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# Use of Water-$TiO_2$ Nanofluid in Horizontal Slinky Collector of Heat Pump

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**Abstract**

The hydrodynamics of water-$TiO_2$ nanofluid in the Ø32×3 mm horizontal Slinky collector of the heat pump, as well as the heat transfer from river water to the nanofluid have been studied in the paper. Water-$TiO_2$ nanofluid provides attractive opportunities of the application in the energy industry due to its enhanced thermal properties. The thermal and hydrodynamic characteristics of the heat transfer fluid with spherical $TiO_2$ nanoparticles in the temperature range from 2 to 12.5 °C have been analysed. The numerical studies have been performed within the range of change in the nanoparticles concentration from 0.3 to 1.3 vol. %. The influence of operating temperatures of water-$TiO_2$ nanofluid on the efficiency of the energy system of a self-sufficient house, in particular, during the heating and non-heating seasons of the heating system operation for Kyiv region has been studied. The paper provides recommendations and confirms that the limitation of the practical use of water-$TiO_2$ nanofluid is the increase in the viscosity of the heat transfer fluid, accompanied by the increase in power for its transportation. The calculated dependencies of the performance efficiency coefficient of water-$TiO_2$ nanofluid application in the energy system on the content of nanoparticles in the heat transfer fluid have been obtained.

**Keywords:** nanofluid use; heat supply system; thermal characteristics; transport characteristics.

## 1. Introduction

The use of nanotechnology in various industries is becoming more common. The energy application of nanofluids, in particular, their use as promising heat transfer fluids in heat supply systems of residential buildings [1], is no exception in this area. With their enhanced thermal properties, nanofluids offer compelling solutions for the increase in the heat transfer efficiency of the elements of such heating systems, in particular, the increase in the effective thermal conductivity is observed due to the nanoparticles in nanofluid, which can significantly intensify the heat transfer [2], [3].

## 2. Analysis of publications and research

The engineering nanofluids are colloids made out of a base fluid and nanoparticles. They have higher thermal conductivity and single-phase heat transfer coefficients compared to their base fluids. The application of nanoparticles is a technique used to improve the heat transfer performance of the base heat-transfer fluids. The scientific studies [2], [3], [4] analyse the unique features of nanofluids, such as improved thermal conductivity, increased heat transfer, Brownian motion, increased surface-to-volume ratio, thermophoresis, etc. For the application of nanofluids in the energy industry, a complete understanding of the mechanism of increasing the forced convection heat transfer in laminar and turbulent flow is required. The ways to achieve a higher heat transfer coefficient and a lower pressure drop for thermal power systems require further study and are particularly relevant today.

$TiO_2$ nanofluids have a wide range of application in heat transfer or other energy fields due to their good dispersion stability in both hydrophilic and lipophilic liquids, non-toxic and non-corrosive properties, chemical

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stability, lower cost and good visual appearance [5]. Thus, $TiO_2$ nanofluids are considered to have come within an ace of practical industrial application due to their better dispersion and chemical stability, economy and safety.

In order to double the overall heat transfer of traditional heat transfer fluid, the pumping capacity usually has to be increased tenfold. However, if the thermal conductivity of the heat transfer fluid is tripled, then the overall heat transfer in one heat exchanger doubles [6]. The required increase in pumping power will be quite moderate, unless there is a sharp increase in the viscosity of the liquid. Thus, significant saving of pumping power can be achieved if the increase in the thermal conductivity can be caused by a small volume fraction of nanoparticles.

Therefore, one of the problems of the practical use of water-$TiO_2$ nanofluid is the increased power for its pumping or increased hydraulic resistance of the heat transfer fluid [7]. The use of nanofluids with a higher viscosity than the base fluids will result in a larger pressure drop and, therefore, requires more pumping power. For further application of $TiO_2$ nanofluids, it is necessary to solve these scientific problems for specific energy systems. It is believed that papers aimed at solving these problems will contribute to the development of nanofluid technology in the future.

## 3. Goal of the paper

The goal of the research is a theoretical study of the thermal and transport characteristics of the river horizontal Slinky collector of the heat pump of the heating system of a house, as well as the study of the efficiency coefficient of application of water-$TiO_2$ nanofluid with four concentrations of nanoparticles. The paper uses methodical approaches to solving the problems of calculation substantiation of the enhanced efficiency of the heating system of a house with the river horizontal Slinky collector of the heat pump using water-$TiO_2$ nanofluid as a heat transfer fluid.

## 4. Presentation and discussion of the research results

The paper studies the Ø32×3mm river Slinky collector of the heat pump, which is a source of heat in the heat supply system of an autonomous house (a residential facility with the area of 200–220 $m^2$) for Kyiv region. The main heat source of the heating system is the Waterkotte EcoTouch DS 5027 Ai 5020.5 heat pump with a capacity of 19.9 kW.

Water-to-water heat pumps use the heat of groundwater, open water, as well as process cooling water. Groundwater has a stable temperature in the range from +7 to +12 °C. Compared to other low-temperature heat sources, water provides the smallest temperature difference ($t_1 - t_2$) and, accordingly, the highest coefficient of performance. Water-to-water heat and power systems mainly use artificial wells and ground boreholes: distributing and receiving ones.

From a theoretical perspective, river water is an attractive source of heat for heat supply with a water-to-water heat pump. The heat pump collector is located in a natural heat source, in particular, in the nearshore part of the Dnipro River. The temperature level of the heat source is 4 – 18 °C, which corresponds to the energy level of the source 0.9 – 51.6 MW. The energy contained in surface water is released in the process of heat exchange between water and atmospheric air, as well as soil. The disadvantages of surface water as a lower source are the problems with obtaining energy in the cold season with low flow, as well as icing up of the heat exchangers at temperatures near 0 °C. Therefore, the most favourable periods for using this source are early autumn and spring.

The scheme of laying the river horizontal Slinky collector of the heat pump of the heating system is shown in Fig. 1.

The calculation for two periods of the heating system operation, heating and non-heating seasons was performed. To determine the temperature conditions of the natural reservoir for Kyiv region, the changes in water temperature in the Dnipro River over the past five years were analysed. In calculations of the heat transfer coefficient of the horizontal Slinky collector of the heat pump, it was assumed that the average water temperature in the river was 6 °C for the heating season and 18 °C for the non-heating season. The average temperature of the heat transfer fluid in the horizontal Slinky collector of the heat pump was 2 °C for the heating season and 12.5 °C for the non-heating season.

To intensify the heat transfer of the horizontal Slinky collector of the heat pump, water-$TiO_2$ nanofluid was used as heat transfer fluid. $TiO_2$ nanoparticles with an average diameter of about 25 nm had a spherical shape. The four concentrations of $TiO_2$ nanoparticles (0.3; 0.6; 1.0 and 1.3 vol.%) were used in the study. The thermal properties of these nanofluids were determined at average temperatures for two periods of the heating system operation in order to analyse the results of heat transfer and pressure drop. The obtained results were compared with similar properties for the base liquid, i.e. water.

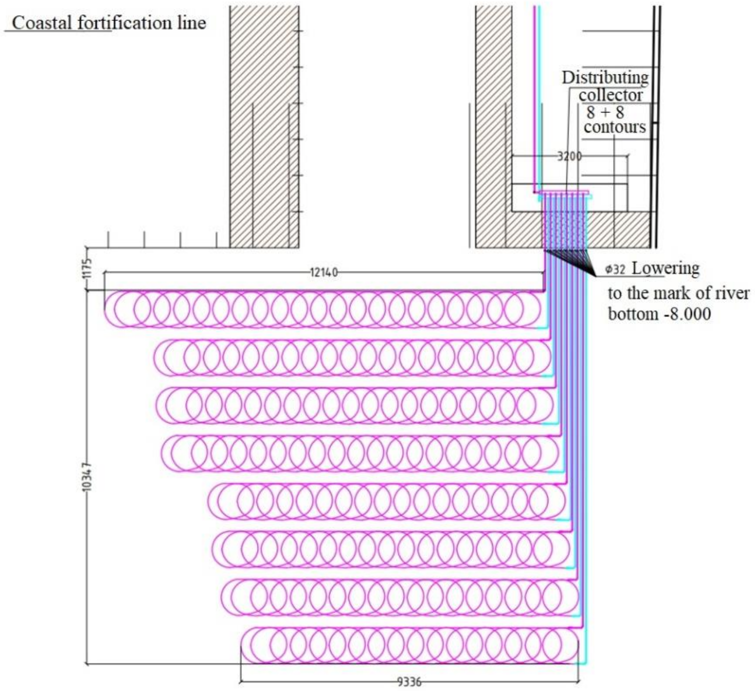

Fig. 1 Laying of the Ø32×3 mm river horizontal Slinky collector of the heat pump of the heating system.

To study the convective heat transfer coefficient of the base fluid, we used the criterion equation for the turbulent flow mode of the heat transfer fluid in round pipes of the collector [1], [10]

$$Nu = \frac{\alpha_w \cdot d_{int}}{\lambda_w} = 0.021 \cdot Re_w^{0.8} \cdot Pr_w^{0.43} \cdot (Pr_w/Pr_{wall})^{0.25}, \tag{1}$$

where $Re_w$ is the Reynolds number for water at the correspondent temperature, $Re_w = \frac{\omega \cdot d_{int} \cdot \rho_w}{\mu_w}$; $Pr_w$ is the Prandtl number for water at the correspondent temperature; $(Pr_w/Pr_{wall})^{0.25}$ is Mikheev's amendment (taken $(Pr_w/Pr_{wall})^{0.25} = 1$ ).

To study the convective heat transfer coefficient of diluted disperse liquids with submicron metal oxide (TiO$_2$) nanoparticles in round pipes of the collector for a turbulent flow mode, the authors [8] proposed the following relationship:

$$Nu = \frac{\alpha_{nf} \cdot d_{int}}{\lambda_{nf}} = 0.021 \cdot Re_{nf}^{0.8} \cdot Pr_{nf}^{0.5}, \tag{2}$$

where $Re_{nf}$ is the Reynolds number for water-TiO$_2$ nanofluid at the correspondent temperature, $Re_{nf} = \frac{\omega \cdot d_{int} \cdot \rho_{nf}}{\mu_{nf}}$; $Pr_{nf}$ is the Prandtl number for water-TiO$_2$ nanofluid at the correspondent temperature, $Pr_{nf} = \frac{\mu_{nf} \cdot Cp_{nf}}{\lambda_{nf}}$.

The main part of the horizontal Slinky collector has a spiral configuration (Fig. 1.), so the convective heat transfer coefficients for nanofluid $\alpha_{nf}^{serp.}$ and water $\alpha_w^{serp.}$ in its curved section (coil) were deduced from the equations [10]:

$$\alpha_{nf}^{serp.} = \alpha_{nf} \cdot \left(1 + 1.77 \cdot \frac{d_{int}}{R}\right), \tag{3}$$

$$\alpha_w^{serp.} = \alpha_w \cdot \left(1 + 1.77 \cdot \frac{d_{int}}{R}\right), \tag{4}$$

where $d_{int}$ is the collector internal diameter, m; $R$ is the radius of the collector coil, m.

The total convective heat transfer coefficient for water-$TiO_2$ nanofluid and water in the straight and spiral sections of the horizontal Slinky collector of the heating system according to Fig. 1:

$$\alpha_{nf}^{\Sigma} = 0.3 \cdot \alpha_{nf} + 0.7 \cdot \alpha_{nf}^{serp.}, \tag{5}$$

$$\alpha_w^{\Sigma} = 0.3 \cdot \alpha_w + 0.7 \cdot \alpha_w^{serp.}. \tag{6}$$

During the heating season of the heating system operation with 0.6 m/s operating velocity of the heat transfer fluid, the increase in the total convective heat transfer coefficient compared to the base fluid is observed:

- for nanofluid with 0.3 vol. % of $TiO_2$ nanoparticles – by 15.85%;
- for nanofluid with 0.6 vol. % of $TiO_2$ nanoparticles – by 12.86%;
- for nanofluid with 1.0 vol. % of $TiO_2$ nanoparticles – by 9.3%;
- for nanofluid with 1.3 vol. % of $TiO_2$ nanoparticles – by 6.84%.

During the non-heating season of the heating system operation with 0.6 m/s operating velocity of the heat transfer fluid, the increase in the total convective heat transfer coefficient compared to the base fluid is observed:

- for nanofluid with 0.3 vol. % of $TiO_2$ nanoparticles – by 13.05%;
- for nanofluid with 0.6 vol. % of $TiO_2$ nanoparticles – by 10.31%;
- for nanofluid with 1.0 vol. % of $TiO_2$ nanoparticles – by 6.93%;
- for nanofluid with 1.3 vol. % of $TiO_2$ nanoparticles – by 4.46%.

Thus, we can see that the increase in the total convective heat transfer coefficient of water-$TiO_2$ nanofluid compared to the base fluid, with the increase in the volume concentration of $TiO_2$ nanoparticles in the studied range of this parameter, decreases for the two periods of operation of the heating system.

The overall heat transfer coefficient from river water to the heat transfer fluid (water) in the Slinky collector during the studied periods of operation of the heating system was determined by the dependence [10]:

$$k_w = \frac{1}{\frac{1}{\alpha_{r.w} \cdot \pi \cdot d_{ext}} + \frac{1}{2 \cdot \pi \cdot \lambda} \cdot ln \frac{d_{ext}}{d_{int}} + \frac{1}{\alpha_w^{\Sigma} \cdot \pi \cdot d_{int}}}. \tag{7}$$

The overall heat transfer coefficient from river water to water-$TiO_2$ nanofluid in the Slinky collector during the studied periods of operation of the heating system was determined by the dependence [10]:

$$k_{nf} = \frac{1}{\frac{1}{\alpha_{r.w} \cdot \pi \cdot d_{ext}} + \frac{1}{2 \cdot \pi \cdot \lambda} \cdot ln \frac{d_{ext}}{d_{int}} + \frac{1}{\alpha_{nf}^{\Sigma} \cdot \pi \cdot d_{int}}}. \tag{8}$$

In formulas (7) and (8): $\alpha_{r.w}$ is the convective heat transfer coefficient from river water to the external wall of the collector at the heat transfer fluid velocity of 0.2 m/s for two periods of operation of the heating system, $W/(m^2 \cdot K)$; $\alpha_w^{\Sigma}$ is the total convective heat transfer coefficient from the internal wall of the Slinky collector to the base fluid, $W/(m^2 \cdot K)$; $\alpha_{nf}^{\Sigma}$ is the total convective heat transfer coefficient from the internal wall of the Slinky collector to water-$TiO_2$ nanofluid $W/(m^2 \cdot K)$; $\lambda$ is the coefficient of thermal conductivity of the collector wall, $W/(m^2 \cdot K)$; $d_{ext}$ is the external diameter of the collector pipe, m; $d_{int}$ is the internal diameter of the collector pipe, m.

According to the results of calculating the overall heat transfer coefficients using the dependences (7) and (8), the dependence diagrams (Fig. 2.) are built, represented by the ratio of the overall heat transfer coefficient for nanofluid with different volume concentrations of $TiO_2$ nanoparticles to the overall heat transfer coefficient for the base fluid.

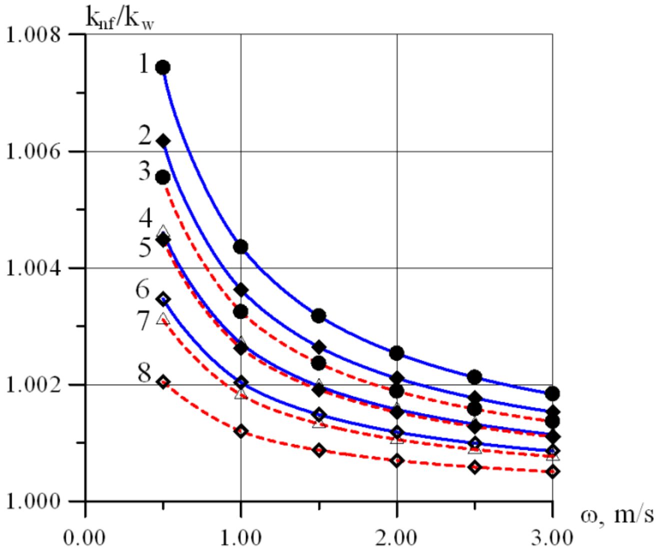

Fig. 2. The ratio of the overall heat transfer coefficient for nanofluid to the overall heat transfer coefficient for water from the velocity of fluid flow along polyethylene pipes of the Ø32×3 mm horizontal Slinky collector of the heat pump in the heating system of a house: 1 – nanofluid for heating season with 0.3 vol. % TiO$_2$; 2 – nanofluid for heating season with 0.6 vol. % TiO$_2$; 3 – nanofluid for non-heating season with з 0.3 vol. % TiO$_2$; 4 – nanofluid for heating season with 1.0 vol. % TiO$_2$; 5 – nanofluid for non-heating season with 0.6 vol. % TiO$_2$; 6 – nanofluid for heating season with 1.3 vol. % TiO$_2$; 7 – nanofluid for non-heating season with 1.0 vol. % TiO$_2$; 8 – nanofluid for non-heating season with 1.3 vol. % TiO$_2$.

The increase in the overall heat transfer coefficient of water-TiO$_2$ nanofluid by 0.3 – 0.64% compared to the base fluid is observed during the heating season for the heating system at an operating velocity of the heat transfer fluid of 0.6 m/s in the pipes, and during the non-heating season – by 0.17 – 0.48%. Thus, as it can be seen from Fig. 2, the efficiency of overall heat transfer of the studied system during the heating season is greater than during the non-heating season.

Compared to water, during the heating season of the heating system operation, the horizontal Slinky collector collected:

- 0.65 kW more thermal energy with nanofluid with 0.3 vol. % TiO$_2$;
- 0.54 kW more thermal energy with nanofluid with 0.6 vol. % TiO$_2$;
- 0.4 kW more thermal energy with nanofluid with 1.0 vol. % TiO$_2$;
- 0.3 kW more thermal energy with nanofluid with 1.3 vol. % TiO$_2$.

Compared to water, during the non-heating season of the heating system operation, the horizontal Slinky collector collected:

- 0.48 kW more thermal energy with nanofluid with 0.3 vol. % TiO$_2$;
- 0.39 kW more thermal energy with nanofluid with 0.6 vol. % TiO$_2$;
- 0.27 kW more thermal energy with nanofluid with 1.0 vol. % TiO$_2$;
- 0.18 kW more thermal energy with nanofluid with 1.3 vol. % TiO$_2$.

Despite this, the capacity of the heating system during the non-heating season is 1.39 times higher than during the heating season.

The value of the coefficient of friction for the collector made of polyethylene in the turbulent mode of fluid motion can be calculated [8]:

$$\lambda_{fric.} = \frac{0.316}{Re^{0.25}} \quad \text{at} \quad Re < 10^5. \qquad (9)$$

The pressure loss to overcome the friction force during the motion of the heat transfer fluid through a polyethylene pipe of the horizontal Slinky collector in its straight section [11]:

- for water-$TiO_2$ nanofluid

$$\Delta P_{nf} = \lambda_{fric.} \cdot \frac{L}{d_{int}} \cdot \frac{\rho_{nf} \cdot \omega^2}{2}, \tag{10}$$

- for water

$$\Delta P_{w} = \lambda_{fric.} \cdot \frac{L}{d_{int}} \cdot \frac{\rho_{w} \cdot \omega^2}{2}, \tag{11}$$

where $\lambda_{fric.}$ is the coefficient of friction; $L$ is the length of the horizontal collector ($L$ = 1500 m); $d_{int}$ is the internal diameter of a polyethylene pipe of the Ø32×3 mm horizontal collector.

The pressure loss to overcome the friction force during the motion of the heat transfer fluid through a polyethylene pipe of the horizontal Slinky collector in its curved section (coil) was deduced from the equations [10], [11]:

- for water-$TiO_2$ nanofluid

$$\Delta P'_{nf} = \left(1 + 3.54 \cdot \frac{d_{int}}{D}\right) \cdot \lambda_{fric.} \cdot \frac{L}{d_{int}} \cdot \frac{\rho_{nf} \cdot \omega^2}{2}, \tag{12}$$

- for water

$$\Delta P'_{w} = \left(1 + 3.54 \cdot \frac{d_{int}}{D}\right) \cdot \lambda_{fric.} \cdot \frac{L}{d_{int}} \cdot \frac{\rho_{w} \cdot \omega^2}{2}, \tag{13}$$

where $d_{int}$ and $D$ are the internal diameter of the Ø32× 3 mm collector and diameter of the lap of coil, m, respectively.

The performance efficiency coefficient of water-$TiO_2$ nanofluid application as a heat transfer fluid in the heating system with the horizontal Slinky collector, we used the dependence [1]

$$\mathrm{PEC} = \frac{\alpha_{nf}^{\Sigma}/\alpha_{w}^{\Sigma}}{\Delta P_{nf}^{\Sigma}/\Delta P_{w}^{\Sigma}}, \tag{14}$$

where $\alpha_{nf}^{\Sigma}$, $\alpha_{w}^{\Sigma}$ are total convective heat transfer coefficients for water-$TiO_2$ nanofluid and water respectively, W/($m^2$·K); $\Delta P_{nf}^{\Sigma}$ is the pressure loss to overcome the friction force and local resistance of the Slinky collector during the motion of water-$TiO_2$ nanofluid, according to the collector design (Fig. 1) taken $\Delta P_{nf}^{\Sigma} = 0.3 \cdot \Delta P_{nf} + 0.7 \cdot \Delta P'_{nf}$, Pa; $\Delta P_{w}^{\Sigma}$ is the pressure loss to overcome the friction force and local resistance of the Slinky collector during the motion of water, according to the collector design (Fig. 1) taken $\Delta P_{w}^{\Sigma} = 0.3 \cdot \Delta P_{w} + 0.7 \cdot \Delta P'_{w}$, Pa.

The obtained results of the theoretical study of the thermal and transport characteristics of the horizontal Slinky collector of the heat pump of the heating system were used to construct the dependence of the efficiency coefficient of water-$TiO_2$ nanofluid application as a heat transfer fluid in the horizontal collector of the heat pump according to the equation (14) on the content of $TiO_2$ nanoparticles in the heat transfer fluid. These calculation results are shown in Fig. 3.

According to Fig. 3, the dependence of the performance efficiency coefficient of water-$TiO_2$ nanofluid of the heat and power system on the volume fraction of $TiO_2$ nanoparticles was obtained for:

- heating season:

$$\mathrm{PEC} = 1.18233 \cdot \exp\ (-0.191507 \cdot \varphi), \tag{15}$$

- non-heating season:

$$\mathrm{PEC} = 1.15585 \cdot \exp\,(-0.190815 \cdot \varphi). \tag{16}$$

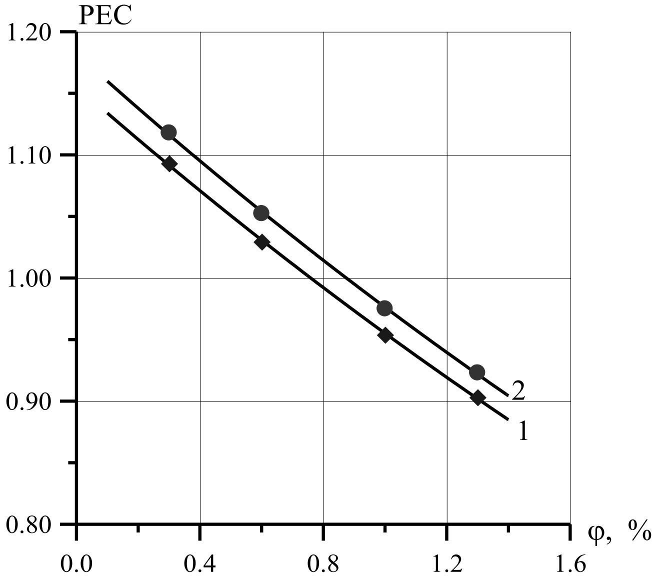

Fig. 3. Dependence of the performance efficiency coefficient of water-TiO$_2$ nanofluid application as heat transfer fluid in the horizontal Slinky collector of the heat pump on the volume fraction of TiO$_2$ nanoparticles during: 1 – non-heating season; 2 – heating season.

The obtained dependences (15) and (16) are valid in the studied range of the volume fraction of TiO$_2$ nanoparticles (Fig. 3), namely, 0.3 vol. % <φ < 1.3 vol. %. The confidence coefficient of approximation R2 for the dependence (15) is 0.999611, and 0.999667 for the dependence (16), which is quite acceptable and characterizes the smoothing as reliable. It is determined that the obtained dependence coefficients are statistically significant.

The increase in the concentration of TiO$_2$ nanoparticles in the nanofluid from 0.3 vol.% to 1.3 vol. % leads to the decrease in the performance efficiency coefficient by 1.06 – 1.2 times, depending on the heating system operation season. As can be seen from Fig. 3, the performance efficiency coefficient of nanofluid application as heat transfer fluid in the horizontal Slinky collector of the heat pump is higher than 1.0 not for all studied periods of operation of the heating system. Thus, concentrated nanofluids (with concentration of 1.0 vol.% and 1.3 vol.% of TiO$_2$ nanoparticles) for the studied Slinky system are not recommended for use, as there is a significant increase in the viscosity of nanofluid and hydraulic resistance. The application efficiency coefficient for these nanofluids is 0.954 – 0.902.

The heat transfer fluid recommended for the studied energy system is water-TiO$_2$ nanofluid with 0.3 vol.% of TiO$_2$ nanoparticles, the application efficiency coefficient of which is 1.118 for the heating season and 1.091 for the non-heating season. As it can be seen, during the non-heating season of the heating system operation, the efficiency of nanofluid application in the Slinky collector is 1.025 times lower than during the heating season.

## 5. Conclusion

According to the data obtained, the increase in the convective heat transfer coefficient of the nanofluid compared to the base fluid with the increase in the volume concentration of TiO$_2$ nanoparticles in the studied range of variation of this parameter decreases during two periods of operation of the heating system. During the heating season of the heating system operation with an operating velocity of the heat transfer fluid of 0.6 m/s, the increase in the overall heat transfer coefficient of the nanofluid, compared to the base fluid, by 0.3 – 0.64% is observed in the pipes and during the non-heating season by 0.17 – 0.48%.

Water-TiO$_2$ nanofluid with 0.3 vol.% of TiO$_2$ nanoparticles is used as heat transfer fluid recommended for the system under study. The performance efficiency coefficient of nanofluid application is 1.118 during the heating period and 1.091 during non-heating season. It can be seen that during the non-heating season of the heating system operation, the efficiency of nanofluid application in the Slinky collector is 1.025 times lower than during the heating season. However, it should be noted that more concentrated nanofluids (with concentration of 1.0 vol.% and 1.3 vol.% of $TiO_2$) for the investigated Slinky collector are not recommended for use, as there is a significant increase in nanofluid viscosity and hydraulic resistance. The calculated dependences of the performance efficiency coefficient of water-$TiO_2$ nanofluid application on the content of nanoparticles in the heat transfer fluid during two periods of operation of the heating system have been obtained.

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# Використання нанорідини «вода-$TiO_2$» у горизонтальному колекторі Slinky теплового насосу

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## Анотація

У роботі досліджено гідродинаміку нанорідини «вода-$TiO_2$» в горизонтальному колекторі Slinky Ø 32 × 3 мм теплового насосу, а також теплопередачу від річкової води до нанорідини. Нанорідина «вода-$TiO_2$» має привабливі можливості щодо застосування у енергетичній галузі завдяки своїм підвищеним тепловим властивостям. Вивчено теплофізичні та гідродинамічні характеристики теплоносія з наночастинками $TiO_2$ сферичної форми у діапазоні температур від 2 до 12,5 °C. Чисельні дослідження виконано в діапазоні зміни концентрації наночастинок від 0,3 до 1,3 об.%. У роботі вивчено вплив робочих температур нанорідини «вода-$TiO_2$» на ефективність роботи енергетичної системи енергонезалежного будинку, зокрема, для опалювального і неопалювального періодів роботи системи теплопостачання для Київської області. У роботі надано рекомендації та підтверджено, що обмеженням для практичного застосування нанорідини «вода-$TiO_2$» є підвищення в’язкості теплоносія, що супроводжується збільшенням потужності на її транспортування. Отримано розрахункові залежності коефіцієнта ефективності використання нанорідини «вода-$TiO_2$» у енергетичній системі від вмісту наночастинок у теплоносії.

**Ключові слова:** використання нанорідин; система теплопостачання; теплофізичні характеристики; транспортні характеристики.