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Fluid selection for space thermal control systems

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The selection of a suitable fluid is one of the first and most important steps for the design of a thermal control system. For example, for a heat pipe it is important to use a fluid with a high surface tension and heat of evaporation, and a low viscosity. These characteristics can be combined in a 'figure of Merit'. This figure of Merit is used to pre-select a number of fluids, after which these fluids are further investigated for material compatibility, safety, radiation hardness etc. This systematic approach results in the selection of the most favourable fluid for each application. In this paper, the fluid selections for heat pumps and pumped loops (both single- and two-phase) are discussed. It is explained for instance why CO_2 is used in the thermal control system of AMS02 (which was launched with the space shuttle in May 2011 and subsequently mounted on the International Space Station). Also discussed is the selection of Galden HT80 for ESA's single-phase Mechanically Pumped Fluid Loop (MPFL) and the selection of isopentane for an ESA Heat Pump application.

Nomenclature

ρ = Fluid density (kg/m^3)
μ = Dynamic viscosity (N/m^2 s or kg/(ms))
σ = Surface tension (N/m)
c_p = Specific heat capacity (J/(kg K))
d = Inner diameter tube or axial groove tube (m)
f = Friction factor(-)
h_{lv} = Specific latent heat of vaporization (J/kg)
h = Specific enthalpy (J/kg)
L = Length of tube or axial groove (m)
$\dot{m}$ = Mass flow (kg/s)
N = Number of axial grooves or parallel channels (-)
P = heat input (W)
p = pressure (N/m^2)
Re = Reynold number (-)
v = Fluid velocity (m/s)
$w_{\mathrm{compressor}}$ = Work carried out by the compressor (W)

I. Introduction

Thermal control systems transport heat from a payload to a heat sink (e.g. the radiators of a spacecraft). Most thermal control systems, such a heat pipes and pumped fluid loops, transport heat in the direction of the temperature gradient i.e. from a high to a low temperature. A heat pump can transport heat against a temperature gradient, i.e. from a cold payload to a hot heat sink. For all these different types of systems, it is crucial to select the most suitable

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fluid. However, the number of fluids to choose from is very large. For example, the NIST Reference Fluid Thermodynamic and Transport Properties Database REFPROP[1] contains around 90 different fluids. Since the fluid properties vary with temperature, a fluid that functions very well at a certain temperature may not be suitable at another temperature. This is especially relevant for space applications, since the temperature range in these applications is often very different from the temperature range in terrestrial applications. So how to select the most suitable fluid for an application? In this paper, we present a systematic approach that is used at the NLR. First, selection criteria are defined for the fluid. Possible criteria are 'high heat transport capacity for certain dimensions', or 'low power consumption'. When a criterion is chosen, the equation for the selection criterion is defined. This equation is called the 'figure of Merit'. This figure of Merit is then plotted for all fluids that are available in the REFPROP database with the use of the Matlab application for the Refprop program. In a second step, the fluids with the highest figure of Merit are investigated in more detail. For example, these fluids are investigated on toxicity, flammability, material compatibility, radiation hardness etc.

II. Selection of Fluids with the use of the figure of Merit

In this section, the pre-selection of fluids with the use of the figure of Merit is discussed for heat pipes, two-phase pumped fluid loops, single-phase pumped loops, and heat pumps. First, the figure of Merit for heat pipes is discussed, since this is the most simple figure of Merit, and is often used in literature[2]. The use of the figure of Merit for the other applications is more complex, and seldom used in literature.

A. Heat Pipes

Heat Pipes are capillary driven two-phase heat transfer devices which can transport thermal energy with small temperature gradients[2]. A Heat Pipe consists of a hermetically sealed tube that is vacuumized and then filled with a small amount of fluid. The inside surface of the tube contains a capillary structure (axial grooves or a porous sintered metal) and this capillary structure transports the liquid from the cold end (condenser) to the hot end (evaporator), and provides the pressure to pump the fluid. As the liquid evaporates at the hot side of the heat pipe, a meniscus develops at the liquid surface in the grooves at the evaporating side. This results in a liquid pressure difference between the hot and the cold side, which results in a liquid mass flow from the condenser to the evaporator (and the same vapor mass flow in the opposite direction). In order to function properly, the maximum capillary pressure in a heat pipe must be larger than the sum of all pressure losses in a heat pipe. This is called the capillary limit of a heat pipe (examples of other limits are the sonic limit and the entrainment limit), and this limit is usually the most restrictive for a heat pipe. The liquid pressure drop in an axial grooved heat pipe can be calculated with the Darcy–Weisbach equation:

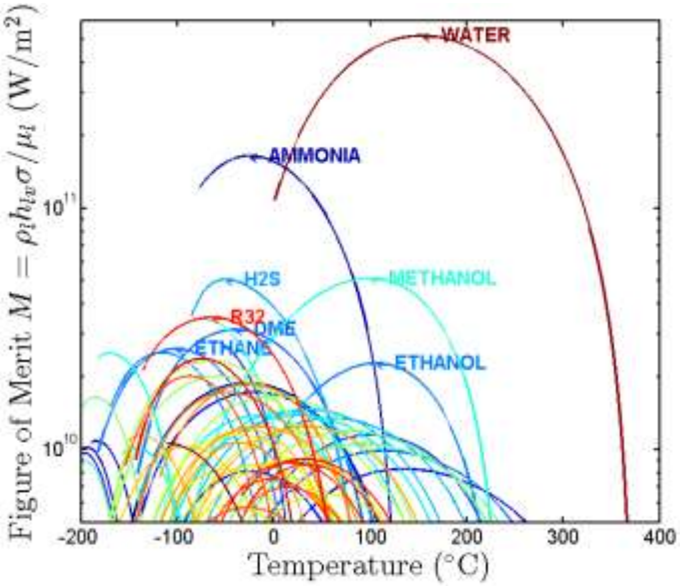

Figure 1 Figure of Merit for a heat pipe for all the fluids in the REFPROP database

$$\Delta p_l = f_l \frac{L}{d}\frac{\rho_l v_l^2}{2} \text{ with } v_l = \frac{\dot{m}}{\rho_l \pi d^2/4} \text{ and } \dot{m} = \frac{P}{h_{lv} N} \quad \textbf{(1)}$$

In the axial grooves of a heat pipe, the flow is laminar, and the friction factor in Eq. (1) can be calculated with:

$$f_l = \frac{64}{\mathrm{Re}_l} \text{ with } \mathrm{Re}_l = \frac{\rho_l d v_l}{\mu_l} \quad \textbf{(2)}$$

The maximum capillary pressure in the grooves is:

$$\Delta p_{\mathrm{cap,max}} = \frac{2\sigma}{d} \quad \textbf{(3)}$$

From the condition that the pressure drop over the axial grooves [Eq. (1)] must be smaller than maximum capillary pressure [Eq. (3)], it follows that the maximum heat input for a heat pipe is proportional to a geometry dependent part and a fluid dependent part:

$$P \propto \frac{d^3 N}{L} \frac{\rho_l h_{lv} \sigma}{\mu_l} \tag{4}$$

The fluid dependent part of Eq. (4) is often called the figure of Merit for heat pipes[2]. Figure 1 shows this figure of Merit for a large number of fluids. The labels for fluids with a low figure of Merit are not shown in order to increase the legibility of the figure. The fluid properties are obtained with the Refprop program [1]. This figure clearly explains why ammonia is most often used as the heat pipe fluid for space applications, and water is most often used for terrestrial applications. Note that the colors of the lines in Figure 1 are only used to distinguish between the different fluids (the fluids are colored according to their alphabetical order).

B. Two-phase pumped cooling system

In a two-phase pumped system, a pump is used to circulate the fluid to an evaporator, where heat from the payload is absorbed while liquid is evaporated. The vapor then flows to a condenser where the vapor is condensed back into liquid. One of the advantages of a two-phase system is that the temperature of the liquid/vapor mixture is the same in the entire system (assuming that the pressure drop is small), and independent of the heat input. This in contrast to a single-phase (e.g. liquid water) cooling system where heat input results in a temperature increase of the liquid. Furthermore, the required mass flow for a two-phase pumped system is much smaller than for a single-phase cooling system, because the heat of evaporation h_{lv} of a fluid is generally much larger than the specific heat capacity of a fluid times the allowed temperature gradient (i.e. $c_p \Delta T$). This results in a much smaller tubing diameter for a two-phase system than for a single phase pumped loop. Because of these reasons, a two-phase pumped system was selected for the thermal control system of the tracker instrument of the Alpha Magnetic Spectrometer (AMS02)[3,4]. AMS02 is a large (8500 kg) space born detector for cosmic rays that was launched with the space shuttle at May 16 2011, and subsequently mounted on the International Space Station. Since this time, the two-phase thermal control system maintains the temperature of the AMS02 well within the requirements. An important requirement for the thermal control system of AMS02 was that the tubing inside the instrument must have a small diameter. However, a small diameter of the tubing results in a large pressure drop, and the available pump only has a limited pressure head. For this reason, an important characteristic of the working fluid for the AMS02 instrument is a small pressure drop for a certain heat transport and geometry. The pressure drop in the liquid and vapour tubes can be calculated with Eq. (1) (where the subscript l is replaced by v for the vapour tubes). The flow in the tubes is turbulent, and the friction factor can be approximated with the Blasius correlation for turbulent flow in smooth-walled tubes:

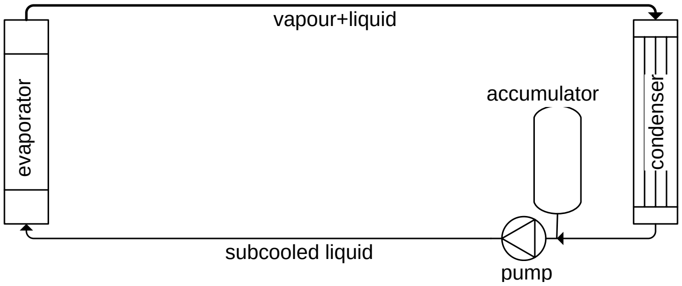

Figure 2 Schematic drawing of a two-phase pumped loop

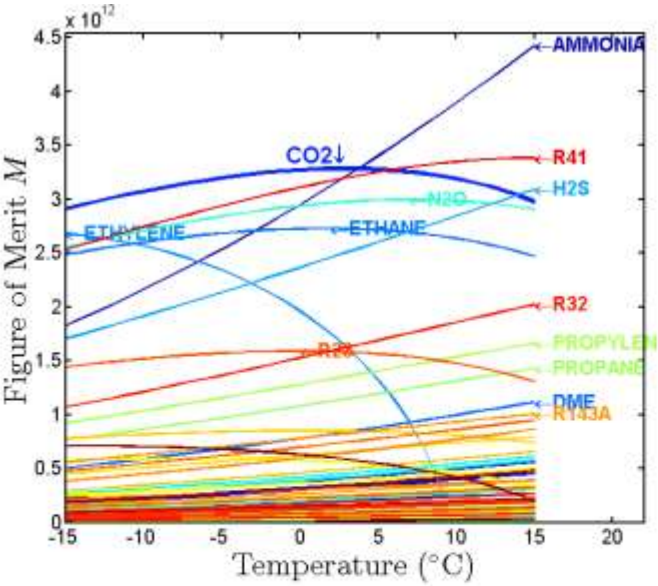

Figure 3 Figure of Merit for a two-phase pumped loop, where the main selection criterium is a low pressure drop

$$f_l = \frac{0.3164}{\mathrm{Re}_l^{0.25}} \tag{5}$$

In order to find a fluid with a small pressure drop, Eq. (1) and Eq. (5) are rearranged to:

$$\Delta p \propto \overbrace{\left(\frac{\mu_l^{1/4}}{\rho_l {h_{lv}}^{7/4}} + \frac{\mu_v^{1/4}}{\rho_v {h_{lv}}^{7/4}}\right)}^{\text{fluid dependant}} \overbrace{\frac{L}{d^{19/4}}}^{\text{geometry dependant}} \overbrace{P^{7/4}}^{\text{Heat input}} \qquad \textbf{(6)}$$

The figure of Merit for the two-phase loop is the inverse of the fluid dependent part of the pressure drop in Eq. (6):

$$M = \frac{1}{\mu_l^{1/4} \big/ (\rho_l {h_{lv}}^{7/4}) + \mu_v^{1/4} \big/ (\rho_v {h_{lv}}^{7/4})} \quad \textit{figure of Merit based on low pressure drop} \qquad \textbf{(7)}$$

Figure 3 shows the figure of Merit for a two-phase loop. CO_2 (R744) has the highest figure of Merit over a large part of the operating range. However, there are a number of fluids with a similar figure of Merit, for example, ammonia (R717), N_2O (R744a), R41 (Fluoromethane), and ethane (R170). Most of these fluids are not commonly used in cooling systems (except ammonia) and would not have been found without the use of the figure of Merit. After a detailed fluid trade-off, CO_2 was chosen as the most suitable fluid for the thermal control system of AMS02, because of its low toxicity, inflammability, excellent radiation hardness, and excellent material compatibility. Furthermore, the ratio between the liquid and vapor density for CO_2 is relative low, and this ensures a ‘smooth’ evaporation process and allows for the use of parallel evaporators[4].

Other criteria for a two-phase pumped cooling system are also possible, for example a low electrical power consumption of the pump. In that case, the figure of Merit would be defined by a small pressure drop and a low volume flow:

$$M = \frac{\rho_l h_{lv}}{\mu_l^{1/4} \big/ (\rho_l {h_{lv}}^{7/4}) + \mu_v^{1/4} \big/ (\rho_v {h_{lv}}^{7/4})} \quad \textit{figure of Merit based on low pump power} \qquad \textbf{(8)}$$

C. Heat Pump

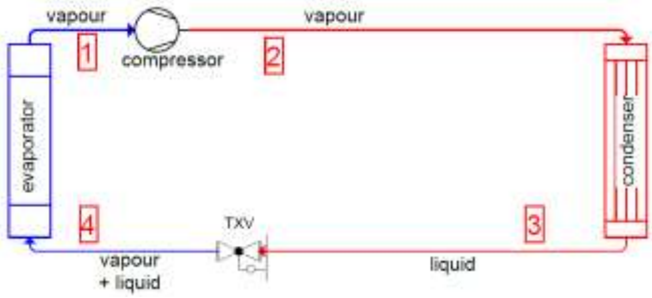

Figure 4 Schematic drawing of a heat pump cycle

In traditional methods for spacecraft thermal control, the radiator temperature must be lower than the payload temperature. A Heat Pump uses a compressor to raise the radiator temperature above the temperature of the payload, which results in a higher heat rejecting capacity compared to a conventional radiator with the same surface area. For this reason, a heat pump for a space application is currently being developed in a project funded by ESA. A Heat Pump consists of a compressor, a heat exchanger at the hot source (i.e. the evaporator), a heat exchanger at the cold sink (i.e. the condenser), and an expansion valve (see Figure 4 for a schematic drawing). In the heat pump cycle, a working fluid enters the compressor as a vapor. The compressor increases the pressure and the temperature of the vapor. The vapor then travels through the condenser, where the vapor is condensed into liquid. The liquid flows through the expansion valve, where the pressure abruptly decreases, causing a partial evaporation of the liquid and a drop in the temperature. The cold liquid-vapor mixture then flows through the evaporator where it absorbs heat and completely turns into vapor before entering the compressor. An example of a heat pump cycle where the temperature is increased from 45 to 100°C is represented in the enthalpy-pressure diagram in Figure 6. There is a difference between the ideal cycle and an actual cycle: In the ideal cycle, the compression process is isentropic, whereas in an actual cycle, the adiabatic efficiency of the compression process is approximately 60%. Furthermore, there is a pressure drop (which is assumed to be 0.4 bar) in the condenser, evaporator and transport lines of an actual heat pump. The difference between the actual and ideal cycle has a significant influence on the fluid selection and must be taken into account.

Defining a figure of Merit for the heat pump fluid selection is relatively complex. One of the most important characteristics of a heat pump is that it has a high Coefficient Of Performance (COP). The COP of a heat pump is the cooling capacity of the heat pump, divided by the power required for the compressor:

$$\mathrm{COP} = \frac{P}{w_{\mathrm{compressor}}} \approx \frac{h_1 - h_4}{h_2 - h_1} \qquad \mathbf{(9)}$$

where the subscripts 1 to 4 refer to the enthalpies at location 1 to 4 in Figure 6. In order to find the most suitable fluid for the heat pump, the COP is calculated for a heat pump cycle for all the fluids in the REFPROP database. In the calculation, it is assumed that the compressor efficiency is 60%, and the pressure drop over the evaporator and condenser is 0.4 bar. Furthermore, the fluid must have a compressor outlet pressure below 14 bar, because of efficiency reasons of the compressor that is used for the project[5]. Figure 5 shows the calculated figure of Merit for a heat pump cycle for which the temperature difference between the evaporator and condenser is 55°C. According to this figure, the most suitable fluids for the heat pump with an evaporator temperature of 45°C are R21, R11, R141b, and R123. However, these fluids are banned or being phased-out according to the Montreal protocol (because of their ozone depletion potential). The next best fluids are R245fa, R245ca, and isopentane (R601a). A detailed analysis of the compressor performance showed that the efficiency of the compressor is higher for isopentane than for the R245 refrigerants, so isopentane was selected for the heat pump application. The flammability of isopentane can be suppressed by blending with 30% molar concentration of R245fa[6].

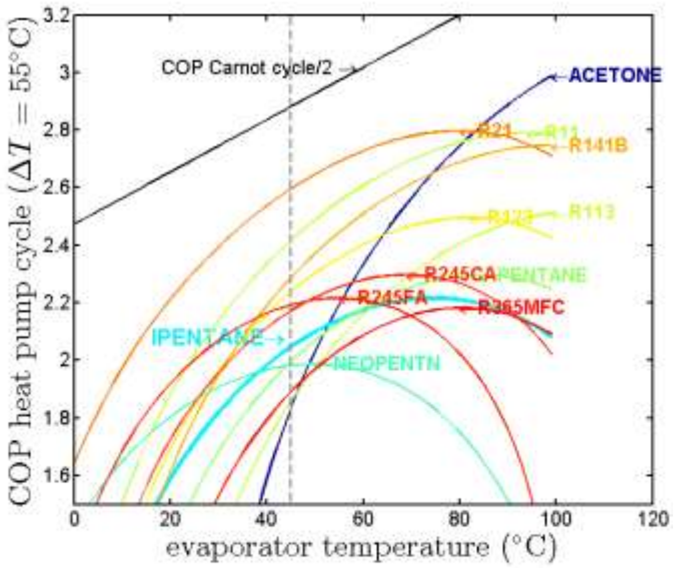

Figure 5 Figure of Merit for a heat pump

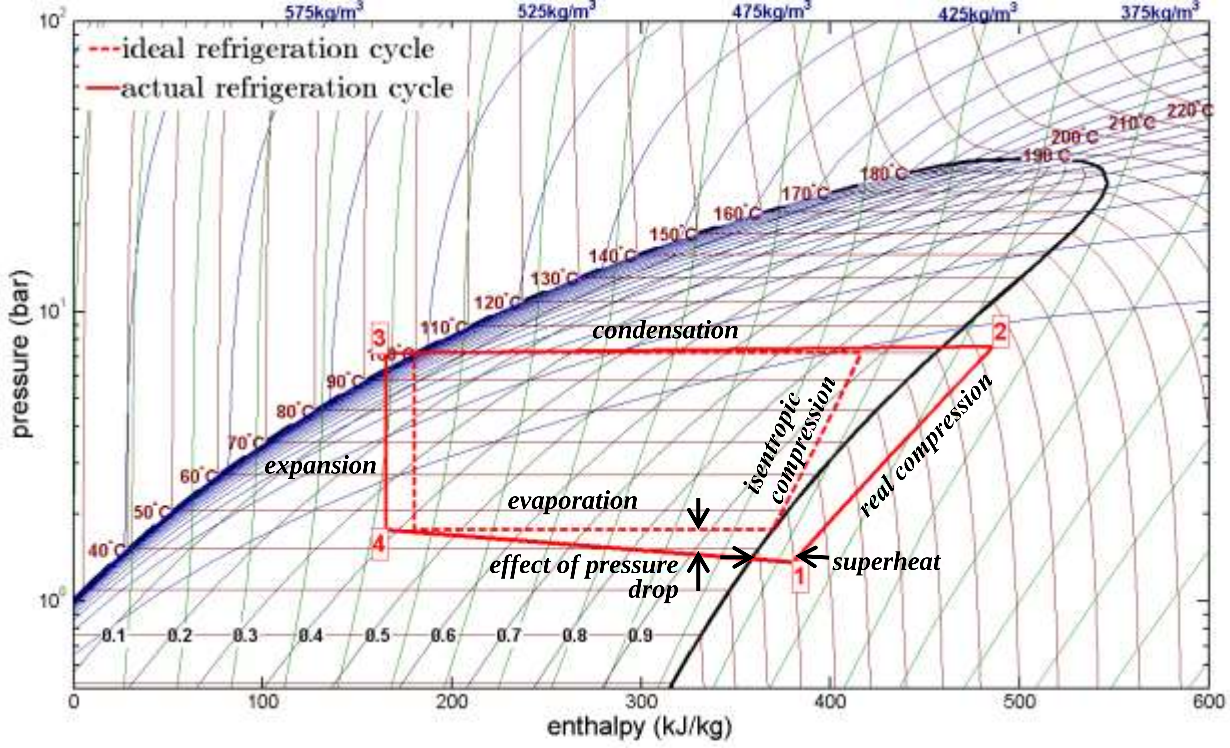

Figure 6 Pressure-Enthalpy diagram of a vapor compression cycle with isopentane (R601a) as refrigerant. The 'skewed dome' in the diagram is the two-phase region, i.e. the fluid in that region is a mixture of liquid and vapor. To the right of the dome, the fluid is vapor, to the left, the fluid is liquid. The green lines in the diagram are isentropic lines, the blue lines are isodensity lines, and the dark red lines are isothermal lines

D. Single-phase pumped cooling system

For the systems discussed in the previous section, the focus was on a single dominant criterion for the fluid selection. However, for the fluid selection for ESA's single-phase Mechanically Pumped Fluid Loop (MPFL[7]), several criteria are important. For example, a very large portion of the total mass of the MPFL is caused by the accumulator, so it is important to select a fluid that does not result in a large accumulator. The following three figures of Merit are defined for the MPFL:

- Minimal pressure drop in the system
- Minimal required pump power
- Minimal size of the accumulator

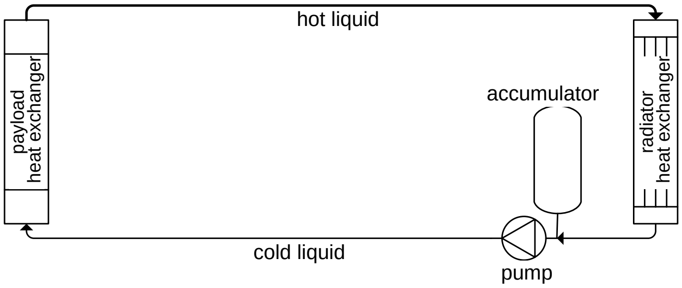

Figure 7 Schematic drawing of a single-phase pumped loop

The calculation of the pressure drop for a single-phase pumped system is similar for a two-phase pumped system, except that only the liquid part is important, and that the heat of evaporation is replaced by the specific heat capacity of the liquid:

$$\Delta p \propto \overbrace{\left(\frac{\mu_l^{1/4}}{\rho_l Cp^{7/4}}\right)}^{\text{fluid dependant}} \overbrace{\frac{L}{d^{19/4}}}^{\text{geometry dependant}} \left.\frac{P^{7/4}}{\Delta T^{7/4}}\right\} \text{Heat input and sensible temperature difference of the fluid} \tag{10}$$

The figure of Merit for minimal pressure drop is the inverse of the fluid dependent part of the pressure drop:

$$M_{\Delta p} = \frac{1}{\mu_l^{1/4} / \left(\rho_l c_p^{7/4}\right)} \quad \textit{figure of Merit based on low pressure drop} \tag{11}$$

The figure of Merit for minimal pump power is based on a small pressure drop and a low volume flow:

$$M_{pump} = \frac{\rho_l c_p}{\mu_l^{1/4} / \left(\rho_l c_p^{7/4}\right)} \quad \textit{figure of Merit based on low power} \tag{12}$$

The temperature range of the MPFL is between -85°C and 100°C. The volume occupied by the liquid at high temperature is higher than at low temperature, and this change in the liquid volume must be accommodated by the accumulator. The figure of merit for the accumulator size is thus:

$$M_{accu} = \frac{\rho_{l\ \text{at}\ 100°\text{C}}}{\rho_{l\ \text{at}\ -85°\text{C}} - \rho_{l\ \text{at}\ 100°\text{C}}} \quad \textit{figure of Merit based on small accumulator size} \tag{13}$$

Table 1 shows the figure of merit for a selection of different fluids. Besides the fluids that are available in Refprop, also some other fluids were included in the analysis, since there are dedicated single-phase cooling fluids commercially available that are not included in the Refprop database. Examples of these fluids are Galden HT80, Coolanol 20, Syltherm XLT, HFE-7500, and FC-87.

fluid	$M_{\Delta p}$	M_{pump}	M_{accu}
Galden HT80	1	1	1
Ammonia	9.7	9.7	0.33
Methanol	2.9	1.9	0.78
Ethanol	2.4	1.6	0.76
DME	3.2	1.8	0.32
Butane	2.7	1.3	0.42
Pentane	2.5	1.2	0.58
Hexane	2.3	1.2	0.67
Heptane	2.2	1.1	0.76

Table 1 Figure of Merits for a single phase loop with 20°C fluid temperature.

From the table, it can be concluded that Galden HT80 performs best on the required accumulator volume. Ammonia performs best on pump power: With the same system, the required pump power is 9.7 times smaller than for Galden HT80. However, ammonia requires a 3 times larger accumulator (although in practice, one would reduce the tubing diameter for ammonia, which results in a smaller accumulator size but higher pump power). Note that, ammonia already freezes at -78°C and the density at -75°C instead of -85°C has been taken to calculate M_{accu}. Methanol has high figures of Merit for all three criteria. According to these figures of Merits, Galden HT80, ammonia, methanol and ethanol are excellent fluids for a single-phase pumped system. After a detailed analysis, Galden HT80 was selected as the fluid for the MPFL because of its low thermal expansion, excellent material compatibility and radiation hardness, and because it has a very low toxicity and flammability.

III. Conclusion

In this paper, ‘figures of Merit’ are used to select the most suitable fluids from the REFPROP database. With this systematic approach, fluids can be selected which would have been overlooked without the use of the figure of Merit. Furthermore, the method offers a large saving in costs and time since the tedious process of finding and analysing possibly suitable fluids can now be carried out with a single push on a button.

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