# Data Center Immersion Coolant Selection Criteria

There are many types of coolants used specifically for immersion cooling IT equipment in data centers. These coolants can be oil-based or fluorocarbons and depending on the properties, may be used in single-phase immersion or two-phase immersion. This article will discuss the main property considerations for coolants used in data center immersion cooling and provide a useful comparison of each chemistry to aid in fluid selection.

When deciding on a coolant to use, the following properties are important [1] [2]:

- **Dielectric Properties** – if the fluid is going to be in direct contact with electronics, it must have sufficient dielectric properties. These include dielectric strength (6 kV/mm minimum per OCP), breakdown voltage, and volume resistivity (2.00 GΩm minimum per OCP).
- **Thermal Performance** – the thermophysical properties, mainly viscosity, thermal conductivity, specific heat capacity, and density need to be accounted for to ensure proper thermal management design. In two-phase, boiling point and latent heat of vaporization also need consideration.
- **Stability** – the fluid adequately maintains its properties under a wide range of conditions. Properties reflective of chemical stability include thermal stability, oxidative stability, and hydrolytic stability. Volatility is a way to assess physical stability and is often cited in single-phase immersion cooling.
- **Safety** – toxicity toward humans and other living things and flammability, notably flashpoint (150°C minimum per OCP) and autoignition point (300°C minimum per OCP) are crucial in fluid selection.
- **Environmental Impact** – biodegradability, global warming potential (GWP), and ozone depletion potential (ODP) are important properties to know when choosing a sustainable coolant. Coolants with high biodegradability, low GWP, and low ODP are more environmentally friendly.
- **Compatibility** – the fluid must have acceptable compatibility with the metals and polymers it will be exposed to, must not interfere with function of mechanical equipment, and must not disrupt signal transmission. Some common materials exposed to immersion coolants include PVC or nitrile clad cables and EPDM, liquid crystal polymer, ptfe and fluoroelastomer connectors and seals.
- **Maintenance and Handling** – fluids vary in their filtration, containment, and PPE requirements. The lifetimes of fluids vary as well, which can affect replacement or top-off frequency. The fluid color and odor can further complicate maintenance and handling procedures.
- **Cost –** price differs significantly and is highly dependent on the base fluid chemistry.

The thermal performance of immersion fluids can be evaluated using figures of merit (FOM). The OCP Base Specification for Immersion Fluids rev1. v1. outlines four FOM: FOM1 (denoted FOM1a) for natural convection of single-phase immersion fluids, FOM2 for forced convection of single-phase immersion fluids, FOM3 for viscosity (as a measure of pressure drop), and FOM4 for the heat transfer effectiveness during pool boiling (the boiling that occurs at the surfaces of submerged components) of two-phase immersion fluids. Incropera 1999 provides

FOMs for natural convection and forced convection (denoted as FOM1b and FOM5, respectively). Simons 2006 also gives a FOM for forced convection under developing laminar flow (FOM6). Table 1 shows the fluid properties of common immersion coolants that were used to determine FOMs for each fluid in Table 2. FOM1a, FOM2, FOM3, and FOM4 have target specifications to adhere to as explained below.

- **FOM1** (natural convection for single-phase immersion) – Natural convection, energy transfer through a fluid without external forces, is the dominant heat transfer mechanism in an immersion tank [3]. Two FOMs are considered here for natural convection.

    a) Natural convection for single-phase immersion [1] – considers fluid properties that affect heat transfer coefficient. A FOM1 score greater than 35 is considered a Tier 1 fluid, and a score greater than 45 is a Tier 2 fluid. Tier 2 fluids provide better heat transfer but may cost more.

$$FOM1_a = k\left(\frac{\beta c_p \rho^2}{\mu k}\right)^n, n = 0.2813$$

    $k$ = thermal conductivity ($W*m^{-1}*K^{-1}$)
    $\beta$ = thermal expansion coefficient ($K^{-1}$)
    $c_p$ = specific heat capacity ($J*kg^{-1}*K^{-1}$)
    $\rho$ = liquid density ($kg*m^{-3}$)
    $\mu$ = dynamic viscosity ($N*s*m^{-2}$)

    b) Natural convection in laminar flow [4] – the values of $m$ depend on the flow regime. For laminar flow, $m$ = 0.25 and for turbulent flow, $m$ = 0.33. Laminar flow ($m$ = 0.25) is applied for this FOM calculation in Table 2.

$$FOM1_b = \frac{k^{1-m}\rho^{2m}c_p^m\beta^m}{\mu^m}$$

- **FOM2** Forced convection for single-phase immersion [1] – Forced convection, energy transfer through a fluid due to motion generated by an external force, occurs by way of pumps in immersion cooling. A FOM2 score greater than 19 is acceptable. FOM2 does not account for the use of heat sinks, which is why fluorocarbons are scored low even though they transport heat well when used with high fin densities. It is equivalent to the heat transfer coefficient in forced convection laminar flow.

$$FOM2 = k\left[\frac{\rho c_p}{k}\right]^{1/3}$$

- **FOM3** Viscosity for pressure drop [1] – Viscosity contributes significantly toward pressure drop, especially in laminar flow (assumed in FOM2), and pressure drop is a major consideration when sizing a pump. The spec target defines a maximum fluid viscosity of 1.5E-2 $N*s*m^{-2}$ (15cP).

- **FOM4** Pool boiling for two-phase immersion [1] – Pool boiling is applicable for two-phase immersion, where the fluid at the heat transfer surface moves due to free convection and the mixing caused by bubble formation and detachment [5]. A score greater than 1.1E6 is acceptable.

$$FOM4 = \sqrt{\rho_g} h_{fg} \left[\sigma g \left(\rho_f - \rho_g\right)\right]^{1/4}$$

$\rho_g$ = vapor density (kg*m$^{-3}$)
$\rho_f$ = liquid density (kg*m$^{-3}$)
$h_{fg}$ = heat of vaporization (J*kg$^{-1}$)
$\sigma$ = surface tension (N*m)
$g$ = gravitational acceleration (9.81 m*s$^{-2}$)

- **FOM5** Forced convection laminar flow [4] – the values of *m* and *n* depend on the flow regime. For laminar fully developed internal flow in a tube, *m* = n = 0. For laminar external flow over a flat surface, m = 0.5 and for turbulent flow, *m* = 0.8. Most values of n range from 0.33 to 0.4. In the case of developing internal laminar flow as is considered for forced convection FOMs in this article, *n* is taken to be 0.33 and *m* is 0.25.

$$FOM5 = \frac{k^{1-n} \rho^m c_p^n}{\mu^{m-n}}$$

- **FOM6** Developing internal laminar flow in heat sink microchannels [6] – the following equation is based on the Mouromtseff number and is applicable to developing laminar flow regimes in microchannels where the thermal length (L/D / RePr) lies between 0.0005 and 0.0013.

$$FOM6 = \frac{k^{0.736} \rho^{0.30} c_p^{0.264}}{\mu^{0.036}}$$

It is important to take a holistic approach when using FOM for heat transfer and the rest of the properties discussed. In natural convection, heat transfer is more dependent on viscosity than in forced convection, as seen by the improvement of more viscous silicone oils and natural esters from FOM1 to FOM2. The flashpoint is important to note for single-phase immersion coolants since oils with higher flashpoints generally have higher viscosities, which will impact FOM comparisons. An example is the biobased renewable hydrocarbon, which has a low viscosity and flashpoint compared to the other hydrocarbon oils listed (PAO, GTL, and white mineral oil), giving it a higher FOM1 than even the PFC. There is not a one-size-fits-all solution and the choice of coolant is largely dependent on equipment compatibility, safety, and cost.

Table 1: Thermophysical Properties of some Data Center Immersion Coolant Chemistries (water is included as a reference).

| | Flash point (°C) | Boiling Point (°C) | Thermal Conductivity (W/m-K) | Thermal Expansion Coefficient (K-1) | Specific Heat (J/kg-K) | Density ($kg/m^3$) | Dynamic Viscosity at 25°C ($N-s/m^2$) | Vapor Density ($kg/m^3$) | Heat of Vaporization (J/kg) | Surface Tension (N/m) |
|---|---|---|---|---|---|---|---|---|---|---|
| Water [7] | | | 0.6178 (40°C) | 2.594E-4 (25°C) | 4183 (25°C) | 997.1 (25°C) | 0.0008905 | | | |
| Polyalphaolefin (Dynalene PAO 2) [8] | 154 | | 0.141 (38°C) | 6.732E-4 | 2203 (40°C) | 798 | 0.00603 | | | |
| Polyalphaolefin (Dynalene PAO 4) [8] | 226 | | 0.150 (38°C) | 6.408E-4 | 2143 (40°C) | 817 | 0.0242 | | | |
| Polyalphaolefin (Dynalene PAO 6) [8] | 239 | | 0.155 (38°C) | 6.282E-4 | 2028 (40°C) | 828 | 0.0491 | | | |
| GTL (Shell S5X) [9] | 198 | | 0.142 (40°C) | 7.00E-4 (20°C) | 2274 | 806 | 0.013 | | | |
| White Mineral Oil (Krystol 70) [10] [11] | 187 | | 0.14 (40°C) | 7.64E-4 | 2220 | 842 | 0.018 | | | |
| Biobased Renewable Hydrocarbon (DC Cooling Biolife 4) [12] [13] | >140 | | 0.14 (40°C) | 7.00E-4 | 2300 | 785 | 0.00392 | | | |
| Silicone Oil (DOWSIL ICL-1000) [14] [15] [4] | 240 | | 0.18 (40°C) | 1E-3 | 2256 (40°C) | 860 (25°C) | 0.0387 | | | |
| Natural Ester (Cargill Naturecool 2000) [16] | 325 | | 0.1644 (20°C) | 7.3066E-4 (20°C) | 2307.6 (60°C) | 920.6 (20°C) | 0.044 | | | |
| Synthetic Ester (MIVOLT DF7) [17] | 194 | | 0.129 (20°C) | 8E-4 (20°C) | 1907 (20°C) | 916 (20°C) | 0.012 | | | |
| Perfluorocarbon (FC-40) [18] | | 165 | 0.065 (25°C) | 12E-4 (25°C) | 1100 (25°C) | 1855 (25°C) | 0.0041 | | | |
| Fluoroketone (Novec 649) [19] [20] | | 49 | 0.059 (25°C) | 18E-4 (25°C) | 1103 (25°C) | 1600 (25°C) | 0.00064 | 15 | 88000 | 0.0108 |
| Hydrofluoroether (Novec 7100) [21] [22] [23] | | 61 | 0.069 (25°C) | 18E-4 (25°C) | 1183 (25°C) | 1510 (25°C) | 0.00058 | 11.2 | 112000 | 0.0136 |
| Hydrofluoroolefin (Opteon 2P50) [24] | | 48.9 | 0.073 (25°C) | | 1090 (25°C) | 1456 (25°C) | 0.00062 | 15.6 | 115000 | 0.011 |

Table 2: FOMs for some Data Center Immersion Coolant Chemistries (water is included as a reference)

| | Water | Dynalene PAO 2 | Dynalene PAO 4 | Dynalene PAO 6 | Shell S5X | Krystol 70 | DC Cooling Biolife 4 | DOWSIL ICL-1000 | Cargill Naturecool 2000 | MIVOLT DF7 | FC-40 | Novec 649 | Novec 7100 | Opteon 2P50 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cooling Method | | Single-Phase | Single-Phase | Single-Phase | Single-Phase | Single-Phase | Single-Phase | Single-Phase | Single-Phase | Single-Phase | Single-Phase | Two-Phase | Two-Phase | Two-Phase |
| FOM1a | 254 | 49.4 | 34.6 | 28.7 | 41.0 | 38.7 | 56.3 | 41.2 | 35.4 | 41.6 | 49.1 | - | - | - |
| FOM1b | 130 | 25.7 | 18.9 | 16.0 | 21.8 | 20.7 | 28.9 | 22.5 | 19.5 | 21.9 | 23.5 | | | |
| FOM2 | 116.8 | 32.7 | 34.0 | 34.3 | 33.3 | 33.2 | 32.8 | 39.8 | 38.6 | 30.7 | 20.5 | - | - | - |
| FOM3 | 8.9E-04 | 6.0E-03 | 2.4E-02 | 4.9E-02 | 1.3E-02 | 1.8E-02 | 3.9E-03 | 3.8E-02 | 4.4E-02 | 1.2E-02 | 4.1E-03 | 6.4E-04 | 5.8E-04 | 6.2E-04 |
| FOM4 | - | - | - | - | - | - | - | - | - | - | - | 1.23E+06 | 1.41E+06 | 1.60E+06 |
| FOM5 | 36.4 | 12.1 | 14.0 | 14.9 | 13.0 | 13.3 | 11.7 | 16.9 | 16.5 | 11.8 | 6.8 | - | - | - |
| FOM6 | 64.799 | 16.102 | 16.027 | 15.837 | 15.925 | 15.682 | 16.374 | 18.563 | 17.735 | 14.761 | 9.901 | - | - | - |

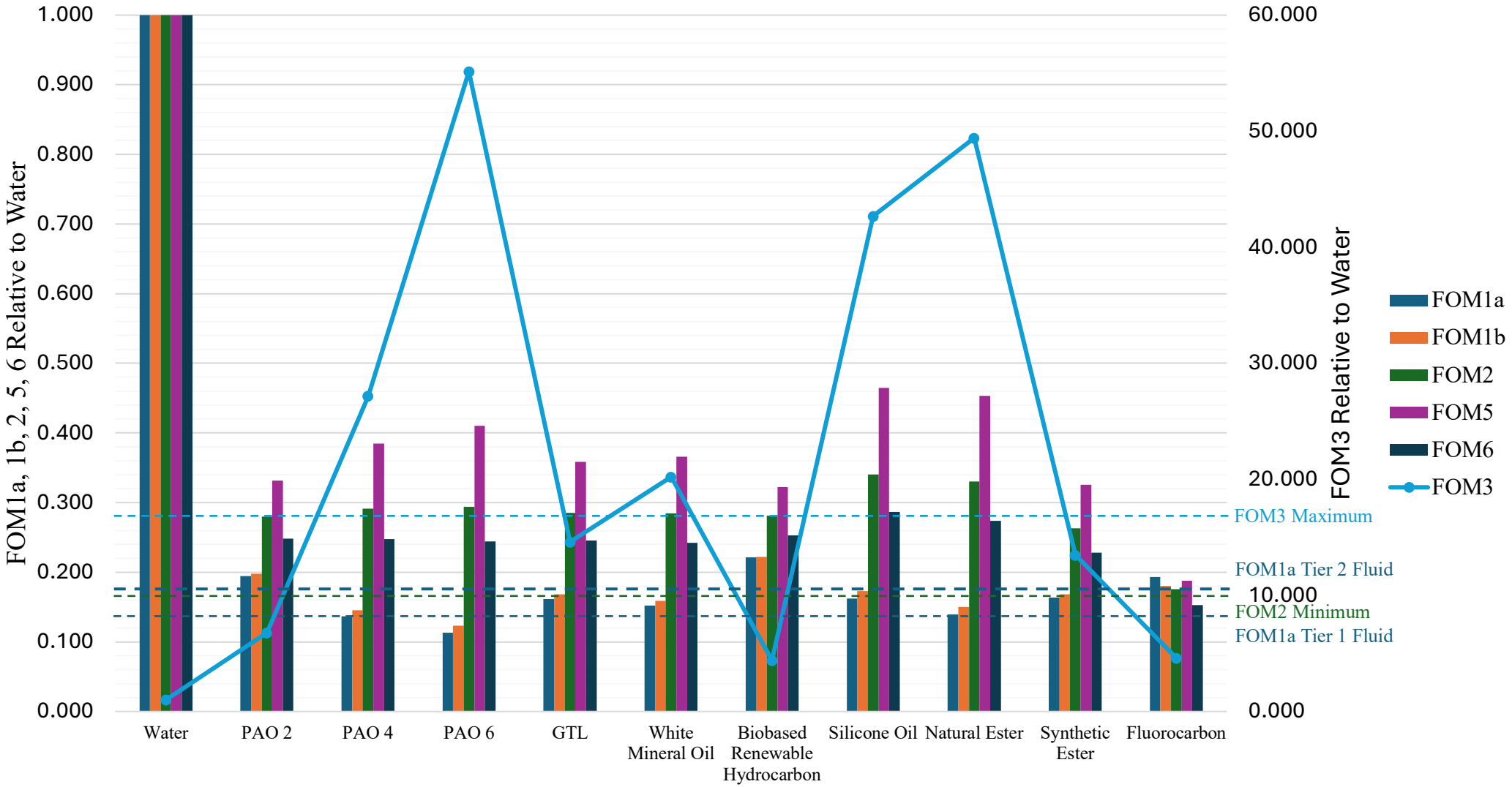



Figure 1: FOMs for single phase immersion coolants relative to water. The colored dashed lines indicate FOM constraints where applicable.

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