

EXPERIMENTAL DETERMINATION AND INVESTIGATION OF HEAT TRANSFER IN A NEW SERIES OF ENERGY-EFFICIENT MECHANICAL AGITATORS IN A LABORATORY REACTOR WITH A COPPER COIL

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Abstract: In the present article, an experimental study of heat transfer is presented for a new series type of energy-saving mechanical agitators installed in a laboratory cylindrical reactor with an internal copper coil. The aim is to evaluate the influence of design parameters and rotational speed on the intensity of heat transfer and the energy efficiency of the system. The experiments were carried out under different mixing regimes measuring the temperatures of the working medium and the heat carrier, as well as the consumed power. Based on the energy balance, the heat flux and the average heat transfer coefficient were determined. A relationship was established between the hydrodynamic regime and the values of the heat transfer coefficient. The results show that the investigated energy-saving agitators provide increased heat transfer intensity at lower specific energy consumption compared to traditional designs. The obtained relationships can be used in the design and optimisation of reactors with intensive heat transfer.

Key words: energy-saving mechanical agitators; heat transfer; laboratory reactor; copper coil; heat transfer coefficient.

ОПИТНО ОПРЕДЕЛЯНЕ И ИЗСЛЕДВАНЕ НА ТОПЛООБМЕНА НА НОВ ТИП СЕРИЯ ЕНЕРГОСПЕСТЯВАЩИ МЕХАНИЧНИ БЪРКАЧКИ В ЛАБОРАТОРЕН РЕАКТОР С МЕДНА СЕРПЕНТИНА

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Резюме: В настоящата статия е представено експериментално изследване на топлообмена при нов тип серия енергоспестяващи механични бъркачки, монтирани в лабораторен цилиндричен реактор с вътрешна медна серпентина. Целта е да се оцени влиянието на конструктивните параметри и обратната скорост върху интензивността на топлообмена и енергийната ефективност на системата. Експериментите са проведени при различни режими на разбъркване, като са измервани температурите на работната среда и топлоносителя, както и консумираната мощност. На база на енергийния баланс са определени топлинният поток и средният коефициент на топлообмен. Установена е зависимост между хидродинамичния режим и стойностите на коефициента на топлоотдаване. Резултатите показват, че изследваните енергоспестяващи бъркачки осигуряват повишена топлообменна интензивност при по-ниска специфична консумация на енергия в сравнение с традиционни конструкции. Получените зависимости могат да бъдат използвани при проектиране и оптимизация на реактори с интензивен топлообмен.

Ключови думи: енергоспестяващи механични бъркачки; топлообмен; лабораторен реактор; медна серпентина; коефициент на топлоотдаване.

Introduction

Mechanical agitation is a fundamental technological process widely applied in the chemical, biotechnological, pharmaceutical, and food-processing industries to enhance mass, heat, and kinetic transfer within reaction volumes. The efficiency of these processes depends on the interaction between the hydrodynamic regime of the fluid, the geometry of the impellers, and the structural characteristics of the vessel, as well as on the capability to control heat transfer within the reactor (Smith et al., 2023; Shah et al., 2024).

The optimisation of the design of new energy-efficient mechanical impellers is a key factor in improving the energy performance of mixing systems. In recent years, numerous modified configurations have been proposed with the objective of minimising specific energy consumption while maintaining satisfactory mixing and heat-transfer performance (Beale et al., 2025; Zhou et al., 2025).

Heat transfer in mechanically agitated vessels is a complex process directly dependent on the hydrodynamic conditions generated by the impeller. The presence of internal heat exchangers, such as copper coils, alters the local flow pattern and leads to specific velocity profiles and temperature gradients in the vicinity of the heat-transfer surface. This necessitates comprehensive experimental investigations, since standard correlations are often insufficient to adequately describe real

operating conditions in systems with complex flow structures (Smith et al., 2023; Shah et al., 2024).

Energy-efficient mechanical impellers represent an innovative class of devices developed with the aim of reducing specific energy consumption and improving heat-transfer performance in reactors. Studies have shown that optimised geometric configurations and the application of specialised impellers can result in a significant reduction in power consumption while maintaining or improving heat-transfer and mixing characteristics (Beale et al., 2025).

Despite the extensive body of literature devoted to the analysis of mechanical impellers, a limited number of studies address an integrated analysis of hydrodynamics, heat transfer, and energy efficiency in systems equipped with internal heat exchangers such as copper coils. This defines the scientific context of the present study, which aims to fill this gap through systematic experimental investigation.

The copper coil functions as an effective heat exchanger due to the high thermal conductivity of copper and the possibility of compact arrangement of the heat-transfer surface within a limited volume. In combination with the flow dynamics generated by the structural characteristics of energy-efficient impellers, it forms a complex thermo-hydrodynamic environment whose influence requires quantitative determination through experimental approaches.

This paper aims to present an experimental determination and investigation of heat transfer for a new series of energy-

efficient mechanical impellers in a laboratory-scale reactor equipped with a copper coil. The main objective is to obtain quantitative relationships between agitation parameters, structural characteristics of the impellers, and heat-transfer performance, which will support the optimisation of systems for sustainable and energy-efficient mixing and heat-transfer processes (Rahman et al., 2025).

Role of the Coil as an Internal Heat Exchanger

The internal coil is one of the most efficient and widely used heat-transfer elements in agitated reactors, particularly in processes requiring precise temperature control throughout the entire reaction volume. Its primary function is to provide intensive heat exchange between the working medium in the reactor and the heat-transfer fluid circulating through the coil. This enables both heating and cooling of the reaction mixture depending on process requirements (Mahir et al., 2021).

➤ Design Advantages of the Coil

The coil represents a tubular heat exchanger installed inside the reactor, typically arranged in a helical configuration. This design offers several key advantages:

- Large heat-transfer surface area within compact dimensions;
- High thermal conductivity, especially when copper is used, as it has one of the highest thermal conductivities among engineering metals;
- Effective contact with the liquid, since the coil is directly immersed in the reaction medium;
- Capability to operate over a wide range of temperatures and pressures.

These characteristics make the coil highly suitable for both laboratory-scale and industrial reactors where temperature control is critical.

➤ Heat-Transfer Mechanism

Heat transfer between the coil and the reaction medium occurs through a combination of:

- heat conduction through the pipe wall;
- convective heat transfer on the part of the heat-transfer fluid inside the coil;
- convection and turbulent mixing on the part of the reaction medium.

The efficiency of heat transfer depends on:

- the flow velocity of the heat-transfer fluid;
- the temperature of the inlet and outlet streams;
- the geometry of the coil (diameter, pitch, number of turns);
- the intensity of agitation within the reactor.

➤ Interaction Between the Coil and Mechanical Agitation

Mechanical agitation plays a key role in the performance of the coil. Without agitation, a stationary boundary layer forms around the coil, significantly reducing the heat-transfer coefficient. New energy-efficient impellers are designed to:

- direct the flow toward the coil surface;
- disrupt the boundary layer;
- increase turbulence near the pipe surface;

- ensure uniform flow distribution along the entire length of the coil.

This results in a substantial increase in both the local and overall heat-transfer coefficients (Farhadi et al., 2008).

➤ Advantages of Copper Coils

The selection of copper as the construction material is determined by its favourable physical properties:

- high thermal conductivity (approximately 400 W/m.K), enabling rapid heat transfer;
- ease of fabrication, allowing production of coils with small radii and complex geometries;
- corrosion resistance over a wide range of operating environments;
- good mechanical strength even at thin wall thickness.

Due to these properties, copper coils respond rapidly to changes in the temperature of the heat-transfer fluid, enabling precise and dynamic process control.

➤ Significance for the Technological Process

Efficient coil performance is critical for:

- maintaining the optimal reaction temperature;
- preventing local overheating or overcooling;
- ensuring homogeneous conditions throughout the reactor volume;
- improving product quality and reproducibility;
- reducing energy consumption.

When combined with energy-efficient impellers, the internal coil enables a significant improvement in the overall energy efficiency of the reactor system (Copper Development Association, 2023).

Investigated Mixing Devices and Working Media

In a previous publication of ours, the power number K_N was investigated both theoretically and experimentally. For the experimental determination of heat transfer, studies were conducted during agitation of two types of liquid systems typical of biotechnological processes:

- single-phase system – water;
- two-phase system – water–vegetable oil emulsion at different concentrations.

The investigations were carried out using developed series of modified energy-efficient mechanical impellers, as follows:

- Modified Narcissus – MN–6.2
- Impeller – IM–6.2
- Modified Propeller – MP–3.2
- “Clover” Propeller – PD–4.2

The investigated designs represent a new series type of energy-efficient mechanical impellers developed with the aim of increasing the hydrodynamic efficiency of the process and reducing specific energy consumption during dispersing, emulsifying, and homogenising of liquid systems typical for biotechnological production (Kraychev et al., 2003).

The newly designed series of impellers are presented in Figs. 1, 2, 3, and 4.



Fig.1. Modified Narcissus - MN-6.2



Fig.2. Impeller – IM-6.2



Fig.3. Modified Propeller – MP-3.2



Fig.4. “Clover” Propeller – PD-4.2

The structural modification of the working elements is directed toward optimisation of the flow structure within the apparatus, limitation of turbulent energy losses, and improvement of momentum transfer within the working volume.

All impellers were precisely manufactured from AISI 304 stainless steel, ensuring:

- high corrosion resistance;
- chemical inertness toward the investigated media;
- compliance with the hygiene requirements for biotechnological applications;
- good mechanical strength at relatively small material thickness.

The main geometric parameters of the impellers are:

- impeller diameter: $d = 0.09$ m
- blade thickness: $\delta = 0.5$ mm.

The selected diameter was chosen in accordance with the working volume of the vessel ($V_R = 14.3$ dm³) and provides an appropriate ratio between the impeller diameter and the vessel diameter. This ratio is necessary for the accurate determination of heat-transfer characteristics and for a comparable evaluation of energy efficiency among the different impeller designs.

Physico-Chemical Characteristics of the Working Media

The experimental investigations were conducted at ambient temperature within the range $T = 15\text{--}20$ °C. The dynamic

viscosity μ of water is 0.001 Pa.s. The liquid media used and their densities were as follows:

- Water: $\rho_{\text{water}} = 998$ kg/m³

Emulsion systems water–vegetable oil:

Two concentrations of the dispersed phase (vegetable oil) were investigated:

- 20% vegetable oil + 80% water - $\rho_{20\%} = 984$ kg/m³
- 40% vegetable oil + 60% water - $\rho_{40\%} = 968$ kg/m³

The dynamic viscosity μ for the dispersed phase concentration at 20% was 0.002 Pa.s, while at 40% it was 0.005 Pa.s. The working liquid volume in the experimental vessel was $V = 12$ L (0.012 m³).

Experimental Setup

The experimental investigations were carried out in a laboratory semi-industrial agitated system implemented in a cylindrical reactor (10) with a nominal working volume $V_R = 14.3$ dm³, manufactured from a transparent polymer material (plexiglass). The selection of a transparent reactor design was determined by the need for visual control of the hydrodynamic flow structure, turbulence development, and spatial phase distribution within the reaction volume. This enables observation of characteristic flow features, including the formation of vortex structures, the degree of gas dispersion, and the efficiency of macro- and micromixing.

To stabilise the hydrodynamic regime and to limit axisymmetric liquid rotation, four vertical baffle plates (4) were installed along the inner periphery of the vessel, evenly spaced at an angle of 90° relative to each other. The presence of baffles significantly reduces the probability of central vortex (“funnel”) formation and the associated development of undesirable secondary flows. Furthermore, these structural elements facilitate the conversion of tangential velocity components into radial and axial components, resulting in an increase in turbulent energy and a substantial improvement in the intensity of heat- and mass-transfer processes within the reaction volume.

In order to provide the required thermal conditions and maintain a specified temperature regime, a horizontally wound copper coil (3) was mounted along the inner wall of the reactor, with a total length of $L_{\text{coil}} = 7.94$ m. The coil functions as an internal heat-transfer surface through which heat exchange occurs between the reaction medium and the circulating heat-transfer fluid. The use of copper as the construction material is due to its high thermal conductivity, which ensures uniform heat-flux distribution and minimises temperature gradients within the reaction volume. The heat-transfer fluid is supplied to the coil from an external heat-exchange unit (12) at a preset temperature, enabling effective control of the thermal balance and stabilisation of the system's thermal regime.

A sparger (11) was installed at the bottom section of the reactor, consisting of a porous gas-distribution element designed to introduce an inert gas into the liquid phase. Gas sparging results in its dispersion into numerous fine bubbles, increasing the interfacial surface area and creating favourable conditions for the intensification of mass-transfer processes.

The agitation system is driven by a vertical shaft (2) made of stainless steel, to which a mechanical impeller (9) with a specified geometric configuration is attached. The shaft is mechanically coupled to a direct-current electric motor (1), ensuring reliable and stable operation over a wide range of

rotational speeds. The use of a DC motor allows smooth regulation of rotational frequency and maintenance of constant hydrodynamic conditions during the experiments. The structural design of the drive system ensures minimal mechanical losses, high reliability, and stability during prolonged operation (Fig.5) (Kraychev, 2023).



Fig. 5. Laboratory reactor in operating mode

The regulation of the rotational speed of the main shaft, and consequently of the impeller, is achieved by means of an autotransformer, allowing smooth variation of the voltage supplied to the electric motor.

Control of the electrical parameters of the system is implemented through potentiometers combined with a voltmeter and ammeter, while the power characteristics of the motor are determined based on previously established calibration relationships.

Measurement of the actual rotational speed of the impeller is performed using an infrared non-contact tachometer (7), which ensures high measurement accuracy and eliminates the influence of mechanical contact on system dynamics. The obtained experimental data are automatically recorded by a data acquisition unit (8), enabling subsequent processing, statistical analysis, and graphical representation of the results.

Temperature control within the system is achieved using highly sensitive manometric thermometers (5) installed at the inlet and outlet of the heat-exchange system. By comparing the inlet and outlet temperatures of the heat-transfer fluid, the quantity of transferred heat is determined and the efficiency of the heat-transfer process is evaluated.

Additionally, a digital flowmeter (6) is integrated into the system to measure the flow rate of the heat-transfer fluid G_1 in real time, as well as the flow rate of the circulating liquid in the reactor G_2 . The inlet and outlet temperatures of the system, denoted as T_1 and T_2 , are recorded, enabling accurate determination of heat fluxes and analysis of the thermodynamic parameters of the process.

A photographic image and a schematic diagram of the experimental installation are presented in Fig. 6 and Fig. 7, respectively, where the main structural elements, measuring devices, and functional units of the system are indicated. The presented scheme allows clear visualisation of the interconnections between individual components and facilitates interpretation of the obtained experimental results (Kraychev et al., 2000).



Fig. 6. Photograph of the experimental installation

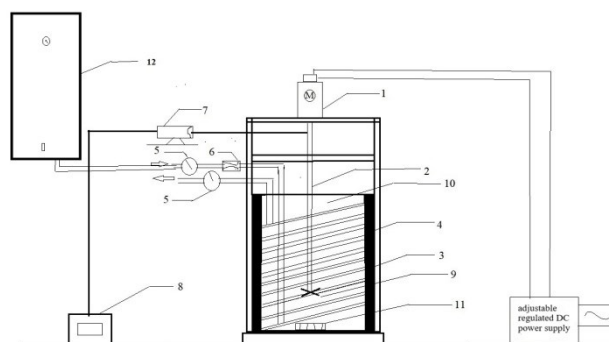


Fig. 7. Diagram of the experimental installation:

- 1 – DC electric motor; 2 – stainless steel shaft; 3 – copper coil;
- 4 – baffles (4 pcs.); 5 – manometric thermometers; 6 – digital flow meter;
- 7 – infrared tachometer; 8 – recording unit;
- 9 – mechanical agitator; 10 – plexiglass reactor; 11 – sparger;
- 12 – heat exchanger

In Fig. 8, a photograph of the experimental stand equipped with a Testo-890 thermal imaging camera model is presented, taken at different viewing angles. The entire emulsion inside the reactor was observably heated to the required operating temperature necessary for determining the heat and mass balance.

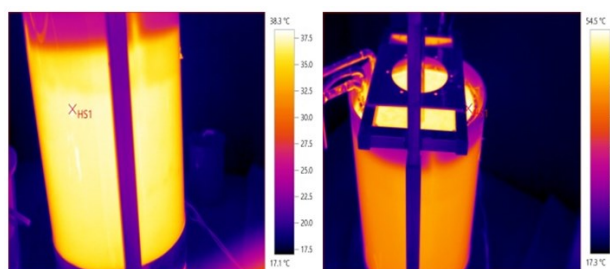


Fig. 8. Photograph of the reactor operating under working conditions with a thermal imaging camera

Research Methodology and Experimental Results

The heat-transfer coefficient (α_2) on the agitation side was investigated, and based on this parameter, the Nusselt number (Nu_2) on the agitation side was determined. For this purpose, the heat-balance method was applied to determine the overall heat-transfer coefficient (k). The heat-transfer coefficient on the heat-carrier side (α_1) was calculated using (Nu_1) from equation

(5), which describes heat transfer during fluid flow in pipes and channels. A correction $\varepsilon_{\Delta t}$ of the temperature difference for the presence of parallel mixed flow was also calculated (Stephan et al., 2019).

The experimental data were processed using a computer program according to the following algorithm:

a) determination of the heat flux

$$\dot{Q} = G_1 \cdot C_p \cdot \Delta t_{avg} \quad (1)$$

b) determination of the effective heat-transfer surface of the horizontally wound copper coil - ($A = 0,147 \text{ m}^2$);

c) determination of Δt_{avg} for each experiment, using counter-flow equations and correction $\varepsilon_{\Delta t}$;

d) calculation of the overall heat-transfer coefficient

$$k = \frac{\dot{Q}}{A \cdot \Delta t_{avg}} \quad (2)$$

e) determination of the heat-carrier velocity in the coil

$$W = G_1 / S_c \quad (3)$$

f) determination of the Reynolds number in the coil

$$Re = W \cdot d_{eq} / \nu \quad (4)$$

g) determination of the Nusselt number Nu_1 in the turbulent region ($Re > 10000$)

$$Nu_1 = 0.0235 \cdot Re^{0.8} \cdot Pr^{0.48} \cdot \left(\frac{Pr}{Pr_w} \right)^{0.11} \quad (5)$$

h) determination of the Prandtl number

$$Pr = \mu \cdot C_p / \lambda \quad (6)$$

i) determination of the heat-transfer coefficient α_1

$$\alpha_1 = \frac{Nu \cdot \lambda_T}{d_{eq}} \quad (7)$$

j) determination of the heat-transfer coefficient α_2

$$\alpha_2 = \frac{k \cdot \alpha_1}{\alpha_1 - k} \quad (8)$$

k) determination of the Reynolds number during agitation

$$Re = \frac{n \cdot \rho \cdot D_a^2}{\mu} \quad (9)$$

l) determination of the Nusselt number Nu_2

$$Nu_2 = C \cdot Re^A \cdot Pr^B \cdot \left(\frac{\mu}{\mu_{wall}} \right)^F \quad (10)$$

Table 1 presents the calculated results obtained from laboratory experiments during the agitation of a 20% vegetable oil – water emulsion using a coil heat-exchange system and four series of newly developed energy-efficient agitators.

Table 1. Results of calculations from laboratory experiments during the agitation of 20% vegetable oil – water emulsion for four impeller series

Modified Narcissus - MN - 6.2											
n	G	t ₁	t ₂	Q	θ ₁	θ ₂	Re	α ₂	Nu ₂	k	Δt _{cp}
min ⁻¹	kg/s	°C	°C	W	°C	°C	-	W/m ² K	-	W/m ² K	°C
200	0.181	50.9	48.3	1964	20.6	45.0	57452	520	230	432	12.8
400	0.181	50.8	48.0	2120	22.0	45.5	74880	620	260	562	10.7
600	0.181	51.8	47.8	2300	22.5	46.0	89900	695	293	634	10.2
800	0.181	50.8	47.6	2415	22.8	45.6	104820	760	327	696	9.8
1000	0.181	50.7	47.4	2512	22.7	45.8	119836	826	353	755	9.4
Impeller - IM - 6.2											
n	G	t ₁	t ₂	Q	θ ₁	θ ₂	Re	α ₂	Nu ₂	k	Δt _{cp}
min ⁻¹	kg/s	°C	°C	W	°C	°C	-	W/m ² K	-	W/m ² K	°C
200	0.181	50.8	48.2	47.9	20.5	44.9	57452	550	240	456	12.8
400	0.181	50.7	47.9	2116	22.1	45.6	74880	654	287	573	10.4
600	0.181	51.8	47.8	3023	22.4	45.9	89900	721	327	654	9.8
800	0.181	50.8	47.6	2418	22.8	45.6	104820	790	355	693	9.9
1000	0.181	50.6	47.3	2494	22.7	45.8	119836	836	391	780	9.3
Modified Propeller - MP - 3.2											
n	G	t ₁	t ₂	Q	θ ₁	θ ₂	Re	α ₂	Nu ₂	k	Δt _{cp}
min ⁻¹	kg/s	°C	°C	W	°C	°C	-	W/m ² K	-	W/m ² K	°C
200	0.181	50.7	48.1	1965	20.4	44.9	57452	430	206	460	12.1
400	0.181	50.6	47.8	2116	22.2	45.6	74880	534	227	584	10.2
600	0.181	50.8	47.8	2267	22.5	45.9	89900	605	255	655	10.0
800	0.181	50.8	47.6	2418	22.8	45.6	104820	685	285	693	9.9
1000	0.181	50.7	47.4	2494	22.7	45.7	119836	750	315	750	9.4
"Clover" Propeller - PD - 4.2											
n	G	t ₁	t ₂	Q	θ ₁	θ ₂	Re	α ₂	Nu ₂	k	Δt _{cp}
min ⁻¹	kg/s	°C	°C	W	°C	°C	-	W/m ² K	-	W/m ² K	°C
200	0.181	50.8	48.2	1965	20.5	44.9	57452	484	220	449	12.6
400	0.181	50.7	47.9	2117	22.1	45.6	74880	585	253	573	10.4
600	0.181	51.5	47.8	2530	22.5	45.9	89900	655	280	648	10.4
800	0.181	50.8	47.6	2417	22.8	45.6	104820	738	315	694	9.9
1000	0.181	50.7	47.7	2500	22.7	45.8	119836	800	340	762	9.4

In Fig. 9, the experimental data showing the relationship between Nu_2 and Re during agitation of a 20% vegetable oil–water emulsion in a coil heat-transfer system are presented for four newly designed impeller series at $T=15\text{--}20 \text{ }^\circ\text{C}$. The relationship was recorded during both increase and decrease of shaft rotational speed n from 200 to 1000 min^{-1} . The rotational speed was controlled using an infrared non-contact tachometer (Kraychev, 2023).

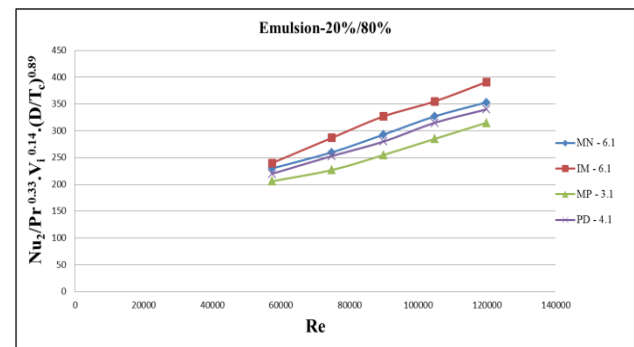


Fig. 9. Dependence of Nu_2 on Re during the agitation of a 20% vegetable oil–water emulsion in a coil heat-transfer system

A comparison was performed between the heat-transfer coefficient (α_2) for the four series of energy-efficient impellers on the agitation side as a function of the Reynolds number (Re_a). The results are presented in Fig. 10.

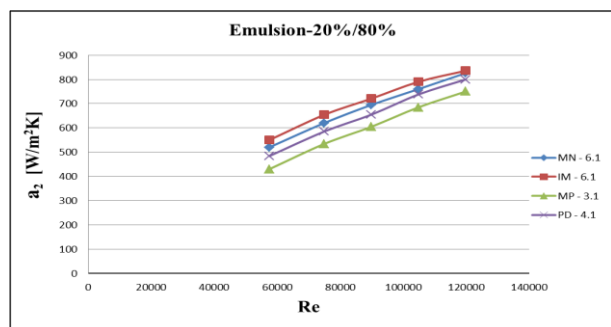


Fig. 10. Comparison of heat-transfer coefficient (α_2) as a function of Reynolds number (Re)

Symbols and Notation

A – heat-transfer surface area of the coil (m^2)
A, B, C – empirical constants (determined experimentally for each impeller type)
Cp – specific heat capacity (kJ/kg.K)
D_a – impeller diameter (m)
d_{eq} – equivalent diameter (m)
F – empirical constant (determined experimentally for each impeller type)
G₁ – heat-carrier flow rate (m^3/h)
G₂ – circulating liquid flow rate (m^3/h)
k – overall heat-transfer coefficient ($\text{kW/m}^2.\text{K}$)
L_{coil} – coil length (m)
n – shaft rotational speed (min^{-1})
Nu₁, Nu₂ – Nusselt numbers describing heat transfer
Pr – Prandtl number
Pr_w – Prandtl number near the coil wall
Re – Reynolds number
 $\dot{Q}$ – heat flux (W)
S_c – cross-sectional area through which the heat carrier flows (m^2)
T – ambient temperature (K)($^{\circ}\text{C}$)
T₁, T₂ – temperatures of heat flows in the system (K)($^{\circ}\text{C}$)
W – heat-carrier velocity (m/s)
 α_1 , α_2 – heat-transfer coefficients ($\text{W/m}^2.\text{K}$)
 ΔT_{avg} – temperature difference between inlet and outlet of the heat carrier (K)($^{\circ}\text{C}$)
 $\varepsilon_{\Delta T}$ – correction factor for temperature difference (K)($^{\circ}\text{C}$)
 λ – thermal conductivity coefficient (W/m.K)
 λ_t – thermal conductivity of the heat carrier (W/m.K)
 μ – dynamic viscosity (Pa.s)
 ν – kinematic viscosity of water (m^2/s)
 ρ – fluid density (kg/m^3)
 θ_1 , θ_2 – emulsion temperatures in the reactor (K)($^{\circ}\text{C}$)

Conclusion

Laboratory investigations of heat transfer were conducted using four series of modified energy-efficient mechanical impellers. The values of Nu₂ and α_2 on the agitation side were experimentally determined using two types of liquid systems. The obtained results were presented in tabular and graphical form as functions of the Reynolds number during agitation (Re_a).

Additional experimental studies were also carried out using two and three impellers mounted along the length of the main

shaft, with the objective of improving mixing time and overall system efficiency. Particularly promising results were obtained with the Modified Propeller – MP-3.2 impeller. When compared in terms of Nu₂ and α_2 , this impeller demonstrated significantly better performance than the other tested designs.

These results may be applied in the design and sizing of reactors equipped with the same type of mechanical impellers for applications in the chemical, food-processing, and biotechnological industries.

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