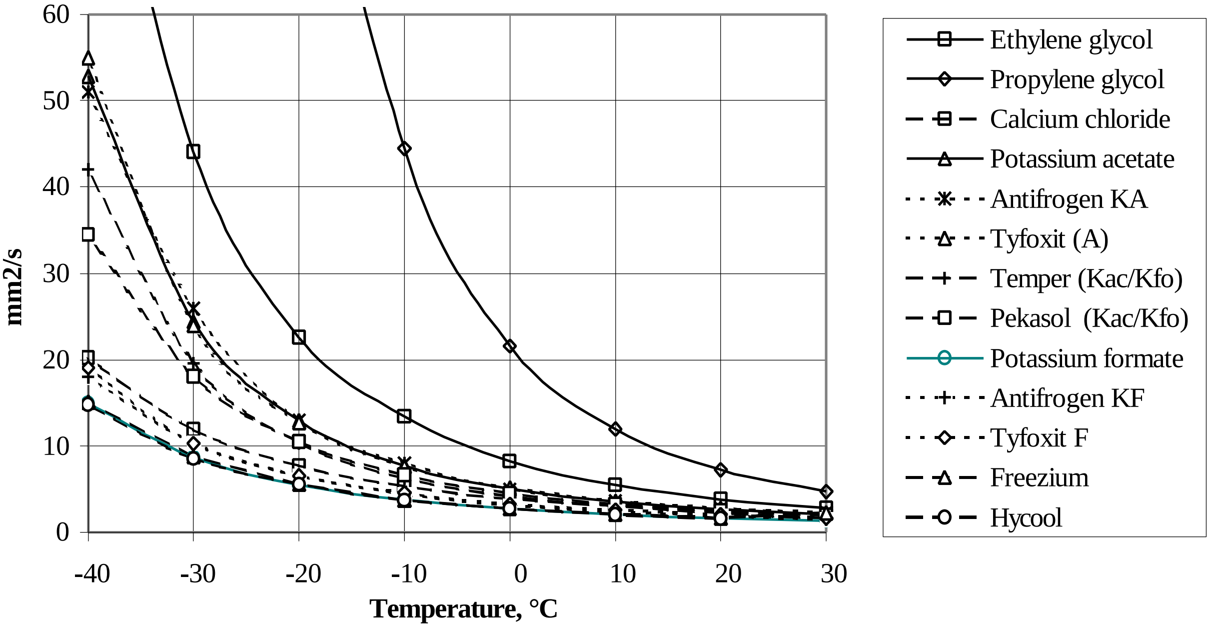

Fig. 2. Kinematic viscosity of some water solutions (with t_{fr} = -40°C)

Fig. 2 incl. a number of commercial products containing organic potassium salts. Temper and Pekasol are mixtures of the potassium salts while the rest are either based on potassium acetate (Antifrogen KA and Tyfoxit A) or formate (Antifrogen KF, Tyfoxit F, Freezium and Hycool). The variation in viscosity of the last four products is mainly because different concentrations of the salt are given for the cooling limit or freezing point, t_{fr} = -40°C.

2.2 Refrigeration capacity and volume flow

The refrigerating capacity, Q [W], that can be transported by means of the fluid with a given volume flow, V [m^3/s], and a given temperature change between fluid entering and exiting the cooling object, $Dt = t_{in} - t_{out}$ [K], is given by the simple relation:

$$Q = (r \cdot c_p) \cdot V \cdot Dt \quad \text{[W]} \tag{1}$$

The refrigerating capacity, Q, is proportional to the volumetric heat capacity, $(r \cdot c_p)$ [kJ/(m^3·K)], the property that characterizes a liquid for its "transport capability". Here r is the fluid density [kg/m^3] and c_p is the specific heat [kJ/(kg·K)].

A comparison is in Fig. 3 made of the volumetric heat capacity, $(r \times c_p)$, of the aqueous solutions with concentrations that give t_{fr} = -40°C and the five non-aqueous liquids that were introduced in Fig 1 (Dowtherm J, Syltherm XLT, Baysilon KT3, Gilotherm D12, HFE-7100).

Note that all aqueous solutions give $(r\times c_{p})$-values that are more than double those of these non-aqueous liquids. Compared to all the water solutions, the non-aqueous liquids require a much larger volume flow and fluid velocity for an application with given refrigeration capacity, temperature change and tube diameter (as we will see also from example 2 in 2.6).

The $(r\times c_{p})$-values of all aqueous solutions differ less than 15%. (Earlier Pekasol data gave higher values but these data have been revised since that was pointed out).

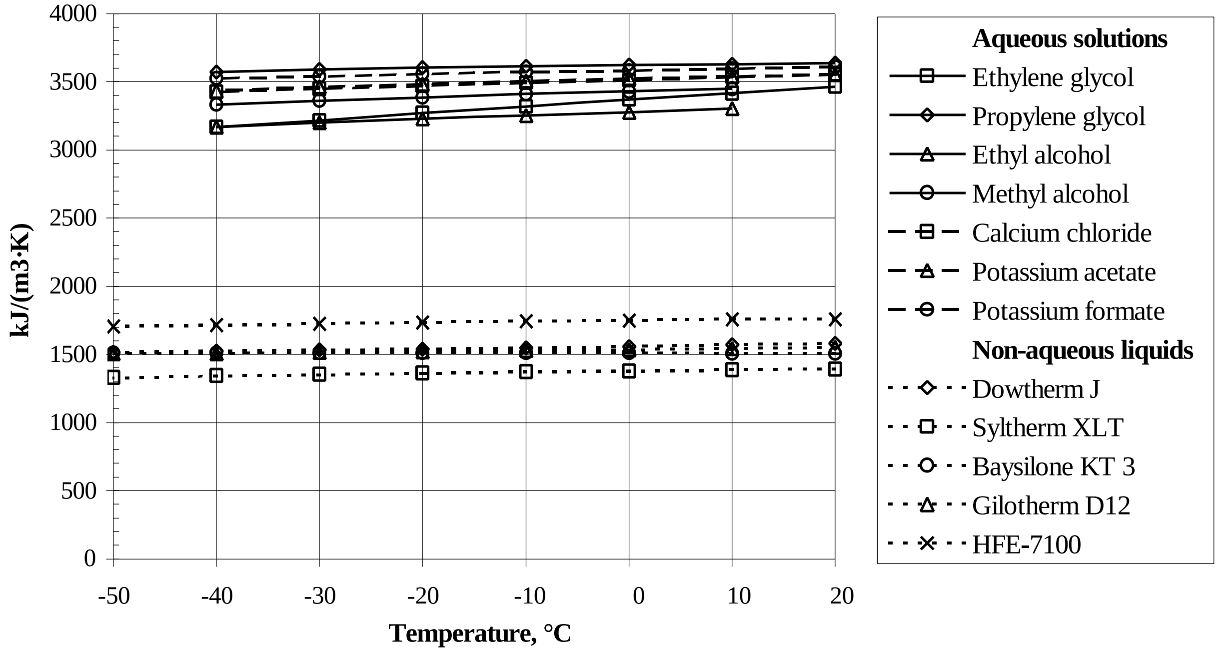

Fig. 2. Volumetric heat capacity of a number of liquids (water solutions with t_{fr} = -40°C)

2.3 Reynolds number and type of flow

The Reynolds number, *Re*, is a good indicator of the type of flow occurring, laminar or turbulent, and can be defined or expressed as $Re = (w\times d)/\nu = 4\cdot V/(p\cdot d\times n)$ [-], where *w* is the fluid flow velocity [m/s], *d* is a characteristic length (tube diameter or hydraulic diameter) [m], ν is the kinematic viscosity [m^2/s] and *V* is the volume flow [m^3/s]. The flow of water will generally be turbulent for *Re* > 2300 - 3000, especially if some form of flow disturbance is used. For lower *Re* number values, the heat transfer coefficient and friction factor decreases rapidly due to transition to laminar flow that usually occurs between 2300 < *Re* < 3000.

Tests made by Kyrk in 1989 with three different water solutions (at temperatures between +10°C and -20°C), in a heated tube section of a loop at our laboratory, confirmed this phenomenon also for these three secondary refrigerants. Temperatures and pressure drop were measured over the section, both with a smooth inlet and with a sharp inlet devise, and values of heat transfer heat transfer coefficient and friction factor were calculated and plotted as a function of the Reynolds number. The results showed that transition to laminar flow occurred between 2300 < *Re* < 3000 with a sharp inlet, while it occurred between 3000 < *Re* < 4000 with a smooth inlet [Melinder, Å., (1998)] and [Granryd, E., etal (1999)].

2.4 Heat transfer

The heat transfer for turbulent flow in circular tubes can be estimated with the equation:

$$Nu = 0{,}023\cdot Re^{0.8}\cdot Pr^{1/3} \quad (\text{for } 10^4 < Re < 2\cdot 10^5) \qquad (2)$$

This equation is based on $f_1 = 0.092 \cdot Re^{0.2}$ by Colburn (1933) and is valid for flow in relatively long smooth tubes and for $10^4 < Re < 2 \cdot 10^5$. Here $Nu = h \cdot d/k$ is the Nusselt number, Re is the Reynolds number (as defined) and $Pr = (m \cdot c_p)/k = (r \cdot n \cdot c_p)/k$ is the Prandtl number. The heat transfer coefficient, h_{turb}, can then be calculated from the following equation where the influence of liquid properties also can be observed:

$$h_{turb} = 0.023 \times k^{2/3} \times (r \times cp)^{1/3} \times n^{(1/3-0.8} \times w^{0.8}/d^{0.2} \quad [\mathrm{W/(m^2 \cdot K)}] \quad (10^4 < \mathrm{Re} < 2 \cdot 10^5) \qquad (3)$$

The heat transfer coefficient h_{turb} can be estimated also into the transition region down to Re = 2300 with a more complex equation by Gnielinski (1976) who uses the friction factor $f = 2 \cdot f_1 = (0.79 \cdot \ln\mathrm{Re} - 1.64)^{-2}$ coupled with the simple relation $h_{turb} = Nu \cdot k/d$:

$$Nu = \frac{(f/8) \cdot (\mathrm{Re} - 1000) \cdot \mathrm{Pr}}{1 + 12.7 \cdot (f/8)^{1/2} \cdot (\mathrm{Pr}^{2/3} - 1)} \qquad (2.3 \cdot 10^3 < \mathrm{Re} < 5 \cdot 10^6) \qquad (4)$$

Heat transfer with laminar flow can be estimated with the following equation where the geometry has a large influence:

$$Nu = 1.86 \times (Re \times Pr)^{1/3} \times (d/L_{\mathrm{str}})^{1/3} \qquad (\mathrm{Re} \leq 2.3 \cdot 10^3) \qquad (5)$$

The heat transfer coefficient for laminar flow, h_{lam}, can be calculated from the following correlation showing the influence of liquid properties, diameter and length of a straight tube:

$$h_{lam} = 1.86 \times k^{2/3} \times (r \times cp)^{1/3} \times [w/(d \times L_{\mathrm{str}})]^{1/3} \quad [\mathrm{W/(m^2 \cdot K)}] \quad (\mathrm{Re} \leq 2.3 \cdot 10^3) \qquad (6)$$

Notice that in this equation the viscosity does not influence h_{lam}. A correction term, $(m/m_w)^{0.14}$, that takes into account the ratio of the fluid viscosity at bulk temperature, m, and at wall temperature, m_w, is sometimes used, but has here been omitted because of rather small temperature difference between the liquid and the tube wall.

The heat transfer coefficient for laminar flow is generally much lower than for turbulent flow. Potassium formate and calcium chloride have in may cases the highest heat transfer values with any of these equations. The best non-aqueous liquids have quite low values but can remain turbulent even at low temperatures when the flow of water solutions is laminar.

The heat transfer coefficient will influence the temperature difference, J_m, between liquid and inner tube wall. This temperature difference, J_m, can be estimated with the basic equation $Q = h \cdot A \cdot J_m$ where $A = p \cdot d_i \cdot L$ for a circular tube. This temperature difference may be too high with laminar flow in circular tubes. How can J_m be reduced? One way used in supermarkets in Sweden is to reduce volume flow in each channel by using parallel circuits (as we will see later in example 3). Other possible ways are to use shorter length of each straight tube, smaller tube diameter or for instance by using rectangular shaped flow channels.

2.5 Pressure drop

The pressure drop due to friction, Dp_f , for flow in a tube can be estimated with the equation $Dp_f = f_1 \times r \times w^2 \times L/d$ [Pa] (in which no consideration is taken for inlet and exit losses or pressure drop in bends and valves etc).

Using the friction factor equations for turbulent flow by Blasius, $f_1 = 0.158 \cdot Re^{0.25}$ (valid for $3 \cdot 10^3 < Re < 10^4$ and used in the examples) and by Colburn (see 2.4) the pressure drop due to friction, $Dp_{f\,turb}$, can be estimated as:

$$Dp_{f\,turb} = 0.158 \times r \times n^{0.25}\, w^{1.75} \times L/d^{1.25} \quad [\mathrm{Pa}] \quad (3 \cdot 10^3 < \mathrm{Re} < 10^4) \qquad (7)$$

$$Dp_{f\ turb} = 0.092 \times r \times n^{0.2}\ w^{1.8} \times L/d^{1.2} \quad \text{[Pa]} \quad (10^4 < \text{Re} < 2 \cdot 10^5) \qquad (8)$$

If the friction factor for laminar flow, $f_l = 32/Re$, is used in the pressure drop equation above, the result is:

$$Dp_{f\ lam} = 32 \times r \times n \times w \times L/d^2 \quad \text{[Pa]} \quad (\text{Re} < 2.3 \cdot 10^3) \qquad (9)$$

The difference in pressure drop between the liquids at turbulent flow is not as great as with the heat transfer, but the best non-aqueous liquids give the lowest pressure drop followed by potassium formate and calcium chloride. The differences in pressure drop for laminar flow are very large at low temperatures, especially propylene glycol gives a very high pressure drop.

2.6. Examples used for comparison of fluids

In the following examples we assume cooling cabinets and freezers with indirect system in a supermarket. In each unit the liquid secondary refrigerant is flowing in copper tubes (that may have fins on the outside with large heat transfer surface). The tubes have a total length *L* = 35 m (9 U-turns) with each straight length 3,25 m and the inside tube diameter *d* = 15 mm.

In the examples in Table 1 and Table 2 the total refrigerating capacity for two parallel tubes is *Q* = 2500 W and the temperature change between fluid entering and exiting the cabinet is *Dt* = 3K. The example in Table 3 has four parallel circuits, each with given dimensions but with *Q* = 2500/4 W. How do the various fluids in the three examples compare as to volume flow and fluid velocity, heat transfer and added temperature difference as well as pressure drop? (The pressure drop from the bends is quite small and is not included in the results.)

Liquid properties chosen: Cooling cabinet application: A comparison is made of all the water solutions, with concentrations giving the freezing point, t_{fr} = -15°C, and at a mean liquid temperature, *t* = -5°C. Freezer application: Some water solutions, with concentrations giving t_{fr} = -40°C and at *t* = -30°C, are compared with two non-aqueous heat transfer liquids.

Liquid symbols: Water solutions: Ethylene glycol, **EG**; Propylene glycol, **PG**; Ethyl alcohol, **EA**; Glycerol, **Glyc**; Potassium carbonate, **K_2CO_3**; Calcium chloride, **$CaCl_2$**; Potassium acetat, **KAc**; Potassium formiat, **KFo**. Non-aqueous liquids: Dowtherm J, **Dow J**; Syltherm XLT, **S XLT**. (Property symbols are given on the next page).

Table 1. Comparing example for cooling cabinet. Aqueous solutions (t_{fr} = -15°C; *t* = -5°C)

Symbols	**EG**	**PG**	**EA**	**Glyc**	**K_2CO_3**	**$CaCl_2$**	**KAc**	**KFo**	**Unit**
$(r \cdot c_p)$	3823	3993	4172	3704	3850	3579	3791	3802	KW/(m^{3}K)
V	0,109	0,104	0,100	0,112	0,108	0,114	0,110	0,110	l/s
w	0,62	0,59	0,57	0,64	0,61	0,65	0,62	0,62	m/s
Re	1800	853	1061	1088	**2709**	**3353**	**2626**	**3928**	-
h_{turb} (3)	840				1320	1474	1225	1549	W/(m^2·K)
h_{turb} (4)	635				**1060**	**1320**	**966**	**1475**	W/(m^2·K)
h_{lam} (6)	**392**	**377**	**380**	**386**					W/(m^2·K)
J_m	1,94	2,01	1,99	1,96	0,72	0,57	0,79	0,51	K
Dpf_{turb} (7)					**0,245**	**0,236**	**0,226**	**0,207**	Bar
Dpf_{lam} (9)	**0,165**	**0,317**	**0,219**	**0,308**					Bar

Property symbols: $(r \cdot c_p)$ = volumetric heat capacity [kW/(m^3·K)]; V = volume flow [m^3/s]; w = fluid flow velocity [m/s]; Re = Reynolds number [-]; h = heat transfer coefficient [W/(m^2·K)]; J_m = temperature difference between liquid and inner tube wall [K]; Dpf = pressure drop due to friction; Index: ***turb / lam*** indicate turbulent / laminar fluid flow; (3) indicate equation the values are based on.

From Table 1 for the cooling cabinet application we note that the values of volumetric heat capacity, volume flow and also fluid velocity are nearly same for all water solutions. All the salt solutions give in this example turbulent flow, ethylene glycol is in the transition region, while propylene glycol, ethyl alcohol and glycerol give laminar flow. The liquids with laminar flow have much lower heat transfer coefficients. This results in larger temperature difference between liquid and inner tube wall that the liquids with turbulent flow. Potassium formate performs best but the differences between the salts are small. Ethylene glycol is in the laminar region and performs less good in this example than the salts. The difference in pressure drop between the liquids is small, even though some liquids give turbulent flow while other give laminar flow.

Table 2. Comparing example for freezer application (two parallel circuits)

	Aqueous solutions (t_{fr} = -40°C; t = -30°C)						**Non-aqueous liquids**		
Symbols	**EG**	**PG**	**EA**	**$CaCl_2$**	**KAc**	**KFo**	**Dow J**	**S XLT**	**Unit**
$(r \cdot c_p)$	3216	3590	3199	3448	3460	3538	1532	1351	kW/(m^3·K)
V	0,130	0,116	0,130	0,121	0,120	0,118	0,272	0,308	l/s
w	0,73	0,66	0,74	0,68	0,68	0,67	1,54	1,75	m/s
Re	250	36	283	861	419	1153	**9234**	**6910**	-
h_{turb} (3)							946	713	W/(m^2·K)
h_{turb} (4)							**963**	**690**	W/(m^2·K)
h_{lam} (6)	**338**	**319**	**299**	**422**	**378**	**399**			W/(m^2·K)
J_m	2,24	2,38	2,53	1,80	2,00	1,90	0,80	1,06	K
Dpf_{turb} (7)							**0,741**	**0,992**	bar
Dpf_{lam} (9)	**1,757**	**9,49**	**1,534**	**0,521**	**1,018**	**0,375**			bar

From Table 2 for freezer applications we find that the values of volumetric heat capacity for all the water solutions are more than double that of the non-aqueous liquids, giving corresponding lower volume flow and fluid velocity. Higher concentrations and lower temperatures give low Reynolds numbers and laminar flow for all water solutions leading to much lower heat transfer coefficients and bigger temperature differences than for the cooling cabinet application. The non-aqueous liquids give high Reynolds numbers and turbulent flow. A temperature difference between liquid and inner tube wall of 3 - 4 K may be rather big as it leads to a correspondingly lower evaporation temperature. Potassium formate and calcium chloride give lowest pressure drop (0.38 and 0.53 bar) while most of the other liquids give much higher pressure drop. The pressure drop of propylene glycol is 9,5 bar, which of course is far too high. What happens when two parallel circuits are used?

Table 3. Comparing example for freezer application (four parallel circuits)

Aqueous solutions (t_{fr} = -40°C; t = -30°C) **Non-aqueous liquids**

Symbols	**EG**	**PG**	**EA**	**$CaCl_2$**	**KAc**	**Kfo**	**Dow J**	**S XLT**	**Unit**
$(r\cdot c_p)$	3216	3590	3199	3448	3460	3538	1532	1351	$KW/(m^3\cdot K)$
V	0,065	0,058	0,065	0,060	0,060	0,059	0,136	0,154	l/s
w	0,37	0,33	0,37	0,34	0,34	0,33	0,77	0,87	m/s
Re	**125**	**18**	**142**	**431**	**210**	**577**	**4617**	**3455**	-
h_{turb} (3)							543	409	$W/(m^2\cdot K)$
h_{turb} (4)							**467**	**316**	$W/(m^2\cdot K)$
h_{lam} (6)	**268**	**253**	**238**	**335**	**300**	**317**			$W/(m^2\cdot K)$
J_m	1,41	1,50	1,60	1,13	1,26	1,20	0,70	0,93	K
Dpf_{turb} (7)							**0,213**	**0,285**	bar
Dpf_{lam} (9)	**0,879**	**4,74**	**0,677**	**0,261**	**0,509**	**0,188**			Bar

From Table 3 we find as expected that the values of volume flow and fluid velocity of all the liquids are only half of those in Table 2. Reynolds numbers and heat transfer coefficients are lower but the temperature differences are smaller in Table 2 for the water solutions because of smaller Q-value in each parallel circuit. The salt solutions in our comparison give a temperature difference between liquid and inner tube wall of 2 K, which may be acceptable. The pressure drop values are only half of those in Table 2. The pressure drop of propylene glycol is still over 2 bar, which is far too high, but the values for the salt solutions are quite reasonable. This example shows that the three salt solutions examined can perform quite well from a thermophysical aspect also for freezer applications.

3. COMPARISON OF GENERAL LIQUID CHARACTERISTICS

Thermophysical properties of secondary refrigerants are very important as already brought out. However, when determining which secondary refrigerant that is to be used in a particular application we also have to take into consideration other aspects such as material compatibility, environmental pollution and toxicity, flammability and handling security as well as cost. It is important that the fluid does not give cause to any material problems by corrosion, is environmentally acceptable, not toxic and can be handled without danger.

All secondary refrigerants seem to have one or more negative sides, as we can note from the following list where some characteristics are listed for each type of liquid. Some commercial products distributed distributed in Sweden (or other parts of Europe) are listed in [xx]:

Water (H2O): Freeze at or just below 0°C. Water (and most aqueous solutions listed below) is corrosive when oxygen is present, if suitable and efficient corrosion inhibitors are not used.

AQUEOUS SOLUTIONS:

Ethylene glycol (EG): Health hazard if consumed (highly toxic for humans); risk of environmental pollution; most commercial products for indirect heat pump and refrigeration systems have good corrosion protection, but that may not be true of glycols for the car industry or of products without corrosion inhibitors. [Commercial products: Antifrogen N (Clariant); Dowcal 10 (Dow); Glyothermin NF (BASF), KB-MEG (Kemetyl); Tyfocor (Tyforop)].

Propylene glycol (PG): Very high viscosity at low temperatures; less toxic than ethylene glycol; risk of environmental pollution; most commercial products for indirect heat pump and refrigeration systems have good corrosion protection. [Commercial products: Antifrogen L (Clariant); Dowcal 20/N (Dow); Glyothermin P44 (BASF); KB-MPG (Kemetyl); Tyfocor (Tyforop)].

Ethyl alcohol (EA): Low boiling point (25-30°C) with flammability risk (consider fire regulations), may cause intoxication if consumed; added as denaturant (in Sweden up to 15% in concentrated product); high viscosity at low temperatures. [Commercial products: KB Etanol (Kemetyl); Svedol KBS (MB Sveda)].

Methyl alcohol (MA): Same as ethyl alcohol, severe health hazard (may cause blindness if consumed); high risk of environmental pollution.

Glycerol (Glyc): Very high viscosity at low temperatures; environmentally friendly. [Commercial product: Biotherm (Binol)].

Potassium carbonate (K2CO3): Rather high pH-value, eutectic point at -37.5°C. [Commercial product: "Pottaska" (Terrawatt Värme)].

Calcium chloride (CaCl2): Highly corrosive with ferrous materials when oxygen is present, rather low pH-value; corrosion inhibitors containing chromates may cause health risk (especially during inhibitor mixing process). [(Brunner Mond; various chemical companies)].

Potassium acetate (KAc): Long term effects not too well known, rather high pH-value. [Commercial products: Antifrogen KA (Clariant); Tyfoxit (Tyforop)].

Potassium formate (KFo): New product. Long term effects not well known yet. Rather high pH-value. Viewed as less toxic than ethylene glycol; [Commercial products: Antifrogen KF (Clariant); Freezium (Kemira); Hycool (Norsk Hydro); Tyfoxit F (Tyforop)].

MIXTURES OF AQUEOUS SOLUTIONS:

Potassium acetate / potassium formate: Long term effects not well known, rather high pH-value. [Commercial products: Pekasol (pro Kühlsole); Temper (Aspen)].

Glycerol / ethyl alcohol: New product for heat pump and cooling applications; long term effects not well known yet; environmentally friendly. [Commercial product: GEM 20 (?)].

NON-AQUEOUS LIQUIDS: The non-aqueous heat transfer liquids have poor ”transport capability” and comparatively poor heat transfer ability. Some of these liquids have low flashpoint, are quite expensive and may have other negative sides. Company information sheets have to be considered closely. [Commercial products considered in [3] and [4]: **Diethylbenzene mixture**: Dowtherm J (DOW Chemicals); **Hydrocarbon mixture**: Gilotherm D12 (Rhône-Poulenc); **Hydrofluoroether**: HFE-7100 (3M Co.); **Polydimethylsiloxan** (silicon oils): Baysilon KT3 (Bayer); Syltherm XLT (DOW Corning); **Terpene from citrus oils**: d-Limonene (Florida Chemicals); **Carbon dioxide** (liquid)].

4. CONCLUSION

Indirect systems in supermarkets work well for cooling cabinets and are an interesting challenge for low temperature freezers. From the cooling cabinet example we see that salt solutions give turbulent flow, while propylene glycol and ethyl alcohol give laminar flow, resulting in lower heat transfer coefficients and larger temperature difference. Potassium formate performs best but the differences between the salts are small. The difference in pressure drop is small.

The given examples show that the water solutions generally will give laminar flow but the salt solutions examined can perform quite well from a thermophysical aspect also for freezer applications. Compared to all the water solutions, the non-aqueous fluids require a much larger volume flow and fluid velocity for an application with given refrigeration capacity and temperature change.

After considering both thermophysical properties and these other general characteristics of the liquids it becomes evident that all liquid secondary refrigerants seem to have one or more negative sides, <u>no secondary refrigerant is ideal for all applications</u>. We should find out which of the different parameters that are especially important in the application we are considering and then try to choose the secondary refrigerant that is best for that particular case. We have to consider company information sheets closely especially when it comes to material compatibility.

NOMENCLATURE

c_p	specific heat [J/(kg·K)]	Dp_f	pressure drop due to friction [Pa]
d	tube diameter [m]	Dt	temperature change [K]
f_1	friction factor [-]	m	dynamic viscosity; $m = n \times r$ [Pa·s]
h	heat transfer coefficient [W/(m^2·K)]	n	kinematic viscosity [m^2/s]
k	thermal conductivity [W/(m·K)]	r	fluid density [kg/m^3]
t	temperature [°C]	J_m	temperature difference [K]
w	fluid flow velocity [m/s]	Nu	Nusselt number; $Nu = a \times d/k$ [-]
A	area [m^2]	Pr	Prandtl number; $Pr = m \times c_p/k$ [-]
L	tube length [m]	Re	Reynolds number; $Re = (w \times d)/\nu$ [-]
Q	refrigerating capacity [W]	*lam*	laminar
V	volume flow [m^3/s]	*turb*	turbulent

REFERENCES

Arias, J., Lundqvist, P., 1999, *Innovative System Design in Supermarkets for the 21st Century*, 20th Int. Congress of Refrigeration, IIF/IIR, Sydney.

Colburn, A.P., 1933, *Trans. AIChE*, **29**, 174.

Gnielinski, V., 1976, *Int. Chem. Eng..*, **16**, 359.

Granryd, E. and Melinder, Å., 1999, *Secondary Refrigerants for indirect systems* , in Refrigerating Engineering, Granryd, E. etal, pp.6:10-11, KTH, Stockholm.

Lindborg, A., 2000, *Rätt utförda Indirekta Kylsystem förbrukar mindre Energi än Direkta*, Scandinavian Refrigeration, Nr.2, 2000, pp.6-8.

Melinder, Å. 1997a, *Thermophysical properties of liquid secondary refrigerants, Tables and Diagrams for the Refrigeration Industry*, Paris, IIF/IIR.

Melinder, Å. 1997b, *Thermophysical properties of liquid secondary refrigerants, Charts and Tables*, Stockholm, Swedish Society of Refrigeration.

Melinder, Å. 1998, *Thermophysical properties of liquid secondary refrigerants, A Critical Review on Literature References and Laboratory Measurements*, KTH, Stockholm.

Skaldeman, S.S., 1996, *Nu kommer indirekt frys*, Kyla, No. 4, 1996, pp.12-15.