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EFFECT OF NANOPARTICLES ON THE COUPLING OF TURBULENCE AND HEAT TRANSFER IN PIPE FLOWS WITH HEAT FLUX

Abstract: *Enhancing the efficiency of heat transfer processes remains one of the key challenges in modern energy and thermal engineering. Conventional working fluids, such as water and ethylene glycol, are limited in terms of thermal conductivity and heat capacity, which reduces their potential under high heat flux conditions. One of the promising approaches is the use of nanofluids – suspensions of nanoparticles in a base liquid that can modify its thermophysical properties and improve heat transfer performance.*

This study presents a numerical investigation of the flow of water and TiO_2-CuO nanofluid in a U-shaped tube channel under a constant heat flux. Computational fluid dynamics (CFD) was applied to analyze the distribution of turbulent kinetic energy (TKE), pressure variations along the channel, as well as integral heat transfer parameters: the heat transfer coefficient and heat absorption.

The results showed that water exhibits higher turbulent activity, with maximum TKE values reaching $1.9 \cdot 10^{-3}$ m^2/s^2, while the overall pressure drop is about 230 Pa. Its relatively low thermal conductivity (0.6 W/m·K) leads to a temperature rise of 5-7 °C at the outlet. For the TiO_2-CuO nanofluid, turbulence intensity decreases on straight sections (10^{-6}-10^{-5} m^2/s^2) and the pressure drop increases up to 270 Pa due to higher viscosity. However, improved thermophysical properties – thermal conductivity (0.702 W/m·K) and density – ensure more effective heat removal, with outlet overheating reduced to 4-5 °C.

Comparative analysis of heat absorption and the heat transfer coefficient revealed the advantage of the nanofluid: h=68.3 W/(m^2·K), Q=143 W compared with water (h=67.6 W/(m^2·K), Q=141.8 W). These results indicate that TiO_2-CuO nanofluid provides higher heat transfer efficiency with an acceptable increase in hydraulic losses, making it a promising coolant for compact and high-load thermal systems.

Key words: *nanofluid; TiO_2-CuO; CFD modeling; turbulent kinetic energy; thermophysical properties.*

Introduction

Modern heat transfer tasks – from solar energy systems to compact heat exchangers – impose high requirements on the efficiency of working fluids. Conventional liquids such as water, ethylene glycol, and their mixtures are limited in thermal conductivity and heat capacity, which often prevents them from achieving the required heat flux in compact designs. One promising solution to this problem is the use of nanofluids - suspensions of nanoparticles (1-100 nm in size) in a base liquid, which can enhance the thermophysical properties of the system. Research in this field has demonstrated that the addition of nanoparticles can improve thermal conductivity, increase effective heat capacity, and influence heat transfer due to Brownian motion, microscale thermal convection, and other effects [1-6].

Despite numerous experimental and theoretical studies, several key issues and contradictions remain:

1 Ambiguity of turbulence influence. Many studies emphasize the intensification of turbulent pulsations kinetic energy (TKE) as one of the main mechanisms of enhanced convective heat

transfer [7, 8]. However, with increased viscosity of nanofluids, small-scale vortices may be suppressed, reducing TKE. At the same time, heat transfer can remain at the same level or even improve due to higher thermal conductivity and heat capacity, which means the effect does not directly depend on turbulence.

2 Interdisciplinary nature of the problem. An adequate evaluation of nanofluid efficiency requires considering not only hydrodynamics Reynolds number (Re), but also the combination of thermophysical properties: viscosity, thermal conductivity, heat capacity, and density. Many studies focus only on thermal conductivity or changes in the Nusselt number (Nu), without analyzing how variations in properties affect the entire heat transfer process. Alami et al. (2023) critically note that the literature often underestimates the importance of the property complex and may overestimate the potential benefits of nanofluids [9].

3 Non-uniform experimental and modeling conditions. Different studies employ varying boundary conditions, such as fixed mass flow rate, different heat fluxes, and geometries [10]. This complicates direct comparison of results and often requires assumptions that may distort conclusions.

While many studies report convective enhancement with nanofluids, the literature rarely decouples turbulence intensity from property-driven effects under identical thermal loading and geometry. In particular, few works jointly examine how reduced turbulent kinetic energy (TKE) can coexist with higher overall heat transfer when thermal conductivity and density improve but viscosity rises. To address this gap, we perform a controlled computational fluid dynamics (CFD) study in a U-shaped tube at fixed wall heat flux and inlet temperature, comparing water and a TiO_2-CuO nanofluid. Our contribution is to (i) quantify the interplay between TKE, pressure loss, and integral heat-transfer metrics (h,Q) under matched boundary conditions; (ii) show that modest gains in h and Q are achievable even with lower TKE, attributable to property changes rather than turbulence intensification; and (iii) provide unit-consistent, reproducible inputs and reporting that facilitate comparison with future experiments and models.

Note on suspension stability and reproducibility. Reported thermophysical properties of nanofluids are sensitive to colloidal stability, which depends on pH control, the choice/dosage of surfactants or polymeric dispersants, and the ζ-potential (as a rule of thumb, $|\zeta| \gtrsim 30$ mV indicates electrostatic stabilization). For hybrid TiO_2-CuO systems, stability protocols should specify sonication time/power, aging time, and sedimentation observations (e.g., turbidity or UV-vis). Because stability directly affects effective k, μ, and c_p, we report input properties with units and uncertainties and discuss that small increases in μ may suppress small-scale turbulence while improved k can still raise h under fixed heat flux.

In this context, the aim of the present work is to perform a comparative analysis of two heat transfer fluids (water as the base liquid and a nanofluid) under a fixed heat flux and fixed inlet temperature, using both numerical approaches (CFD with evaluation of TKE) and classical correlations of heat transfer coefficients. The main focus is on clarifying whether a nanofluid can demonstrate comparable or improved heat transfer despite lower turbulence levels, due to its enhanced thermophysical properties.

Methods

For the numerical analysis, a section of a tubular heat exchanger designed as a U-shaped tube was considered. This configuration was chosen deliberately: the straight sections make it possible to trace the development of the turbulent regime at the inlet, while the bend allows the study of secondary flow formation and its effect on temperature distribution. Such a model is convenient for comparing different heat transfer fluids under conditions close to real operation.

The inlet condition for both cases was a coolant temperature of T_{in} =20°C. A constant heat flux of q=1000 W/m^2 was applied to the channel wall, ensuring comparability of regimes when using different working fluids.

Two variants of coolants were selected for analysis: water and the TiO_2-CuO nanofluid, which represents a suspension of titanium dioxide and copper oxide nanoparticles in water. This choice was motivated by the high thermal conductivity and chemical stability of TiO_2, as well as the enhanced thermal conductivity of CuO, which makes the combination promising for use in heat exchange systems.

The thermophysical properties of the working fluids are presented in Table 1. The data show that the nanofluid has higher density and thermal conductivity compared with water, while also being characterized by increased viscosity and somewhat lower heat capacity. This combination of properties determines both the improvement in heat transfer efficiency and the increase in hydraulic losses.

Table 1 – Thermophysical properties of water and TiO_2-CuO nanofluid

Property	Water	Nanofluid TiO_2-CuO
Density	998,2 kg/m^3	1161 kg/m^3
Heat capacity	4182 J/kg·K	3533,6 J/kg·K
Thermal conductivity	0,6 W/m·K	0,702 W/m·K
Viscosity	0,001003 kg/m·s	0,0011533 kg/m·s

The channel model included two straight sections and a smooth bend (Figure 1). Such a design makes it possible to simultaneously evaluate the development of the boundary layer and the features of heat transfer in the region of the increased pressure gradient arising at the bend.

Figure 1 – Geometry of the investigated channel

For the discretization of the computational domain, a hybrid mesh was used, consisting of prismatic elements along the walls and tetrahedral elements in the channel volume. This approach made it possible to combine high accuracy in the near-wall region with optimized computational cost (Figure 2).

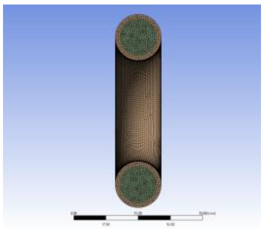

Figure 2 – Computational grid with local refinement in the near-wall region

Results and Discussion

The maximum values of turbulent kinetic energy (TKE) reach approximately $11.9 \cdot 10^{-3}$ m^2/s^2 and are observed in the bend region of the tube, which is associated with the formation of secondary flows and the intensification of velocity fluctuations (Figure 3). In the straight sections, TKE remains relatively low and uniform, at the level of 10^{-6}-10^{-4} m^2/s^2, which reflects the stabilization of the flow. Due to its low viscosity, water promotes freer development of turbulent fluctuations, which intensify when the flow direction changes.

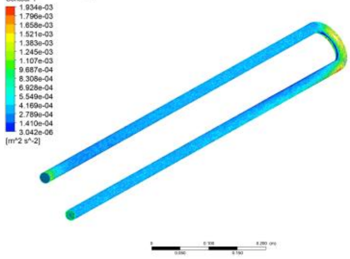

Figure 3 – Distribution of turbulent kinetic energy in the channel (working fluid – water)

The pressure distribution is shown in Figure 4. Pressure decreases smoothly from ≈233 Pa at the inlet to values close to zero at the outlet. The highest gradients are recorded in the bend region, where the pressure drop is about 50-70 Pa over a short section. The pressure decrease is associated with hydraulic losses due to friction and the redistribution of velocities during curvilinear motion. For water, the total pressure losses are relatively small (about 230 Pa along the entire channel length) due to its low viscosity, which makes it an effective base coolant under moderate loads.

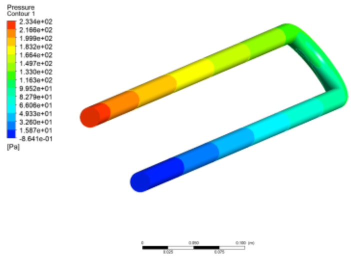

Figure 4 – Pressure distribution along the channel (working fluid – water)

The simulations showed that water is characterized by:

– higher TKE values compared with the nanofluid;

– relatively low pressure losses;

– uniform heating along the channel, with a noticeable temperature increase at the outlet.

Therefore, water provides intensive turbulent mixing; however, its efficiency is limited by relatively low thermal conductivity. This forms the basis for comparison with the TiO_2-CuO nanofluid, which has a different balance of thermophysical properties.

Figure 5 shows the pressure distribution during nanofluid flow. In the case of the nanofluid, the pressure values are higher compared to water: they reach ≈268 Pa at the inlet and decrease almost to zero at the outlet. This is associated with the increased viscosity of the TiO_2-CuO suspension and leads to greater hydraulic losses along the channel. The most pronounced pressure drop is observed in the bend region, where the local gradient reaches about 60-80 Pa over a short section.

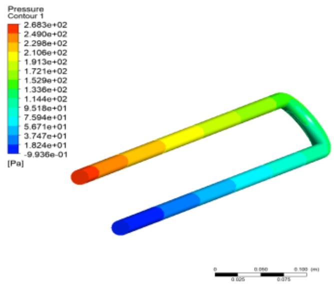

Figure 5 – Pressure distribution along the channel (working fluid – TiO_2-CuO nanofluid)

The distribution of TKE for the nanofluid is shown in Figure 6. The values of turbulent kinetic energy are lower than in the case of water: in the straight sections, the values are only 10^{-6}-10^{-5} m^2/s^2, whereas for water they reached 10^{-6}-10^{-4} m^2/s^2. This is explained by the higher viscosity of the suspension, which suppresses small-scale vortices and reduces the intensity of turbulent fluctuations. In the bend region, the TKE maximum of about $1.9 \cdot 10^{-3}$ m^2/s^2 is preserved; however, its level is lower compared to the base fluid, where more extensive areas of increased turbulence were observed.

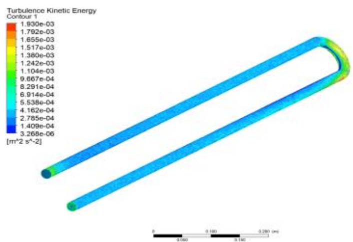

Figure 6 – Distribution of turbulent kinetic energy (working fluid – TiO_2-CuO)

For the TiO_2-CuO nanofluid, the following features are observed:

– a greater pressure drop compared to water, which is associated with increased viscosity;

– preservation of the overall flow pattern, but with a less pronounced turbulent structure.

Despite the reduction in turbulence, the heat transfer efficiency of the nanofluid remains high due to its improved thermophysical properties – thermal conductivity and heat capacity. This is further confirmed by the results of heat absorption and heat transfer coefficient analysis, presented in Figure 7.

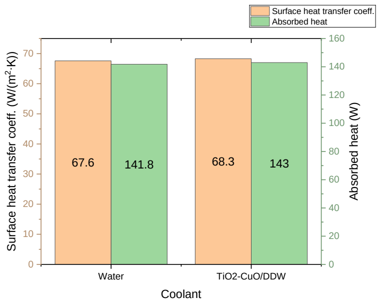

Figure 7 – Comparison of heat absorption and heat transfer coefficient for water and TiO_2-CuO nanofluid

Figure 7 clearly illustrates the differences between the two coolants. For water, the heat transfer coefficient is 67.6 W/(m^2·K), while heat absorption is 141.8 W. For the TiO_2-CuO nanofluid, the values are slightly higher: the heat transfer coefficient reaches 68.3 W/(m^2·K), and heat absorption is 143 W.

The results indicate that the nanofluid exhibits a small but consistent advantage in both heat transfer coefficient (+1%) and heat absorption (+0.8%). This confirms the effectiveness of using composite coolants in compact channels and under high thermal loads.

Conclusions

The numerical study made it possible to compare the thermohydraulic characteristics of water and the TiO_2-CuO nanofluid in a U-shaped tubular channel under an imposed heat flux.

The results showed that:

1 Water is characterized by higher turbulent activity: the maximum values of turbulent kinetic energy reach ≈$1.9 \cdot 10^{-3}$ m^2/s^2, while in the straight sections they remain at the level of 10^{-5}-10^{-4} m^2/s^2. The pressure losses amount to only about 230 Pa along the channel length. However, the thermal conductivity of water (≈0.6 W/m·K) is limited, which reduces heat transfer efficiency: the outlet temperature rise is ≈5-7 °C.

2 The TiO_2-CuO nanofluid shows the opposite behavior: turbulent kinetic energy is lower (10^{-6}-10^{-5} m^2/s^2 in straight sections, with a maximum in the bend also around $1.9 \cdot 10^{-3}$ m^2/s^2). The inlet pressure is higher (≈268 Pa), and the pressure drop across the channel is about 270 Pa due to increased viscosity. At the same time, the improved thermophysical properties - thermal conductivity of 0.702 W/m·K and higher density – provide more efficient heat removal, resulting in a smaller overheating of the fluid (≈4-5 °C at the outlet).

3 A comparison of heat absorption and heat transfer coefficient showed that for water, the total heat absorption was 141.8 W with an average heat transfer coefficient of 67.6 W/(m^2·K), while for the TiO_2-CuO nanofluid, heat absorption was 143 W and the heat transfer coefficient 68.3 W/(m^2·K). This indicates that water provides higher integrated heat absorption due to more developed turbulence, while the nanofluid demonstrates a slightly higher heat transfer coefficient owing to its enhanced thermal conductivity.

The use of TiO_2-CuO nanofluid therefore makes it possible to increase the heat transfer coefficient against the background of a moderate rise in hydraulic losses. These findings confirm the potential of composite coolants for application in compact heat exchangers and systems with increased requirements for heat transfer efficiency.

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ВЛИЯНИЕ НАНОЧАСТИЦ НА СВЯЗЬ ТУРБУЛЕНТНОСТИ И ТЕПЛООТДАЧИ ПРИ ТЕПЛОВОМ ПОТОКЕ В ТРУБАХ

Повышение эффективности процессов теплообмена является одной из ключевых задач современной энергетики и теплотехники. Традиционные рабочие жидкости, такие как вода и этиленгликоль, ограничены по теплопроводности и теплоёмкости, что снижает их потенциал в условиях высоких тепловых нагрузок. Одним из направлений решения этой задачи является применение наножидкостей – дисперсий наночастиц в базовой жидкости, способных корректировать её теплофизические характеристики и повышать эффективность теплоотдачи.

В работе проведено численное исследование течения воды и наножидкости TiO_2-CuO в U-образном трубчатом канале при постоянном тепловом потоке. Для анализа использовалось моделирование методом вычислительной гидродинамики (CFD), позволившее оценить распределение турбулентной кинетической энергии (TKE), изменение давления вдоль канала, а также интегральные показатели теплообмена: коэффициент теплоотдачи и тепловосприятие.

Результаты показали, что вода обладает более высокой турбулентной активностью: максимальные значения TKE достигают $1.9\cdot10^{-3}$ м²/с², при этом суммарное падение давления составляет около 230 Па. Ограниченная теплопроводность (0.6 Вт/м·К) приводит к росту температуры на выходе на 5-7 °С. Для наножидкости TiO_2-CuO характерно снижение уровня турбулентных флуктуаций на прямолинейных участках (10^{-6}-10^{-5} м²/с²) и увеличение перепада давления до 270 Па, однако более высокая теплопроводность (0.702 Вт/м·К) и плотность обеспечивают более эффективный отвод тепла, снижая перегрев жидкости до 4-5 °С на выходе.

Сравнительный анализ тепловосприятия и коэффициента теплоотдачи показал преимущество наножидкости: h=68.3 Вт/(м²·К), Q=143 Вт по сравнению с водой (h=67.6 Вт/(м²·К), Q=141.8Вт). Эти результаты свидетельствуют о том, что наножидкость TiO_2-CuO способна обеспечить более высокую эффективность теплопередачи при допустимом увеличении гидравлических потерь, что делает её перспективным теплоносителем для применения в компактных и энергонапряжённых системах.

Ключевые слова: *наножидкость, TiO_2-CuO, CFD-моделирование, турбулентная кинетическая энергия, теплофизические свойства.*

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НАНОБӨЛШЕКТЕРДІҢ ҚҰБЫРЛАРДАҒЫ ЖЫЛУ АҒЫНЫ КЕЗІНДЕ ТУРБУЛЕНТТІЛІК ПЕН ЖЫЛУ БЕРІЛІСІНІҢ БАЙЛАНЫСЫНА ӘСЕРІ

Жылу алмасу үдерістерінің тиімділігін арттыру қазіргі энергетика мен жылу техникасының негізгі міндеттерінің бірі болып табылады. Су, этиленгликоль сияқты дәстүрлі жұмыс сұйықтықтары жылу өткізгіштік пен жылусыйымдылық тұрғысынан шектеулі, бұл олардың жоғары жылулық жүктеме жағдайындағы мүмкіндіктерін азайтады. Бұл мәселенің ықтимал шешімдерінің бірі – базалық сұйықтықтағы нанобөлшектер дисперсиясы болып табылатын наносұйықтықтарды қолдану, олар жүйенің термофизикалық қасиеттерін түзетіп, жылу алмасудың тиімділігін арттыра алады.

Бұл жұмыста тұрақты жылу ағыны жағдайында U-тәрізді түтікшелі арнадағы судың және TiO_2-CuO наносұйықтығының ағыны сандық тұрғыдан зерттелді. Зерттеу үшін есептеу гидродинамикасының (CFD) әдістері қолданылды, олар турбуленттік кинетикалық энергияның (ТКЭ) таралуын, арна бойындағы қысым өзгерістерін, сондай-ақ жылу алмасудың интегралдық көрсеткіштерін ‒ жылу беру коэффициенті мен жылуды сіңіру шамаларын – бағалауға мүмкіндік берді.

Нәтижелер көрсеткендей, су жоғары турбуленттік белсенділікке ие: ТКЭ-нің максималды мәндері $1.9\cdot10^{-3}$ м²/с²-ге жетеді, ал қысымның жалпы түсуі шамамен 230 Па құрайды. Жылу өткізгіштігінің шектеулі болуы (0.6 Вт/м·К) шығыстағы температураның 5-7 °С-қа дейін көтерілуіне әкеледі. TiO_2-CuO наносұйықтығына түзу учаскелерде турбуленттік тербелістер деңгейінің төмендеуі (10^{-6}-10^{-5} м²/с²) және қысым айырмасының 270 Па-ға дейін артуы тән. Дегенмен, жоғары жылу өткізгіштік (0.702 Вт/м·К) пен тығыздық жылуды тиімдірек әкетуді қамтамасыз етіп, шығыстағы сұйықтықтың қызуын 4-5 °С-қа дейін төмендетеді.

Жылуды сіңіру мен жылу беру коэффициентін салыстыру наносұйықтықтың артықшылығын көрсетті: h=68.3 Вт/(м²·К), Q=143 Вт, ал су үшін бұл көрсеткіштер h=67.6 Вт/(м²·К), Q=141.8 Вт болды. Бұл нәтижелер TiO_2-CuO наносұйықтығының гидравликалық шығындардың қабылданатын артуы аясында жылу алмасудың жоғары тиімділігін қамтамасыз ете алатынын, сондай-ақ оны ықшам және энергияға қаныққан жүйелерде болашағы бар жылу тасығыш ретінде қолдануға болатынын дәлелдейді.

Түйін сөздер: *наносұйықтық; TiO_2-CuO; CFD-модельдеу; турбуленттік кинетикалық энергия; теплофизикалық қасиеттер.*

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STUDY ON THE GRINDING EFFICIENCY OF NON-DESIGN KARAZHYRA COAL IN BALL DRUM AND HAMMER MILLS

Annotation: *This paper presents a comparative study on the grinding efficiency of non-design Karazhyra coal using two main types of milling equipment: ball mills and hammer mills. The research was conducted to assess the suitability of local fuel for combustion in boiler units not originally designed for this type of coal. Laboratory sieve analysis was performed to determine the particle size distribution of the pulverized fuel. For the first time, polydispersity coefficients for Karazhyra coal dust, processed in both types of mills, were obtained and analyzed. Sieve residue measurements showed that in the product of the hammer mill only 0.2% of particles remained on the 400 μm sieve, whereas in the product of the ball drum mill this value was 2.5%. This indicates an almost complete elimination of coarse fractions during grinding in the hammer mill. It was found that with both grinding methods about 88% of coal dust particles are smaller than*