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Dimensionless criteria energy dissipation of dynamically heating surfaces

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Abstract: In this paper, a discussion of results is presented for the dimensionless analysis of generating irreversibility of vessels in which mixing and heating of fluid are done simultaneously. In the first case, the impeller inside the mixing vessel is the heating body, and in the second case heating body is a fixed ring and the impeller inside the vessel provides only mixing of the fluid. The paper presents a comparative analysis of typical irreversible dimensionless parameters in both cases. A mathematical model is established to describe the thermal-hydraulic irreversibility of heating-mixing vessel which indirectly gives them the ability to minimize and maximize the efficiency of such a system. Also, the paper established typical relations between the dimensionless entropic values and power number, as for the water heater impeller and also for impeller, combined with a heating ring, which will enable comparison of the required power numbers

Keywords: Entropy Number, Heated Impeller, Mixing of Fluid, Thermal and Hydraulic Irreversibility, Ring, Vessel

1. Introduction

Heat transfer rates in agitated vessels are very important for many applications, and there are many papers and studies on heat transfer in mixing vessels [1]. Many studies and analyzes of agitated vessels are based on finding a correlation between the geometry of vessel and impeller, the physical properties of the agitated fluid, and correlations between the power and Reynolds number, etc. [2-3]. Many types, designs and sizes of agitators are used to mix fluids in vessels. Many studies and analyses discuss theoretical aspects and effects of fluid mixing in different vessels. For example, technical applications of various impeller types are discussed [3-8]. Highly viscous fluids are normally mixed by screw or helical ribbon impellers, which have relatively large convective heat transfer coefficients [6-10]. Installation of an electrical heating element inside an impeller blade [11] extends the overall role of the blade from only mechanical to included thermal effects due to heat transfer with the fluid. For a given blade geometry, the heating rate depends on the temperature gradient between the blade and the fluid and the convective heat transfer coefficient. Increasing the speed of rotation increases the heat transfer coefficient, decreases the blade surface temperature and affects the fluid temperature as it increases to reach thermal equilibrium with the temperature of the impeller blades. Increasing the electrical current intensity through the heater increases the blade temperature and establishes a steeper temperature gradient between the heated blades and the fluid, thus increasing the fluid heating rate. When heated blades rotate, irreversibility develops due to hydraulic friction, blade geometry and thermal irreversibility, which is caused by the existence of a temperature gradient between the heated blades and the fluid [12]. Therefore, considering the impeller and fluid as a closed system, the total entropy of this system is the sum of the thermally and hydraulically generated fluid entropy and the thermal entropy generated in the heat source, i.e., the heated blades. The rates of hydraulic and thermal irreversibility for constant convective impeller surfaces depend on the rotation speed of the impeller, the temperature differences between impeller and the fluid, the impeller geometry and the mass and physical properties of the fluid. If the fluid temperature in a closed vessel increases continuously and the impeller surface temperatures remain constant, then the temperature difference between the impeller and the fluid decreases, and, in general, transient convection occurs. Transient convection induced in this way generates transient fluid entropy before fluid entropy is thermally generated. An analysis of the causes for increases in the fluid entropy and the effects of heating impeller indicate possible methods for minimizing the losses caused by thermal and hydraulic irreversibility and maximizing the efficiency of similar irreversible heating-mixing fluid systems. This paper analyzes the typical thermal-hydraulic effects in a mixing vessel for modified anchor impeller with different rotating speeds, and different power number.

2. Heated Impeller

A diagram of simultaneously mixing and heating a fluid, e.g., water and thermal oil, in a vessel with heated impeller is shown in Figure 1. [11]. In this analysis, the impeller has a form of modified anchor impeller, which is immersed in a vessel of height H and diameter D, Figure 1. Fluids used in this case, are water and thermal oil. Heated surfaces of impeller are only vertical cylindrical parts of impeller within which are installed electric heaters, as shown in Figure 1. Electric motor that rotates the impeller within the vessel generates tangential flow field. Characteristic parameters for this system are given in Table. 1

***Table 1**. Characteristic parameters and values of variable used in this analysis.*

Physical properties at 40 °C	
Water	Thermal oil
$c = 4.175\ \mathrm{kJkg^{-1}K^{-1}}$	$c = 1.718\ \mathrm{kJ\,kg^{-1}\,K^{-1}}$
$\mu = 658.026 \cdot 10^{-6}\ \mathrm{Pa\,s}$	$\mu = 1.78 \cdot 10^{-3}\ \mathrm{Pa\,s}$
$\lambda = 0.633\ \mathrm{Wm^{-1}K^{-1}}$ Pr = 4.34	$\lambda = 0.12\ \mathrm{Wm^{-1}K^{-1}}$ Pr = 25.5
$\rho = 992.2\ \mathrm{kgm^{-3}}$	$\rho = 956\ \mathrm{kgm^{-3}}$
Geometrical properties of impeller and vassal	
$d_h = 0.008\,\mathrm{m}$, $h_i = 0.15\,\mathrm{m}$, $h_r = 0.023\,\mathrm{m}$, $d = 0.1\,\mathrm{m}$	
$D = 1.05 \cdot d$, $H = 0.33\,\mathrm{m}$	

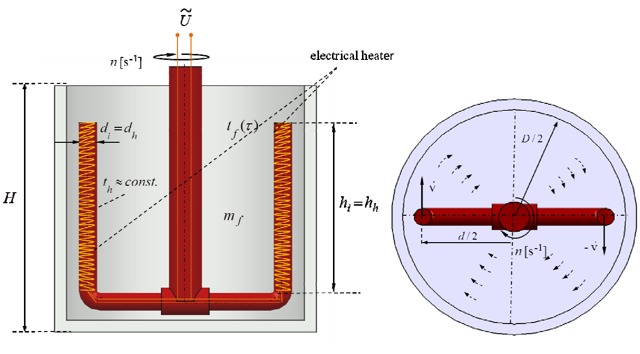

***Figure 1.** The simultaneously mixing and heating of the fluid heated impeller.*

As the main flow field around the heater is tangential, we will assume that the velocity of the flow around vertical heated surface is equal to its peripheral impeller speed. Temperature of the surface of the heated impeller is held constant, by regulating intensity of electric current through an electric heater inside the body of the impeller. For each test fluid, for water and thermal oil, the starting temperature is 30° C, while their physical properties are taken to average temperature of 40 ° C and are presented in Table 1.

The same table shows values of the geometrical characteristics of the modified anchor impeller, according to Figure 1. When simultaneously mixing and heating the fluid within the vessel, heat exchange between the heated impeller and fluid are established, and that also leads to the formation of hydraulic resistance between the surface of impeller and fluid. As already pointed heat exchange is established between the vertical parts of the impeller, while the hydraulic losses in this paper are calculated for the entire impeller area (heated and unheated part). Heat exchange between the impeller and the surface of heated fluids, as well as the generation of hydraulic losses within the vessel cause the creation of thermal and hydraulic irreversibility, and thermal and hydraulic entropy. On the other hand, knowledge of this irreversibility was achieved through their ability to minimize and maximize the efficiency of the process fluid within the mixing vessel while heating. In this paper, the description of the total generated irreversibility instead of generated entropy, will be used via the entropy number. The final expression for the total number of transient entropy is represented by the following equation [13].

$$\mathrm{N_{gen}}(\tau)=\ln\left(\frac{T_f(\tau)}{T_{f,o}}\right)+\frac{\rho_f\ (d\pi\cdot n)^3 C_{\mathrm{d}}(2h_i+d)\pi d_i}{2\ T_f(\tau) m_f c_f}\tau-\frac{2\alpha\left[t_h-t_f(\tau)\right]h_i d_i \pi}{T_h m_f}\tau \qquad (1)$$

where the $T_{f,o}$ initial fluid temperature, T_h surface temperature of heated impeller, the α convective heat transfer coefficient of the heated fluid to the impeller mass m_f, where fluid temperature during all time is calculated on the basis of equation (2), [6, 8].

$$t_f(\tau) = t_h-(t_h-t_{f,o})\ e-2\alpha d_i \pi\ h_i \frac{\tau}{m_f c_f} \qquad (2)$$

According to equations (1) and (2), Figure 2 presents the entropy numbers and fluid temperatures for water and thermal oil as a function of time

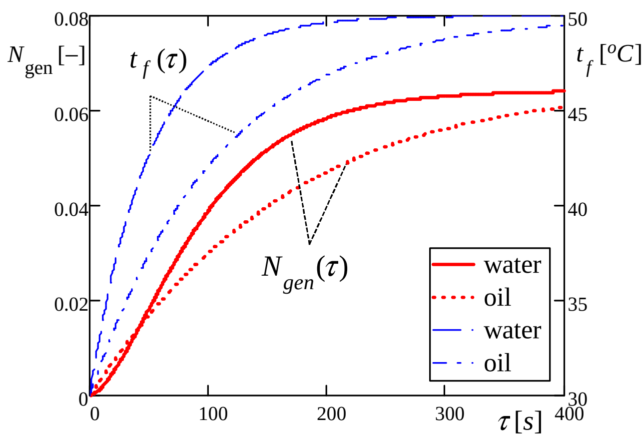

***Figure 2.** Entropy number and temperature of the fluid within the vessel.*

Convective heat transfer coefficient of the heated impeller to fluid α within the vessel is calculated in accordance with the Nu number for the flow of cross cylindrical body. In this analysis, we consider that the surface of the heated impeller is as fluid velocity $\vec{v}$, i.e. the same intensity of the peripheral velocity of the heated impeller i.e. $|\vec{v}| = |-\vec{v}_p|$. If the working fluid is water, then total entropy number at the start time of first $50\,s$ of the heating is more slowing compared to the thermal oil.

In the further process of heating, generated total entropy of water has a faster growth and higher value relative to oil, and after the heating start value of the entropy number of water becomes constant.

3. The Impeller and Heated Ring

In addition to previously analyzed heated impeller which simultaneously stirs and heats the fluid within the vessels, the case is considered when the vertical impeller parts are heating bodies, but electric heater ring with inner diameter D is embedded in the vessel wall. The annular heater is only in contact with the fluid within the vessel via inner surface, and the surface of the ring is equal to the surface of the heated impeller $2h_i d_i \pi$ which we have previously analyzed.

The temperature of the heated ring is kept constant during the test and is equal to the temperature of heated impeller i.e. $t_h = 50\ ^\circ C$. Fluid mass within the vessel is equal to the mass of fluid within the vessel as in previously tested heated impeller. The vessel is open and the surface of the fluid in the vessel is free.

Compared to the previous case with heated impeller, the value of Reynolds number for this case is taken for the whole vessel in which is established fluid mixing.

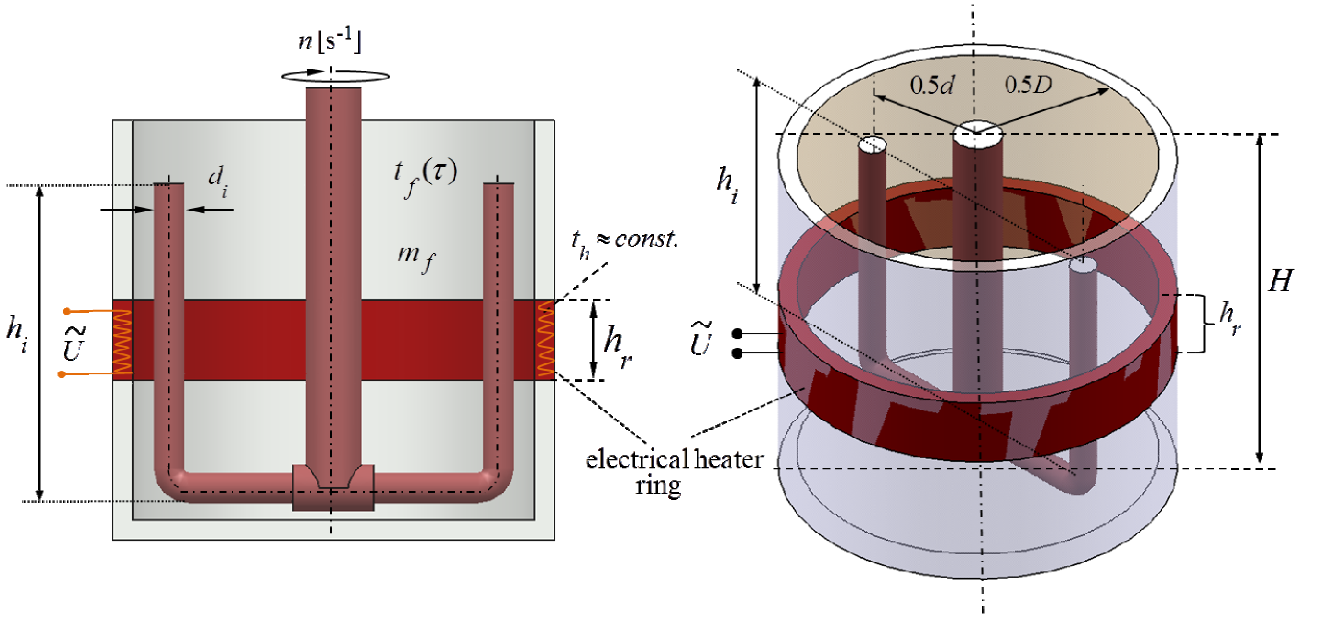

Figure 3. *Impeller and heated ring are the same and constant temperature.*

Convective heat transfer coefficient from heated ring to fluid within the vessel is determined by equation (3). As we noted, the exchange of heat between the annular electric heater and fluid within the vessel is realized only through the inner surface of the ring. Since the value of the Reynolds number is more than 10^4, for this mixing fluid within the vessel, the heat transfer coefficient from the electric ring heater in the fluid within the vessel is calculated as

$$\alpha = 0.38 \left(\frac{nD^2 \rho_f}{\mu_f} \right)^{\frac{2}{3}} \mathrm{Pr}^{\frac{1}{3}} \frac{\lambda_f}{D} \tag{3}$$

while functions N_{gen} and t_f presented in Figure 5.

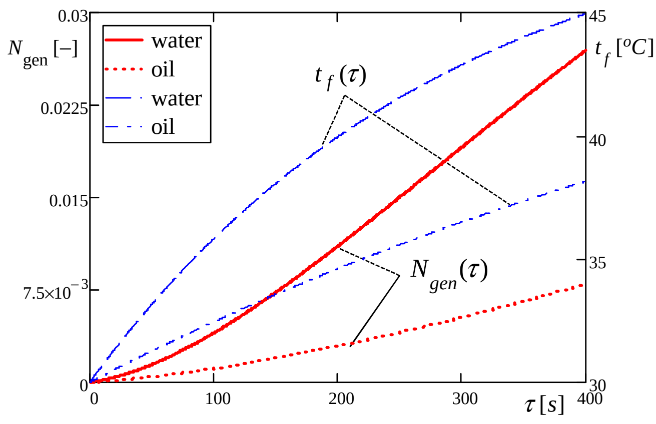

Figure 4. *The entropy number and fluid temperature – heated ring.*

4. Comparative Analysis

We will now establish a comparative analysis of the dimensionless thermal and hydraulic irreversibility of mixing fluid within the vessel with heated impeller and heated ring.

The surface temperature for both cases, when the heating bodies are impeller or when the ring is held at a constant value of 50 °C. The time interval of the process of heating water and thermal oil within the vessel is 400s. Now introduce the entropy number N_{gen} of in function power number $N_p = P_{em} D^{-5} n^{-3} \rho_f^{-1}$, when the impeller is heating body, or when the heating body is a ring, Figure 5.

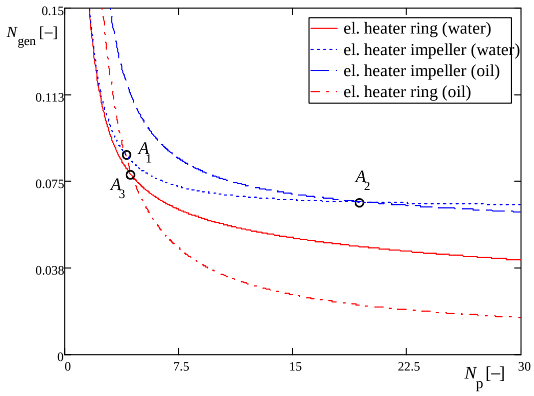

***Figure 5**. The relationship between entropy number and power number.*

The power number N_p is used to relate the resistance force to the inertial force of the fluid within the mixing vessel. By increasing the value of the power number N_p, total generated entropy S_{gen} decreases, or the value of the entropy number N_{gen}. The appropriate entropy number values power numbers for different types of fluids and different heating bodies, and what counts is presented, A_1, A_2 and A_3. The higher the value of the power number N_p means a lower speed impeller n, which indirectly implies a lower value of the entropy number or less irreversibility of such mixing system. On the other hand, maximizing the efficiency of such systems can be achieved by minimizing the total thermal hydraulic irreversibility.

In the dimensionless thermal-hydraulic analysis of irreversibility, except entropy number N_{gen}, Bejan number Be is also often used, which represents the ratio of heat transfer irreversibility to total irreversibility due to heat transfer and fluid friction within the vessel.

Bejan number and irreversibility distribution rate, will be analyzed in relation to the power number N_p.

Bejan number represents the ratio of entropy generation due to heat transfer exchange and total generated entropy, and derived an expression for Bejan number [13] is represented by equation (4).

$$\mathrm{Be(Np)} = \frac{S_{gen,\Delta T}(\mathrm{Np})}{S_{gen,\Delta T}(\mathrm{Np}) + S_{gen,\Delta p}(\mathrm{Np})} =$$

$$= \frac{\dfrac{m_f}{\tau} c_f \ln\left(\dfrac{T_f(\mathrm{Np})}{T_{f,o}}\right) - 2\dfrac{\alpha(\mathrm{Np})\cdot(t_h - t_f(\mathrm{Np}))d_i \pi h_i}{T_h}}{\dfrac{m_f}{\tau} c_f \ln\left(\dfrac{T_f(\mathrm{Np})}{T_{f,o}}\right) + \dfrac{\rho_f \left[d\pi \left(\dfrac{2\pi M_\omega}{\rho_f d^5 \mathrm{Np}} \right)^{0.5} \right]^3 C_d (2h_i + d)\pi d_i}{2T_f(\mathrm{Np})} - 2\dfrac{\alpha(\mathrm{Np})\cdot(t_h - t_f(\mathrm{Np}))d_i \pi h_i}{T_h}} \tag{4}$$

where $S_{gen,\Delta T}$ the entropy generation due heat transfer exchange, $S_{gen,\Delta p}$ entropy generation due to hydraulic losses.

As we have previously noted, other than these two dimensionless values N_{gen} and Be that were used, another dimensionless parameter is used i.e. irreversibility distribution rate ϕ. The irreversibility distribution rate ϕ is the ratio between the generated entropy due to hydraulic losses $S_{gen,\Delta p}$ in relation to the generated entropy caused by thermal processes $S_{gen,\Delta T}$, equations 6.

The irreversibility distribution rate $\phi(\mathrm{Np})$ is shown by the following equation [13].

$$\phi(\mathrm{Np}) = \frac{S_{gen,\Delta p}(\mathrm{Np})}{S_{gen,\Delta T}(\mathrm{Np})} =$$

$$= \frac{\dfrac{\rho_f \left[d\pi \left(\dfrac{2\pi M_\omega}{\rho_f d^5 \mathrm{Np}} \right)^{0.5} \right]^3 C_d (2h_i + d)\pi d_i}{2T_f(\mathrm{Np})}}{\dfrac{m_f}{\tau} c_f \ln\left(\dfrac{T_f(\mathrm{Np})}{T_{f,o}}\right) - \dfrac{2\alpha(\mathrm{Np})\cdot(t_h - t_f(\mathrm{Np}))d_i \pi h_i}{T_h}} \tag{5}$$

With increased values of power number, the intensity of irreversibility distribution rate ϕ decreases, while there is an increase in the value of Bejan number Be, Figure 6. The fastest decrease in irreversibility distribution rate is apparent in mixing vessels with heated impeller and the working fluid water. Bejan number for this case has a maximum value in the whole interval of power number Np.

Figure 6 shows the characteristic points F_1, F_2, F_3 i F_4 as a cross of function $\mathrm{Be(Np)}$ and $\phi(\mathrm{Np})$. The characteristic feature of these points is that they lie in the same direction, in our case the value of Bejan number is 0.62, and this value also has the irreversibility distribution rate $\phi(\mathrm{Np})$. Based on the obtained direction F - F, where the equality that $Be(\mathrm{Np}) = \phi(\mathrm{Np})$ the conclusion was reached that the various changes in the operating parameters of both fluid and change the operating parameters of the heated body, place sectional function which must lie on a straight line F - F. The above feature enables indirect finding of function $\phi(\mathrm{Np})$ over $\mathrm{Be(Np)}$ and vice versa.

According to Figure 6, when using thermal oil and water it leads to the conclusion that to obtain the same value of Be i.e. ϕ at mixing thermal oil it is necessary to use a higher value of the power number Np or speed impeller velocity must be less than in the case where the working fluid is water. Also, on the basis of Figure 6 and earlier definition of Be and ϕ, the following equation is reached that links the generated entropy caused by thermal and hydraulic irreversibility.

$$S_{gen,\Delta T}^{2} - S_{gen,\Delta p} S_{gen,\Delta T} - S_{gen,\Delta p}^{2} = 0 \qquad (6)$$

whose solving obtains exact irreversibility distribution rate and Bejan number

$$\phi = Be = \frac{2}{1+\sqrt{5}} \approx 0.62$$

which also coincides with the values obtained in Figure 6.

5. Conclusions

Mixing of fluid within the agitated vessel with heated impeller quickly heats fluid, comparing to the motionless heater with same power with established mixing by impeller.While simultaneously mixing and heating a fluid with heating impeller, hydraulic and thermal fluid irreversibility is generated by interaction with the heating impeller, and thermal irreversibility is also generated because the heating impeller is sources of constant temperature.

Faster heating of the fluid causes a rapid rise of thermal irreversibility compared with existing agitated vessels. Higher impeller speed pulls greater hydraulic losses and generates more entropy due to hydraulic effects. The results obtained in this paper established the dimensionless mathematical model of mixing and heating in agitated vessel. Dimensionless irreversibility criteria such as the entropy number, irreversibility distribution rate and Bejan number are presented as function of power number.

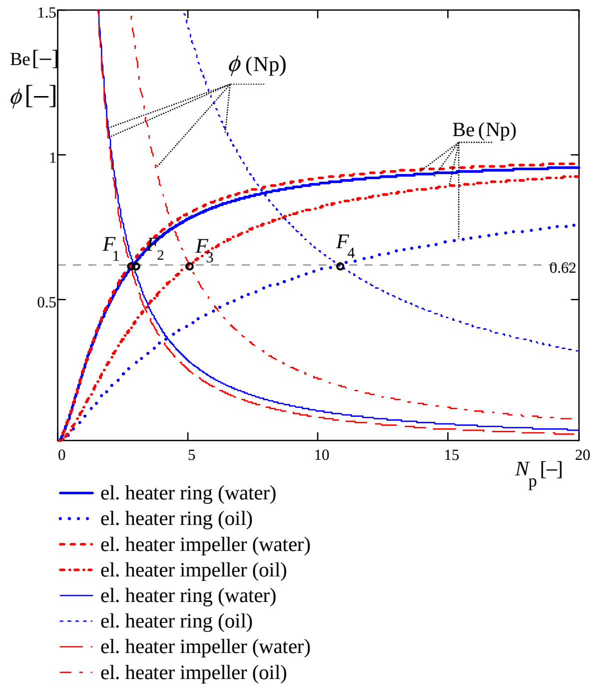

***Figure 6.** The fluid temperature within the vessel in the function of heater speed.*

Obtained results and functional dependency led to the results which give an answer to how time and power number influences the dimensionless irreversibility parameters of this system. Based on the obtained results, a new mathematical model for minimizing the total generated entropy of the system can be established, maximizing its efficiency rate. When analyzing the joint presentation of Bejan number and irreversibility distribution rate, in this paper, the establishment of a new function, equation 7, is presented which gives the functional dependence of $S_{gen,\Delta T}$ and $S_{gen,\Delta p}$, in case where the value of Bejan number and irreversibility distribution rate are same.

Namely, in this study we came to the conclusion that the functions $\mathrm{Be(Np)}$ and $\phi(\mathrm{Np})$ always intersect in the same direction, i.e. the same value of approximately 0.62, which is shown through mathematical equations, solution 7.

The results obtained in this study show the dominance of heated impeller in relation to heating of the fluid within the vessel using impeller and motionless heater. Hydraulic and thermal irreversibility indirectly suggest unwanted losses, and there are multiple methods possible for minimizing these losses and maximizing the efficiency of this system.

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Nomenclature

d - impeller diameter [m]
P_{em} - mechanical power required by the impeller [W]
M_{ω} - torque [N m]
t_h - temperature of a heated impeller [°C]
t_f - fluid temperature [°C]
t_w - fluid temperature (water) [°C]
t_{oil} - fluid temperature (thermal oil) [°C]
$t_{f,o}$ - initial fluid temperature [°C]
n - impeller speed [s^{-1}]
A – total blade surface [m^2]
Pr_o - Prandtl number for fluid (thermal oil), dimensionless
I - electrical current intensity through heater [A]
c_w - fluid specific heat capacity (water) [kJ kg^{-1} K^{-1}]
Re_w - Reynolds number, dimensionless
Pr_w - Prandtl number for fluid (water), dimensionless
N_{gen} - entropy number, dimensionless
N_p - power number, dimensionless
Be - Bejan number
$S_{gen,H}$ – entropy generation due to hydraulic losses [W K^{-1}]
$S_{gen,T}$ – entropy generation due to heat transfer exchange [W K^{-1}]

Greek symbols

ρ_f - fluid density [kg m^{-3}]
ρ_w - fluid (water) density [kg m^{-3}]
ρ_o - fluid (thermal oil) density [kg m^{-3}]
μ_w - fluid dynamic viscosity (water) [Pa s]
μ_o - fluid dynamic viscosity (thermal oil) [Pa s]
λ_w - fluid thermal conductivity (water) [W m^{-1} K^{-1}]
λ_o - fluid thermal conductivity (water) [W m^{-1} K^{-1}]
τ - time [s]
ω - angular impeller velocity [rad s^{-1}]
ϕ - irreversibility distribution ratio, dimensionless

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