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ANALYSIS OF THE THERMOPHYSICAL PROPERTIES, ENERGY EFFICIENCY AND ENVIRONMENTAL SAFETY OF HEAT TRANSFER FLUIDS FOR SOLAR COLLECTOR CIRCULATION CIRCUITS

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Abstract. *An analysis of the thermophysical properties of heat transfer fluids used in domestic solar systems for hot water supply has been carried out. Water, aqueous solutions of propylene glycol, ethanol solutions of various concentrations, organic oils and nanofluids have been considered. Comparative data on the heat capacity, thermal conductivity, viscosity, and density of working fluids are presented in tables and graphs. The advantages and disadvantages of each fluid are highlighted. The feasibility of using alcohol solutions as a promising budget option is substantiated, as well as the possibility of using nanofluids to improve the energy efficiency of solar collectors.*

Key words: *heat transfer fluids, HTF, thermophysical properties, solar collectors, heat capacity, thermal conductivity, working fluids.*

Introduction.

Modern solar systems for converting solar energy into heat are developing amid a global transition to renewable energy sources. Their application covers domestic, municipal and industrial needs: from water heating to supporting technological processes. The efficiency of solar collectors depends largely not only on design solutions and the intensity of solar radiation, but also on the choice of heat transfer fluid.

The thermophysical parameters of a fluid determine the system's ability to transport energy efficiently. Choosing an unsuitable heat transfer fluid can lead to increased heat loss, deposit formation, pipe corrosion, or equipment failure at low temperatures. The optimal choice of heat transfer fluid determines the efficiency of the collector, the stability of heat transfer, and the durability of the system [5, 9, 11, 12]. In this context, a comparative analysis of different groups of heat transfer fluids (HTF)

is a relevant task for research and practice.

For maximum efficiency, heat transfer fluids must combine the following properties [2, 5, 10]: high heat capacity and thermal conductivity, low viscosity to minimise hydraulic losses, resistance to high temperatures and freeze/thaw cycles, chemical inertness; availability and economic feasibility; safety for human health and the environment.

Taking into account all requirements for heat transfer fluids, the following substances were selected for study: water [10, 12], propylene glycol [2, 10, 12], ethanol solutions (10% - 40%) [4, 11], mineral oils [7], nanofluids (water + 1% Al_2O_3) [5, 9, 13].

This list is limited primarily by environmental characteristics; in particular, it does not include highly toxic ethylene glycol and environmentally problematic fluorocarbons. Methanol solutions are also rejected due to their toxicity. $CaCl_2$ and NaCl salts are not considered due to their strong corrosive activity on steel, copper and aluminium used in manifolds. This makes them unsuitable for most modern systems without special anti-corrosion coatings. In addition, salt precipitation is possible during heating, which reduces heat transfer efficiency and can lead to pipe blockages. Furthermore, salt solution leaks can have a negative impact on soil and water.

The aim of the work is to conduct a comparative analysis of the thermophysical properties, energy efficiency and safety of heat transfer fluids for both the environment and solar system materials over a wide range of operating temperatures.

Main text.

Based on the analysis of a number of literary sources and reference books [1–13], basic information was prepared on the main thermophysical characteristics of the liquids selected for study at 20 °C (Table 1).

Analysis of Table 1 shows that, from the point of view of thermophysics and energy efficiency, the best heat transfer medium under normal conditions is water, which has maximum heat capacity, high thermal conductivity and low viscosity. If distilled water is used, the heat capacity will be 1–2% higher due to the absence of salts and ions that reduce the mobility of molecules.

Table 1 - The thermal properties of HTF

Heat transfer fluid	Heat capacity, kJ/kg·K	Thermal conductivity, W/m·K	Viscosity, mPa·s	Density, kg/m³
Вода	4.18	0.60	1	998
Пропіленгліколь 50%	3.3	0.39	5	1040
Етанол 10%	3.9	0.57	1.6	975
Етанол 20%	3.65	0.54	1.9	960
Етанол 30%	3.4	0.50	2.2	945
Етанол 40%	3.15	0.46	2.6	930
Мінеральне масло	1.8	0.13	30–50	870
Нанофлюїд (вода + 1% Al_2O_3)	4.0	0,65	1.2	1010

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The thermal conductivity of distilled water is also 2–5% higher, which makes it more efficient as a heat transfer fluid. Adding 1% Al_2O_3 nanoparticles to water leads to a slight increase in viscosity and a decrease in heat capacity, but improves thermal conductivity, making nanofluids a promising heat transfer fluid. Adding ethanol to water leads to a deterioration in its thermophysical properties: as the alcohol content increases, the heat capacity and thermal conductivity decrease, and the viscosity increases slightly. At the same time, compared to propylene glycol, which is currently the most popular heat transfer fluid for solar collectors, alcohol solutions (water-ethanol, 10–40%) have lower viscosity, higher thermal conductivity and heat capacity, and good biodegradability, which makes them potentially more efficient and environmentally friendly.

Let us consider the temperature limitations for the use of each fluid, assuming stable operation of the heat transfer medium in the system.

The minimum operating temperature will be the freezing point, and the maximum temperature is the temperature at which the working fluid can be used without intense evaporation (for water, alcohol solutions), boiling (for glycol mixtures), chemical degradation (for organic oils and glycols), or loss of stability (for nanofluids).

Based on the analysis of literary sources [1, 7, 8, 9, 12, 13], a table with operating temperature ranges for potential heat transfer fluids has been compiled (Table 2).

At the same time, the boiling point of pure ethyl alcohol is significantly lower – about 78°C, which can lead to its partial evaporation before the solution begins to boil.

Table 2 – Operating temperature range of HTF

Heat transfer fluid	Minimum temperature, °C	Maximum temperature, °C
Water	0	100
Propylene glycol 50%	–25	120
Ethanol 10%	–4	95
Ethanol 20%	–9	95
Ethanol 30%	–15	95
Ethanol 40%	–23	95
Mineral oil	–15	250-350
Nanofluid (water + 1% Al_2O_3)	~0	100

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Laboratory studies conducted by the authors on ethanol solutions in distilled water with concentrations ranging from 10 to 40% showed deviations in the freezing point from the theoretical values of the table 2. In particular, a 10% solution placed in a glass test tube in a freezer froze only at -15°C. Prolonged observation of this solution at a temperature of -9 °C did not reveal even the formation of initial crystallisation centres, which indicates the relevance of further research in this direction and the possible expansion of the temperature range of application of alcohol solutions. Freezing samples of tap and distilled water showed different ice structures: in tap water, the crystals were evenly distributed throughout the volume, while in distilled water, a clearly defined centre was observed, indicating a difference in the crystallisation processes, which may affect their permissible operating temperature thresholds and requires further practical research.

In the circulation circuits of solar systems that are operated throughout the year, the actual temperature can vary within a fairly wide range from -30 to +200 °C, so it is important to analyse the change in the properties of heat transfer fluids in this range. To find the values of the main parameters, we will use data at +20 °C and approximation formulas for calculation according to the nature of their dependence on temperature.

Thermal conductivity decreases linearly with increasing temperature due to the increase in intermolecular distance and the decrease in effective energy transfer. Therefore, we accept a simple approximation formula:

$$\lambda(t)= \lambda_{20}[1+\alpha_\lambda \cdot(t-20)], \quad (1)$$

where λ_{20} is the theoretical value of thermal conductivity at 20 °C given in table 1;

α_λ is the temperature coefficient of thermal conductivity change, 1/K.

The density of liquids also decreases almost linearly with increasing temperature due to thermal expansion. Accordingly, a similar relationship can be used:

$$\rho(t)=\rho_{20}[1+\alpha_\rho\cdot(t-20)], \quad (2)$$

where ρ_{20} is the theoretical value of thermal conductivity at 20°C given in table 1;

α_ρ is the temperature coefficient of density change, 1/(kg/m^3).

The specific heat capacity of liquids increases almost linearly with temperature, which is associated with the activation of the vibrational and rotational degrees of freedom of molecules. Therefore, we can also accept the formula with sufficient accuracy:

$$c_p(t)=c_{p,20}[1+\alpha_{cp}\cdot(t-20)], \quad (3)$$

where $c_{p,20}$ is the theoretical thermal conductivity value at 20 °C given in table 1;

α_{cp} is the temperature coefficient of specific heat capacity change, 1/(kJ/kg·K).

Based on the Arrhenius model, viscosity decreases exponentially when heated according to the following relationship:

$$\mu(t)=\mu_{20}\cdot e^{-\beta\mu\cdot(t-20)}. \quad (4)$$

The results of the calculations are presented in the form of graphs (Figure1-4).

As can be seen from the graph (Figure1), at higher temperatures, the difference between the thermal conductivity values of different HTF decreases, with nanofluids and water being the clear leaders (0.65 and 0.6 W/m·K at 20 °C, respectively), propylene glycol being significantly lower, and mineral oil being the lowest. At the same time, thermal conductivity is a key factor for effective heat transfer in the collector. Thus, nanofluids with consistently high thermal conductivity values (~10% higher than water) are promising for intensifying heat exchange processes. The use of mineral oils with $\lambda\approx0.13$ W/m·K does not satisfy the criterion of energy efficiency.

Analysis of the graphs showing changes in density and heat capacity (Figures 2 and 3) shows that there is a stable, slight difference between the parameters of HTF in different temperature ranges, with only mineral oil standing out with significantly lower values. Propylene glycol is predicted to have the highest density. Ethanol

solutions become lighter as their concentration increases.

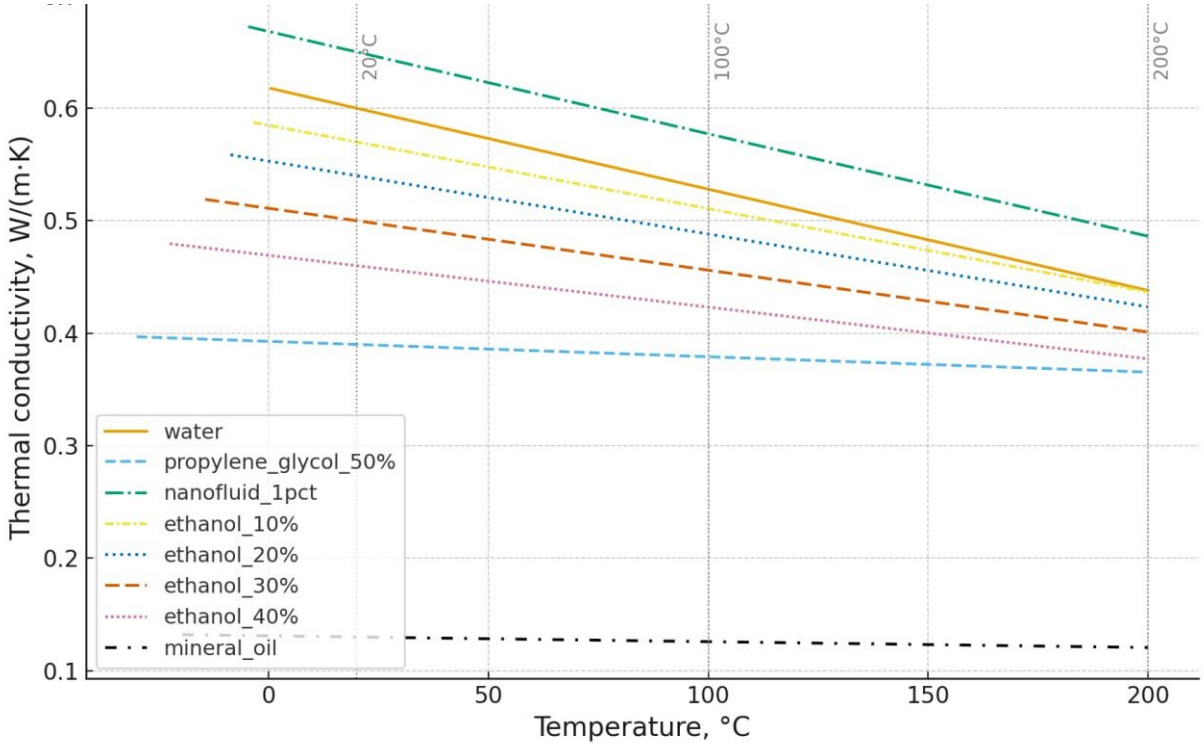

Figure1 – Dependence of the thermal conductivity of heat transfer fluids on temperature

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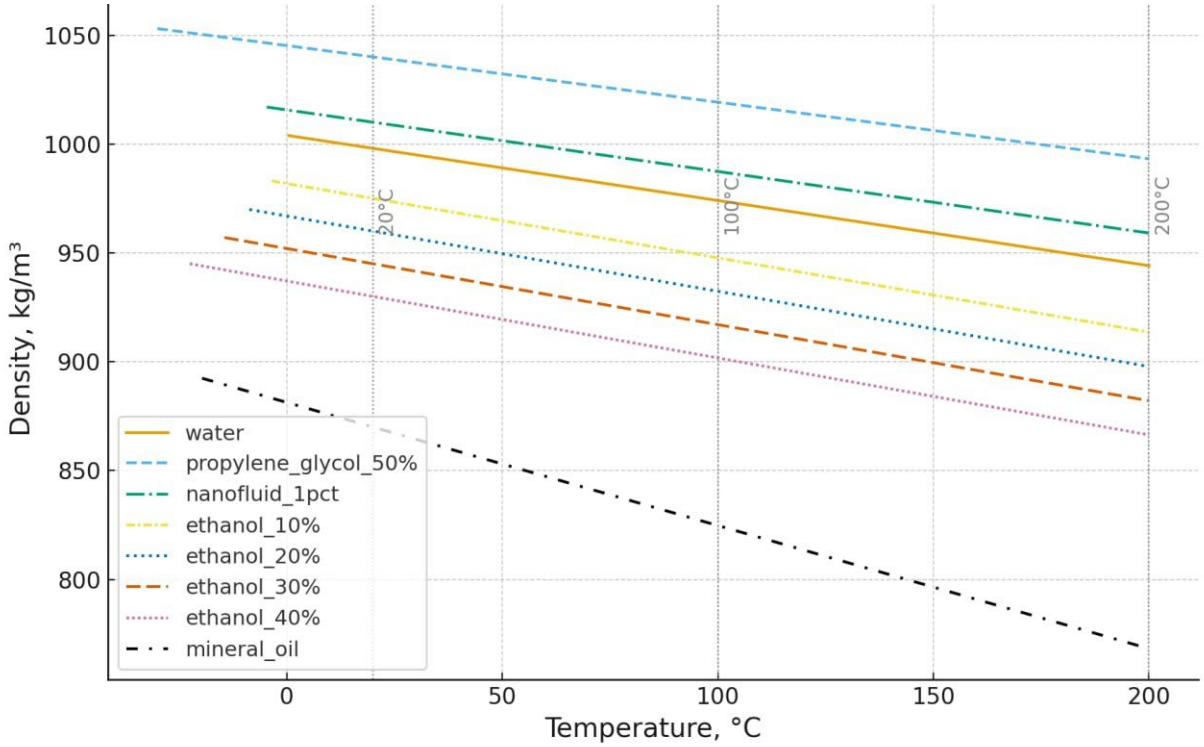

Figure2 – Dependence of the density of heat transfer fluids on temperature

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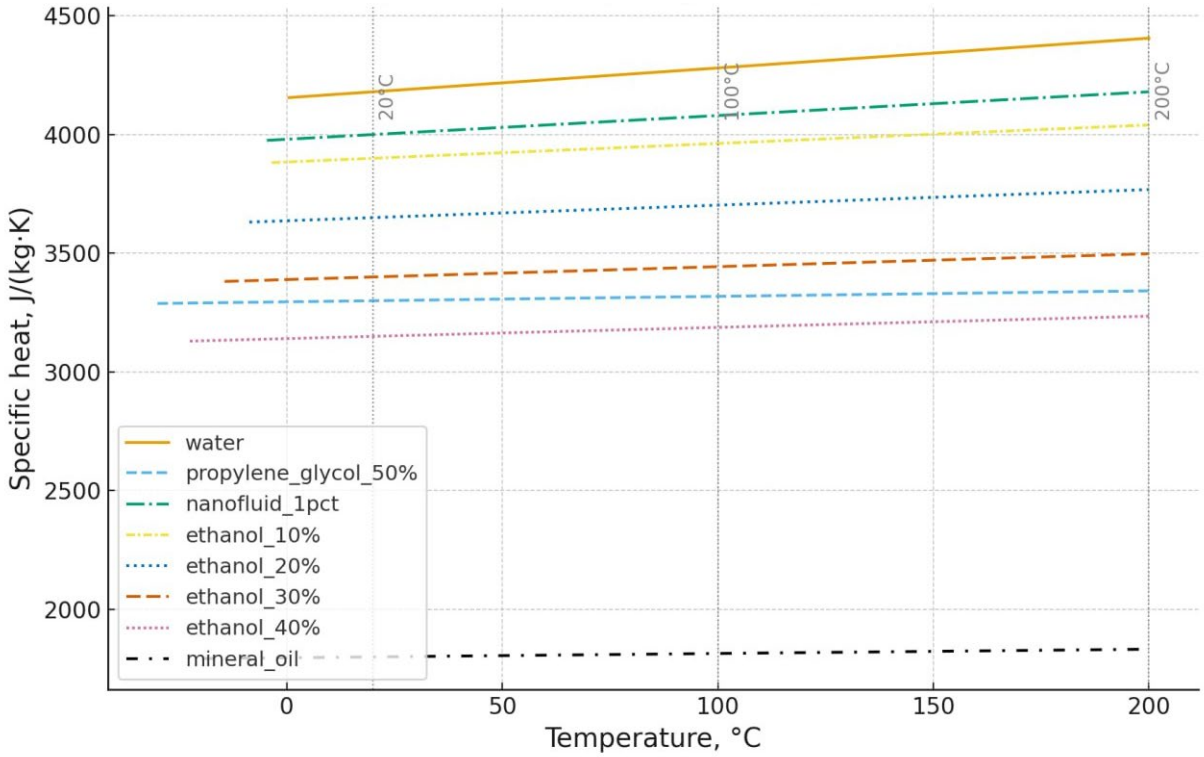

Figure3 – Dependence of the specific heat capacity of HTF on temperature

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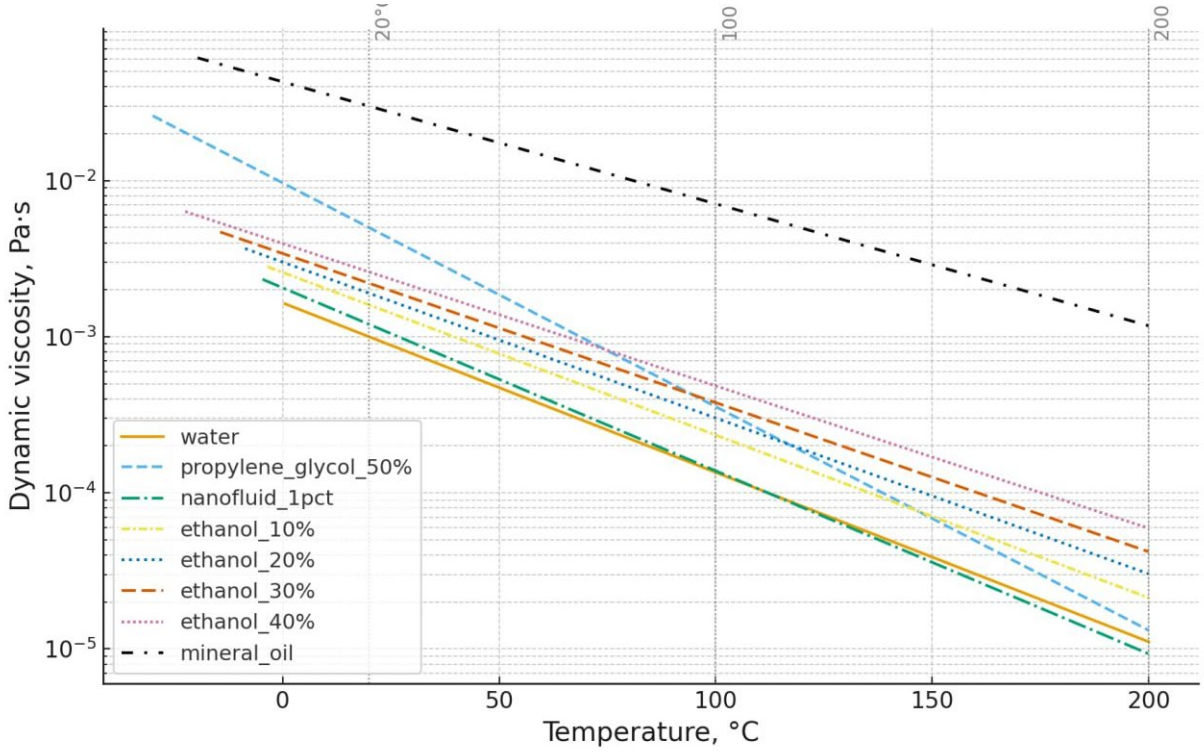

Figure4 – Dependence of the dynamic viscosity of HTF on temperature

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According to Figure 3, water has the highest heat capacity ($c_{p,20}$≈4180 J/kg·K), which provides the greatest capacity for heat energy accumulation. Ethanol solutions show a tendency to decrease heat capacity as the alcohol content increases (from ~3900 to ~3150 J/kg·K), while a 10% solution has a fairly high heat capacity (the graph line is close to nanofluids).

As can be seen from the graph (Figure 4), mineral oil is characterised by a significantly higher dynamic viscosity. This parameter has a strong influence on hydraulic losses, so the circulation of mineral oil in the system will require significant energy consumption. Propylene glycol 50% is 4–5 times more viscous than water at low temperatures, which increases pressure losses, but at higher temperatures this difference is significantly reduced. Water and ethanol solutions have low viscosity (μ≈1–2 mPa·s), which minimises the energy costs required for pumping.

Therefore, from the point of view of thermal conductivity, heat capacity and low viscosity, water is the optimal heat transfer fluid, but there is a problem with low frost resistance (it freezes at 0 °C). Propylene glycol 50% provides protection against freezing, but at the cost of reduced heat transfer and increased hydraulic losses, which reduces thermal efficiency. Nanofluids are potentially the best solution (high thermal conductivity, moderate increase in viscosity), but they remain expensive and under-researched in long-term operating conditions. Mineral oils are only suitable for high-temperature industrial collectors where thermal stability is required, but their low thermal conductivity and high viscosity make them ineffective in classic flat-plate or vacuum solar collectors. Ethanol solutions are a cheap alternative to propylene glycol: they have acceptable thermal conductivity and low viscosity, but reduced heat capacity.

Summary and conclusions. The study allowed us to establish the thermophysical characteristics of heat transfer fluids and construct graphs of their changes in the operating temperature range. The limits of application for each heat transfer fluid were established, and optimal and promising HTF options for widespread use in domestic solar systems were substantiated. Further development of solar technology may be linked to the search for optimal composite heat transfer fluids that combine high heat capacity, frost and heat resistance, low viscosity and chemical inertness.

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