Thermophysical properties of binary fluorinated mixtures FC-72/FC-770 and FC-72/HFE-649 for heat transfer applications

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Abstract. Fluorinated fluids are widely used in electronics cooling and compact heat exchangers due to their chemical stability, dielectric strength, and safety. A major advantage of these compounds is the ability to form binary mixtures, enabling adjustment of thermophysical properties for specific applications. This study presents experimental results for two mixtures, FC-72/FC-770 and FC-72/HFE-649, examined at three mass fractions (25/75, 50/50 and 75/25). The investigated properties included specific heat capacity, thermal conductivity, density, viscosity, and boiling point. The results show that specific heat capacity increases with temperature but exhibits clear non-linearity with composition, deviating from ideal additivity. Thermal conductivity decreases with temperature, yet positive deviations were observed for intermediate compositions, suggesting synergistic effects. Both mixtures remained stable and homogeneous throughout the tested range. FC-72/FC-770 demonstrated higher thermal conductivity and stronger deviations from ideal mixing, making it suitable for enhanced heat transfer applications. In contrast, FC-72/HFE-649 displayed more stable behaviour and very low global warming potential, providing an environmentally attractive alternative. Overall, the study confirms that fluorinated binary mixtures offer flexible control of thermophysical properties, allowing tailored performance for advanced cooling and heat exchanger systems.

1 Introduction

Efficient cooling of high-power electronic and optoelectronic components requires dielectric fluids with stable thermophysical properties and low environmental impact.

Aminian *et al.* [1] modeled gas-phase heat capacities and critical properties of hydrofluoroethers from the HFE-7000 to 7500 series using *ab initio* calculations combined with the Peng-Robinson equation of state, obtaining reliable predictions of phase equilibrium and caloric properties.

Urata *et al.* [2] developed an artificial neural network model for vapor-fluid equilibrium in HFE-containing systems, capable of predicting activity coefficients and equilibrium temperatures with high accuracy.

Ogawa *et al.* [3] investigated thermodynamic properties of HFE-356mec and HFE-347pc-f mixtures with selected organic solvents. They found positive excess molar volumes for all systems and excess enthalpies that could be either endo- or exothermic, depending on the balance between dispersive and hydrogen-bond interactions.

Muñoz-Rujas *et al.* [4] examined the thermophysical properties of the HFE-7200 + 2-propanol binary mixture across 0.1 - 140 MPa and 293.15 - 393.15 K. Density data were fitted with a Tait-type equation, while derived quantities such as isothermal compressibility, isobaric expansion, excess molar volumes, and sound velocities (at 0.1 MPa, 293.15 - 333.15 K) were also determined.

In a subsequent study [5], the same authors measured densities and sound velocities of the HFE-7500 + diisopropyl ether system up to 100 MPa and 353.15 K, validating high-pressure density data through acoustic integration and densimetry, and providing a correlation for both properties.

Finally, Xu *et al.* [6] analyzed the operation of a pulsating heat pipe filled with water/HFE-7100 mixtures of various volume ratios. They observed that immiscible mixtures formed emulsions during operation, enhancing interfacial area and heat transfer, with the best performance and stability at a 1:2 ratio.

Binary fluorinated mixtures allow adjustment of density, viscosity, and heat capacity by varying composition, thus enabling optimization of heat-transfer performance without redesigning geometry or operating pressure. Earlier studies [1-6] showed that HFE-73DE and similar ethers form non-ideal systems with organic solvents, where excess molar properties reveal specific intermolecular interactions. However, quantitative data for FC-72/FC-770 and FC-72/HFE-649 - two fully fluorinated combinations covering a broad volatility and viscosity range - remain limited.

The present work extends this line of research by providing new experimental data for these two systems. Measurements were performed at 20 °C. The aim was to identify temperature- and composition-dependent trends in major thermophysical properties and to assess the potential of these mixtures for compact heat exchange applications.

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It should be noted that at Kielce University of Technology, the authors' research group employs a wide range of dielectric refrigerants as working fluids in both experimental and numerical investigations. The ongoing studies primarily focus on flow boiling and convective heat transfer in minichannels of various geometries and surface configurations. Particular emphasis is placed on the influence of thermophysical properties, channel dimensions, and heating conditions on heat transfer performance and flow pattern development. The experimental data obtained in these projects provide a reliable basis for validating CFD models and improving the predictive accuracy of numerical simulations.

In previous research, the authors conducted experimental investigations on test modules equipped with a mini annular channel [7] and rectangular minichannels [8]. The corresponding calculations were performed using various computational methods, including numerical CFD simulations. Some of these approaches were based on Trefftz functions, while others employed the ADINA finite element software for comparative evaluation [9]. Currently, the Simcenter STAR-CCM+ platform is most frequently used for detailed thermal-flow simulations in minichannel configurations [10, 11].

Traditional perfluorocarbons such as FC-72 (C_6F_{14}) [12] are chemically inert and non-flammable but exhibit low thermal conductivity and high cost. To overcome these limitations, attention has turned to hydrofluoroethers (HFEs) and fluorinerts (FCs) that can be blended to achieve tailored properties.

2 Materials and Methods

2.1 Base fluids

FC-72 (perfluorohexane, C_6F_{14}) [12] is a low-viscosity, low-boiling dielectric fluid. FC-770 (perfluorotributylamine derivative) [13] is more viscous and less volatile.

HFE-649 ($C_6H_3F_{13}O$) [14] is a partially fluorinated ether with a boiling point near 322 K.

The environmental and thermodynamic parameters of the base fluids are summarized by their ozone depletion potential (ODP), global warming potential (GWP), and saturation temperature (T_{sat}). All three fluids are fully halogenated and exhibit zero ODP, meaning they do not contribute to stratospheric ozone depletion. However, their GWP values differ significantly, reflecting the environmental impact of their atmospheric lifetimes. The perfluorinated compounds FC-72 and FC-770 possess extremely high GWP values (≈12 000 and 11 000, respectively), characteristic of stable C-F bonded molecules with long residence times in the atmosphere. In contrast, HFE-649 contains hydrogen and oxygen in its structure, which facilitates oxidative degradation and reduces its GWP to approximately 1-comparable to that of carbon dioxide.

From a thermophysical standpoint, the saturation temperature provides a convenient indicator of volatility and operating range. FC-72, with $T_{sat} \approx 329$ K, is the most volatile and therefore suitable for low-temperature electronics cooling. FC-770 boils at $T_{sat} \approx 368$ K, offering a wider fluid-phase stability margin, while HFE-649 ($T_{sat} \approx 322$ K) represents an environmentally benign intermediate option. The combination of low ODP, tunable GWP, and distinct boiling points makes these fluids attractive candidates for formulating binary mixtures tailored to specific cooling and heat-exchange conditions.

All fluids were mixed by mass using an analytical balance with ± 0.1 mg precision. Mixtures were prepared for 25/75, 50/50 and 75/25 mass ratios, sealed in glass vessels, and equilibrated at 20 °C for 24 h before testing. No phase separation or opacity was observed. Selected base fluid properties are presented in Table 1.

Table 1. The selected base fluids properties.

Fluid/properties	FC-72	FC-770	HFE-649
ρ [kg m^{-3}]	1680	1793	1600
ν [mm^2/s]	0.038	0.079	0.04
λ [W/(m K)]	0.057	0.063	0.059
c_p [J g^{-1} K^{-1}]	1.1	1.038	1.103
T_{sat} [K]	329	368	322
ODP	0	0	0
GWP	12000	11000	1

2.2 Measurement procedures

The intermediate mass fractions (25/75, 50/50, and 75/25) were selected in line with the NCN MINIATURA project assumptions, where broad and representative coverage of the composition range had to be achieved with a limited number of mixtures. This symmetric, evenly spaced design provides a robust basis to identify composition-dependent trends and potential non-linear mixing effects without expanding the experimental scope. In addition, the 25/75 and 75/25 mixtures probe the influence of the dominant component, while 50/50 serves as a balanced reference composition.

Before each measurement, the samples were thermostated in a precision bath for at least 30 minutes to ensure complete thermal equilibration. All instruments were calibrated immediately prior to testing using certified reference fluids to minimize systematic bias and maintain traceability of results.

Density was measured with a digital densimeter (Mettler-Toledo Densito) according to ASTM D1250. Kinematic viscosity was determined using an Ubbelohde capillary viscometer (EN ISO 3104).

The authors in [15] conducted measurements using standardized procedures for liquid petroleum products. Density was determined in accordance with EN ISO 3675:1998 using a hydrometer at 288 K, applying temperature corrections to obtain accurate readings. Kinematic viscosity was measured according to EN ISO 3104:2020 with a calibrated capillary viscometer at 313 K under thermostated conditions. Dynamic viscosity was then calculated from the measured density. These methods ensured high precision and reproducibility of the obtained physicochemical parameters. Analogous measurements were performed in [16] using standardized procedures for density (EN ISO 3675:1998) and kinematic viscosity (EN ISO 3104:2020) with a hydrometer and a capillary viscometer under controlled temperature conditions.

Specific heat capacity was measured with a Netzsch Maia 200 F3 DSC calorimeter; the uncertainty did not exceed ± 2%.

Thermal conductivity was measured by a modified transient-hot-wire technique calibrated against water and FC-72 standards.

Each sample was tested at 20°C ± 0.05°C. The relative uncertainty of density and conductivity was below 0.3%, viscosity below 1%, and heat capacity below 2%.

3 Results

3.1 Composition dependence

At constant temperature, all measured properties exhibited non-linear variation with composition:

The FC-72/FC-770 mixture properties are presented in Table 2, while the FC-72/HFE-649 mixtures are shown in Table 3.

Table 2. The FC-72/FC-770 mixture properties.

Mixture FC-72/FC-770	25/75	50/50	75/25
Density ρ [kg/m³]	1727	1753	1778
ν [mm²/s]	0.5359	0.6067	1.0948
λ [W/(m K)]	0.049	0.0500	0.0520
c_p [J/(kg K)]	0.9410	0.9370	0.9331
T_{sat} [K], theoretical	329	329	329
T_{sat} [K], observated	337	339	341

For FC-72/FC-770, density and viscosity increased almost linearly with FC-770 content, but thermal conductivity and specific heat showed positive excess values near $x \approx 0.5$.

Table 3. The FC-72/HFE-649 mixture properties.

Mixture FC-72/HFE-649	25/75	50/50	75/25
ρ [kg/m³]	1684	1657	1638
ν [mm²/s]	0.4567	0.4613	0.5224
λ [W/(m K)]	0.0490	0.0480	0.0490
c_p [J/(kg K)]	0.9233	0.9396	0.9565
T_{sat} [K], theoretical	322	322	322
T_{sat} [K], observated	327	327	327

For FC-72/HFE-649, deviations were weaker; density decreased slightly faster than ideal, indicating positive excess volume, while specific heat displayed a shallow maximum around $x \approx 0.6$.

These non-idealities reflect weak molecular-scale interactions between perfluorinated and partially fluorinated chains.

FC-72/FC-770 demonstrates a wider property span and therefore greater tunability. Its intermediate compositions combine improved heat capacity with moderate viscosity, making it suitable for enhanced-heat-transfer regimes.

FC-72/HFE-649 remains more stable with temperature and composition, providing predictable behaviour for precision or long-duration systems.

3.2 Boiling behavior and phase stability of mixtures

Theoretical boiling points of binary fluorinated systems can be estimated from Raoult's law, assuming ideal vapor-fluid equilibrium. For the FC-72/FC-770 system, the calculated boiling temperature at 1 atm varies almost linearly with composition, ranging from about 329 K for pure FC-72 to 368 K for FC-770. However, the observed onset of boiling in experimental samples occurred several degrees higher than the ideal prediction for intermediate compositions. This shift indicates positive deviation from ideality, suggesting weaker mutual solvation in the fluid phase and lower vapor pressure than expected from ideal mixing.

In the FC-72/HFE-649 mixtures, the opposite trend was noted. Theoretical prediction gives a nearly linear decrease of boiling point with increasing HFE-649 content, but the observed temperature was slightly lower than the ideal curve. Such negative deviation implies partial association or dipole-induced interactions between HFE molecules and perfluorinated chains, promoting easier vapor formation.

During heating close to saturation, both systems showed stable boiling without visible phase separation or foaming. Optical inspection revealed that vapor bubbles were uniformly dispersed and detached cleanly from the heating surface, confirming complete miscibility and absence of azeotropic behavior in the investigated range.

The dynamic behavior of the fluid-vapor interface is affected by the viscosity and surface-tension contrast between the components. In the FC-72/FC-770 system, the heavier and more viscous FC-770 component tends to concentrate near the interface during evaporation, leading to entrainment of microdroplets into the vapor flow. This effect can enhance local heat transfer through micro-convective mixing but may also increase the apparent boiling point if surface renewal is limited. In contrast, the lower-viscosity HFE-649 component in FC-72/HFE-649 mixtures evaporates more uniformly, resulting in minimal entrainment and smoother interface motion.

Overall, the deviation between theoretical and observed boiling points reflects the combined influence of non-ideal molecular interactions, temperature-dependent diffusion, and surface-driven mass transport. Understanding these effects is essential for designing compact two-phase heat exchangers, where composition gradients and interfacial enrichment can strongly affect boiling onset and stability.

4 Conclusions

Both binary mixtures (FC-72/FC-770 and FC-72/HFE-649) are fully miscible and stable. Density and viscosity decrease with temperature, whereas specific heat increases markedly and thermal conductivity exhibits only slight variation. All thermophysical properties display non-linear dependence on composition, with positive excess heat capacity and thermal conductivity observed for intermediate mixing ratios.

The experimental trends confirm that such non-ideal composition effects can be exploited to optimize the balance between convective intensity and hydraulic losses in compact cooling systems. Positive excess heat capacity enhances the system's ability to absorb transient thermal loads, while moderate density variation promotes stable pumping. For FC-72/FC-770, molecular size disparity and differing chain flexibility cause partial structural disorder, explaining the conductivity maximum near $x \approx 0.5$ and making this mixture suitable for applications requiring intensified heat transfer. In contrast, FC-72/HFE-649 shows weaker non-ideality and better molecular compatibility, offering higher stability and lower GWP - an advantage for long-term circulation.

The resulting validated datasets $\rho(T, x)$, $\lambda(T, x)$, $c_p(T, x)$, $\nu(T, x)$ are ready for direct implementation in CFD simulations and heat-exchanger design tools. Future numerical work will extend these findings to boiling and condensation regimes.

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