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Original Research Article
**The Impact Of Temperature On the Removal Of
Nitrogen Compounds In Activated Sludge
System**

ABSTRACT

Introduction: The temperature, as one of the essential factors affecting the growth and survivability of all microorganisms, may have an impact on them in two opposite directions: the change in the temperature (its increase and decrease) may have a positive impact on the growth rate or may lead to the irreversible inactivation and degradation of the components. It influences on the efficiency of biological wastewater treatment carried out by microorganisms.

Aims: This paper presents the results of test performed in the model activated sludge system. The impact of temperature on the nitrogen compounds removal processes was investigated, within the temperature ranging between 10 and 37°C.

Methodology: The evaluation of the temperature impact on the processes of removal of nitrogen compounds was made on the basis of the laboratory tests conducted in the activated sludge system. The system was supplied with synthetic wastewater in the composition approximated that of the typical household wastewater. Each value of analyzed parameters (TKN, N-NH₄, N-NO₃, BOD₅, COD, X) was determined as the average of the values measured in the following nine days. The formulations of ASM Models were used to calculate the kinetic parameters of transformations of the nitrogen compounds in the activated sludge process.

Results: The degree of removal of total nitrogen from the wastewater within the temperature range between 10 and 34°C was at the level of 75.5-90.6% (12.5-4.8 gN/m³), and at the temperature of 37°C, it amounted to 71.8% (14.4 gN/m³). The highest efficiency of overall nitrogen removal was observed within the temperature range from 10°C to 22°C and from 32°C to 35°C. Temperature coefficient values Θ was different in various temperature ranges.

Conclusion: It was determined that the assumption of an exponential increase in the rate of biochemical reactions together with an increase in the temperature does not take into account the changes of the physiological condition of microorganisms. The activity of the bacteria does not change exponentially together with the increase in temperature, but rather demonstrates the minimum and maximum values. Temperature coefficient value Θ can be regarded as a constant only within a strictly defined temperature range, characteristic for the respective groups of microorganisms.

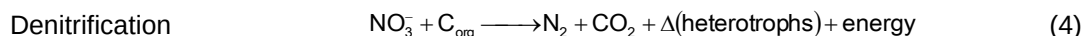
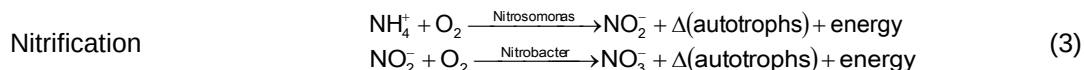
Keywords: temperature coefficient, nitrification, denitrification, activity of bacteria

1. INTRODUCTION

The works on the selection of the highly efficient technology of removal of nitrogen compounds from wastewater have been conducted for many years in scientific-research centres. They concentrate on nitrification and denitrification processes, which run simultaneously with the bio-oxygenation processes of organic substances, most often with the use of active sludge biomass.

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21 The simplified stoichiometric model of the process of wastewater treatment, including the
 22 biochemical transformation of nitrogen compounds can be put down in the form of formulas:



23 In general, it is assumed that the active sludge biomass comprises:

- 24 1. heterotrophic biomass X_H , which covers all organisms that decompose the organic
 25 substances and are responsible for ammonification and denitrification;
- 26 2. autotrophic biomass X_A , covering mainly nitrificants. Due to the fact that no nitrites
 27 are singled out as a separate substance in the technological evaluation of the
 28 nitrification process, the division into organisms that oxidise ammonia nitrogen to
 29 nitrites (*Nitrosomonas*) and those that conduct the second phase of oxidation to
 30 nitrates (*Nitrobacter*) is unnecessary.
- 31 3. the inactive part of active sludge mass X_i , which constitutes the sum of a part of
 32 biologically neutral suspended matters at the supply of sewage to the system, and
 33 the neutral mass produced as a result of biomass atrophy [3].

34 The share of the respective groups of microorganisms in the bacterial culture depends on
 35 the conditions inside the activated sludge chamber. Above all, the changes occurring in the
 36 activated sludge flocs, including the effect of removal of nitrogen compounds from
 37 wastewater, are affected, by the temperature, pH and environment alkalinity, aeration,
 38 mixing, nutrients and toxic substances (inhibitors).

39 The temperature, as one of the essential factors affecting the growth and survivability of all
 40 **microorganisms**, may have an impact on them in two opposite directions: the change in the
 41 temperature (its increase and decrease) may have a positive impact on the growth rate or
 42 may lead to the irreversible inactivation and degradation of the components. The final result
 43 will be the inhibition of the growth or death of the given cell [8, 27]. The studies of the
 44 dependencies of the growth rate on the temperature show that the point or the narrow range,
 45 in which the cell growth is the highest, is achieved for each species of microorganisms taking
 46 part in the wastewater treatment process. This is the optimal temperature. Different optimal
 47 temperature ranges correspond to the development of different organisms. The minimum
 48 and maximum temperatures determine the possible limits of the cell growth and
 49 development. These three points often referred to as cardinal temperatures, are not fixed
 50 values for the respective microorganisms, but can be subject to a shift as a result of changes
 51 in other factors, as well as to the adaptive ability of the microorganisms. For instance, the
 52 *Zooglea ramigera* bacteria, which impact the formation and the structure of an activated
 53 sludge floc, occur within the temperature range between 10 and 40 °C, and their optimal
 54 growth takes place within the temperature range between 28 and 30 °C [15, 25].

55 In principle the temperature of household wastewater in the moderate climate ranges
 56 between 10 and 20 °C. It follows from the above that the household wastewater temperature
 57 conditions the development of the activated sludge organisms within the temperature range
 58 optimal for psychrophilic bacteria [18].

59 The equations analogous to the dependencies used in the description of the impact of
 60 temperature on the kinetics of simple chemical reactions are used for the description of the
 61 temperature impact on the processes of biochemical degradation of organic substances as
 62 well as oxygenation and reduction of nitrogen compounds with the participation of activated
 63 sludge microorganisms [6].

64 Arrhenius, described the relationship between the reaction rate constant k and temperature
 65 T by the following equation [20]:

66 $k = A \cdot e^{-E/R \cdot T}$ (5)

67 The Arrhenius equation is true for the majority of simple chemical reactions and the E
 68 coefficient has a clearly specified physical sense only for them. For complex reactions, the
 69 Arrhenius equation may be fulfilled when the total speed of the process is equal to the speed
 70 of the stage which is the slowest. In case of treatment of the wastewater with the use of
 71 activated sludge, equation (5) may be expressed in the following form:

72 $k_t = k_{20} \cdot \Theta^{(T-20)}$ (6)

73 In spite of elaborating upon other relationships in the subsequent years, at present, equation
 74 (6) is used most frequently in determining the impact of temperature on the processes of
 75 biological treatment of wastewater with the use of activated sludge.

76 The higher the value of temperature coefficient is, the greater the impact of temperature on
 77 the rate of degradation, and therefore, the biodegradability of substrates, is.

78 The value of temperature coefficient set for the processes run in different technological
 79 conditions was specified in Table 1.

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81 **Table 1. The value of temperature coefficient Θ for different biochemical processes**

Process	Factor Θ	References
activated sludge		
load a) > 0,5 kg BOD ₅ / kg d.o.m. d	1.0	[28]
b) < 0,5 kg BOD ₅ / kg d.o.m. d	1.0-1.04	
aerobic ponds	1.035	[21]
anaerobic ponds	1.070-1.080	[14]
nitrification process	1.120	[9]
denitrification process	1.060-1.130	[1]
	1.013	[16, 17]
anaerobic digestion of sewage sludge	1.066	[4]
	1.07	[29]

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83 The values of the temperature coefficient were specified in Table 2 for the nitrification and
 84 denitrification processes, running with the participation of the activated sludge
 85 microorganisms.

86 **Table 2. The values of temperature coefficient Θ for the nitrification and**
 87 **denitrification processes**

Process	Temperature, °C	Sample	Factor Θ	References
Nitrification	4-10	synthetic wastewater	1.165	[13]
	5-20	municipal wastewater	1.12	[10]
	7-15	municipal and	1.02	[19]
	2-6	industrial wastewater	1.4	

		dry mass of sewage sludge (mg/dm ³)		
	4-25	3200	1.129	[23]
		1200	1.061	
		430	1.028	
	4-10	synthetic wastewater	1.132	[13]
Denitrification	5-20	municipal wastewater	1.15	[10]
	7-15	municipal and	1.06	
	2-6	industrial wastewater	1.30	[19]

The studies conducted by Schroeder and Friedman [22] proved that equation (6), may be used only to a limited extent in order to specify its impact on the kinetics of the biological wastewater treatment. The application of this equation to describe the impact of temperature on kinetics of the process of nitrogen removal from wastewater gives results which deviate significantly from the reality. These differences are a result of the dependence of the temperature coefficient values on the type of substrates and the adaptive ability of the respective groups of bacteria to the given wastewater treatment temperature. Not only does an increase in the temperature affect the rate of biochemical reactions (metabolism), but also the physiological condition (structure) of the microorganisms. The mathematical relationships presently used to interpret the experimental studies (including equation (6)) do not consider the impact of temperature on the type and properties of substrates and the series of other parameters and phenomena such as the ones mentioned below:

- fluid viscosity,
- the value of surface tension
- the concentration of dissolved oxygen,
- the kinetics of gas exchange between the gas-liquid-gas phases,
- the course of the process of mixing the content of the activated sludge chamber,
- the solubility of nutrients (substrates),
- the sedimentation of suspended matter, including activated sludge flocs,

which may also impact the speed of the course of the process significantly.

The problem of proper determination and assumption of the temperature coefficient values becomes significant at the stage of designing the volume of activated sludge chambers. The calculated maximum rate of nitrificant growth depends on this value, and in turn, this parameter affects the age of the activated sludge, and thus the capacity of the wastewater treatment facilities. This issue is of standing importance, especially in the technology of treatment of wastewater with enhanced temperature and in warm climate.

2. METHODOLOGY

2.1 Scope Of The Test

The evaluation of the temperature impact on the processes of removal of nitrogen compounds was made on the basis of the tests conducted in the activated sludge system. The activated sludge used in the tests was collected from the municipal sewage treatment plant and adapted to the operation in the system for 2 weeks. The temperature range between 10 and 37°C was changed every 3°C, in time intervals required as the adaptation period of the activated sludge microorganisms (7-14 days).

The system was supplied with synthetic wastewater in the composition approximated that of the typical household wastewater. The organic contamination was modelled with the use of starch (100 g/m³), glucose 240 (g/m³) and sodium glutamate (250 g/m³), and the

ammonium chloride (95 g/m^3) was used as the source of non-organic nitrogen. Micronutrients were the salts of zinc, manganese, molybdenum and copper. The batch of wastewater with the volume of 5 dm^3 was prepared every day. The physico-chemical parameters of the synthetic wastewater were specified in Table 3. The characteristic quotients for the prepared synthetic wastewater were as follows: $\text{P/BOD}_5 = 0.035$, $\text{N/BOD}_5 = 0.156$, $\text{COD/BOD}_5 = 2.26$.

Table 3. Physico-chemical properties of synthetic wastewater

	Parameter	Unit	Value
1.	pH	-	7.3
2.	Alkalinity	mval/dm^3	4.5
3.	Total solids	g/m^3	1132
4.	Dissolved substances	g/m^3	818
5.	Total suspension	g/m^3	314
6.	Organic suspension	g/m^3	269
7.	COD	$\text{g O}_2/\text{m}^3$	736
8.	BOD_5	$\text{g O}_2/\text{m}^3$	326
9.	N-NH_4^+	$\text{g N-NH}_4/\text{m}^3$	31
10.	N_{org}	g N/m^3	20
11.	Phosphates	$\text{g PO}_4^{3-}/\text{m}^3$	35

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The test station consisted of:

- 140 - the denitrification chamber with the volume of $V = 2.52 \text{ dm}^3$
- 141 - the nitrification chamber with the volume of $V = 4.21 \text{ dm}^3$
- 142 - the secondary clarifier with the volume of $V = 1.9 \text{ dm}^3$
- 143 - the feed tank with the volume of $V = 5 \text{ dm}^3$.

144 The gravity wastewater flow ($4 \text{ dm}^3/\text{d}$) was provided for in the system. Hydraulic retention time, calculated in relation to the volume of the nitrification and denitrification chamber, respectively, for the relevant processes was equal to 1.05 and 0.63d. Sludge retention time depends on temperature. It was from 18.7d (10°C) to 12.7 d (37°C).

145 The required oxygen concentration in the nitrification chamber equal to $1.5 \text{ mgO}_2/\text{dm}^3$ was
 146 ensured by the fine bubble-diffused aeration of wastewater. The sludge-wastewater mixture
 147 was kept in constant motion in the activated sludge chambers by low speed mixers. The
 148 external recirculation of activated sludge (in order to obtain the constant biomass
 149 concentration in the system) amounted to 100%, and the internal recirculation used to
 150 intensify the denitrification process amounted to 200% in relation to the average daily
 151 wastewater flow. The following measurements were performed in the activated sludge
 152 chambers by means of the Multiline P4 WTW meter: temperature, oxygen concentration and
 153 oxygen reduction potential. The constant required temperature of the sludge-wastewater
 154 mixture in the system was kept by means of the thermostating system, which consisted of: a
 155 thermostat, a contact thermometer, a water jacket and thermal insulation.

156 Within the framework of the analytic process control 90 series of determinations were
 157 performed. The physico-chemical properties of the wastewater discharged from the system,
 158 the process parameters in the activated sludge chambers, the activity of the activated sludge
 159 and its morphological composition were examined.

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164 The activated sludge from the microscopic examinations was collected from the aeration
 165 chamber. The following elements were analysed during the observation: resilience,
 166 appearance, structure and size of the flocs, existence of organic compounds, composition of
 167 flocs and in particular, the number of protozoans, rotifers and nematodes, *Zooglea* and
 168 *Treponema Pallidum*. The microscopic analysis of the activated sludge aimed at
 169 determination of the changes in the population of microorganisms at the time of the tests and
 170 depending on the temperature of running the wastewater treatment process. The
 171 observations were made by means of the optic microscope, performing five analyses at a
 172 given temperature in 2-days intervals.
 173 The analyses of the quality of raw and treated wastewater were performed in accordance
 174 with the applicable standards (Standard Methods for the Examination of Water and
 175 Wastewater APHA) [24].

176 2.2 Methodology Of Calculations

177 The parameters of kinetics of the nitrification and denitrification processes were determined
 178 on the basis of the following results of measurements and calculations: wastewater flow,
 179 concentration of substrate at the supply and discharge (in reference to the TKN - nitrification,
 180 nitrate nitrogen - denitrification), biomass concentration, oxygen and age of sludge and
 181 substrate uptake rate. The maximum growth rate of *Nitrobacter* is much greater than the
 182 maximum growth rate of *Nitrosomonas*. In the established conditions of the wastewater
 183 treatment process, the nitrites do not accumulate in the biological treatment system in great
 184 quantity. The growth value of the nitrificants may be determined only when the limited growth
 185 value of the nitrification bacteria, leading to the transformation of ammonia nitrogen into
 186 nitrites, is taken into account.

187 While determining the kinetic parameters of the nitrification and denitrification processes, it
 188 was assumed that:

- 189 - the growth rate of nitrificants and denitrificants in the activated sludge chamber was not
 190 limited by the concentration of phosphorus and alkalinity;
- 191 - the process of assimilation of ammonia, nitrite and nitrate nitrogen may be omitted in the
 192 description of the nitrification and denitrification process kinetics;
- 193 - the growth rate of the denitrificants may be determined only when the limited growth rate of
 194 denitrification bacteria, leading to the transformation of nitrate nitrogen into free nitrogen, is
 195 taken into account.

196 The following formulations were used to calculate the kinetic parameters of transformations
 197 of the nitrogen compounds in the activated sludge process (ASM Model) [2]:

$$198 \quad Y = \frac{(Q_w \cdot X_r + Q_e \cdot X_e)}{(S_o - S_e) \cdot Q_e} \quad [\text{kg d.o.m./kg}] \quad (7)$$

199 It must be noticed that depending on the assumed substrate (e.g. BOD₅, TKN, N-NO₃) we
 200 will receive the value of parameter Y expressed in [kg d.o.m./ kg BOD₅] or [kg d.o.m./kg N-
 201 NH₄], [kg d.o.m./ kg N-NO₃]. The same remark refers to such parameters as U , r_{su} :

$$202 \quad U = \frac{Q}{V_k} \cdot \frac{S_o - S_e}{X} \quad [\text{kg/kg d.o.m.} \cdot \text{d}] \quad (8)$$

$$203 \quad r_{su} = \frac{S_o - S_e}{\text{HRT}} \quad [\text{kg/m}^3 \cdot \text{d}] \quad (9)$$

$$204 \quad q_A^{\max} = \frac{U_A}{\left(\frac{S_{\text{NH}_4, e}}{K_{\text{NH}_4} + S_{\text{NH}_4, e}} \right) \cdot \left(\frac{S_{\text{O}_2}}{K_{\text{O}_2} + S_{\text{O}_2}} \right)} \quad [\text{kg/kg d.o.m.} \cdot \text{d}] \quad (10)$$

$$205 \quad q_H^{\max} = \frac{U_H}{\left(\frac{S_{\text{NO}_3}}{K_{\text{NO}_3} + S_{\text{NO}_3}} \right) \cdot \left(\frac{S_{\text{NH}_4, e}}{K_{\text{NH}_4} + S_{\text{NH}_4, e}} \right) \cdot \left(\frac{S_{\text{O}_2}}{K_{\text{O}_2} + S_{\text{O}_2}} \right) \cdot \left(\frac{S_{\text{ChZT}}}{K_F + S_{\text{ChZT}}} \right)} \quad [\text{kg/kg d.o.m.} \cdot \text{d}] \quad (11)$$

$$\mu_r = Y \cdot U \quad [d^{-1}] \quad (12)$$

$$\mu_r^{net} = \frac{1}{SRT} \quad [d^{-1}] \quad (13)$$

$$k_d = \mu_r - \mu_r^{net} \quad [d^{-1}] \quad (14)$$

$$\mu_A^{max} = \frac{\mu_A^r}{\left(\frac{S_{NH_4,e}}{K_{NH_4} + S_{NH_4,e}} \right) \cdot \left(\frac{S_{O_2}}{K_{O_2} + S_{O_2}} \right)} \quad [d^{-1}] \quad (15)$$

$$\mu_H^{max} = \frac{\mu_H^r}{\left(\frac{S_{NO_3}}{K_{NO_3} + S_{NO_3}} \right) \cdot \left(\frac{S_{NH_4,e}}{K_{NH_4} + S_{NH_4,e}} \right) \cdot \left(\frac{S_{O_2}}{K_{O_2} + S_{O_2}} \right) \cdot \left(\frac{S_{ChZT}}{K_F + S_{ChZT}} \right)} \quad [d^{-1}] \quad (16)$$

In equations (10), (11), (15), (16), the values of saturation constants were assumed in accordance with the guidelines included in the study of the mathematical model of wastewater treatment in the activated sludge process.

The percentage of X_A and X_H in the activated sludge biomass belongs to one of the basic parameters necessary to determine the kinetic coefficients of the processes of organic compound biooxygenation and nitrogen compound removal from the wastewater.

The mass of autotrophies X_A was calculated on the basis of the percentage share of the nitrification bacteria in the activated sludge biomass depending on quotient $\Delta BOD_5/\Delta TKN$ [26]. The inactive part of activated sludge biomass X_i was determined from a relationship included in (17), taking into account the fraction of the biologically neutral organic suspensions at the wastewater supply (without the share of neutral mass produced as a consequence of biomass atrophy, which ranges between 0.5% and 6% of biomass depending on the temperature) [5]:

$$X_i = 0,6 \cdot TS \cdot \rho \cdot SRT, \quad [kg \text{ d.o.m.}/m^3] \quad (17)$$

The mass of heterotrophies X_H , capable of denitrification was calculated from equation (18), assuming the share of denitrificants in the biomass of heterotrophies: $\eta_D = 0,6$ [3]:

$$X_H = \eta_D (X - X_A - X_i), \quad [kg \text{ d.o.m.}/m^3] \quad (18)$$

In each of the tested temperatures, determinations of X_{smo} were made on the basis of three samples during nine consecutive days. The mean results of determinations were the basis for calculations of the mass of heterotrophies X_H , autotrophies X_A , and part of the inactive mass of activated sludge X_i .

3. RESULTS

3.1 Microscopic observations

Within the whole temperature range, the activated sludge flocs were rounded, brown, strong and with compact structure (internal structure of the flocs contained few perforations). Because of the content of filamentous bacteria, the activated sludge was classified into category 1 (the filamentous bacteria occurred in small quantity) [7].

Within the temperature range between 10°C and 28°C, an increase in the number of protozoans was observed. Above the temperature of 28°C, their number was decreased and at the temperature of 37°C, they occurred sporadically. The activated sludge contained anchored ciliates - *Vorticella* and *Opecularia*, as well as *Carchesium*, *Epistilis*, and *Aspidisca*, crawling among the flocs, which confirmed the correct course of the sewage treatment process. Flagellates in the tested activated sludge occurred sporadically. Within the temperature range between 10 and 13°C, a group of *Rhizopoda* appeared. The microorganisms from the group of rotifers, regarded as bioindicators of the correct wastewater treatment process, occurred within the whole temperature range. Above the

temperature of 34°C, a sudden reduction in the number of all the species of microorganisms was observed.

3.2 The Concentrations Of Nitrogen Compounds In The Treated Wastewater

The course of changes in the quantity of organic nitrogen, ammonia nitrogen, nitrite nitrogen and overall nitrogen in the treated wastewater, depending on the temperature of tests, was presented in Fig.1.

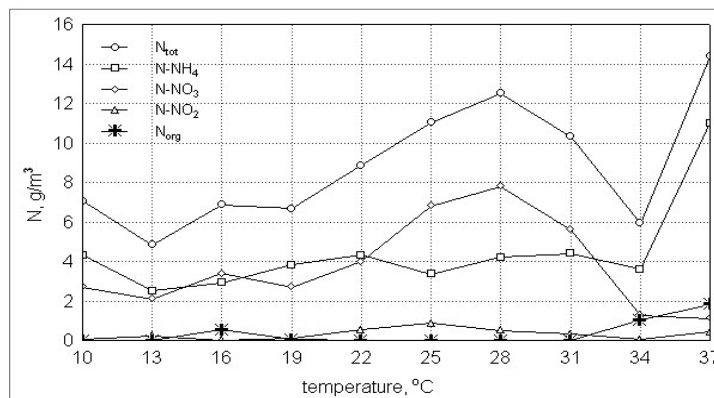


Fig. 1. Changes of various forms of nitrogen in the treated wastewater within the temperature range of 10 - 37°C

The changes in the concentrations of all the nitrogen forms in the treated wastewater, depending on the temperature in which the process was run, confirmed the proper course of the nitrification and denitrification processes.

The course of changes in the concentrations of the overall nitrogen and nitrate nitrogen in the wastewater treated within the temperature range between 10 and 34°C, was comparable. The nitrate nitrogen concentrations ranged between 1.27 and 7.80 gN-NO₃/m³, with the maximum at the temperature of 28°C. The concentrations of organic nitrogen, ammonia nitrogen and nitrite nitrogen did not show clear changes in relation to the temperature increase within the tested range of values. The sudden increase in the concentration of the ammonia nitrogen and organic nitrogen at the temperature of 37°C was an exception. Observed increase of the concentration of ammonia nitrogen in temperatures above 34°C, was due of microorganisms death and hydrolysis process occurring organic nitrogen contained in the body proteins.

The ammonia nitrogen was oxidised to a high and comparable extent (85.7-91.9%). Its concentration in the treated wastewater changed within the range from 2.50 to 4.42 g N-NH₄/m³. At the temperature of 37°C, the concentration of ammonia nitrogen at the discharge was several times higher and amounted to 11.0 gN-NH₄/m³ (degree of removal 64.5%).

The degree of removal of the organic nitrogen, within the temperature range between 10 and 34°C was kept at the level from 94.5% to 100% (concentration ranging between 0.0 and 1.02 gN_{org}/m³), and fell to 91% (1.83 gN_{org}/m³) at the temperature of 37°C.

The degree of removal of total nitrogen from the wastewater within the temperature range between 10 and 34°C was at the level of 75.5-90.6% (12.5-4.8 gN/m³), and at the temperature of 37°C, it amounted to 71.8% (14.4 gN/m³). The highest efficiency of overall nitrogen removal was observed within the temperature range from 10°C to 22°C and from 32°C to 35°C.

3.2 The Kinetic Parameters Of Nitrogen Compound Transformations In The Activated Sludge Process

The result of the mathematical analysis of the measuring data was the determination of basic dependencies of basic kinetic parameters on the temperature of wastewater treatment and then the determination of temperature coefficient values. The values of the kinetic parameters of the nitrification and denitrification processes were calculated within the tested temperature range from 10 to 37°C, in 3°C intervals. Within the framework of the conducted tests, the dependencies of the following parameters on the temperature were determined from equations 7-16:

- efficiency of microorganism growth (Y),
 - substrate uptake rate (U),
 - referred to the total activated sludge biomass;
 - and
 - maximum nitrificant and denitrificant growth rate ($\mu_A^{\max}$ and $\mu_H^{\max}$);
 - nitrificant and denitrificant efficiency growth (Y_A and Y_H);
 - biomass self-oxidisation coefficient (k_{dA} and k_{dH});
 - maximum substrate uptake rate ($q_A^{\max}$ and $q_H^{\max}$)
- referred to the biomass of denitrification autotrophies and heterotrophies. The calculations were included in Table 4.

Table 4. Experimentally determined values of kinetic coefficients of nitrification and denitrification

T	$q_H^{\max}$	$q_A^{\max}$	Y_H	Y_A	k_{dH}	k_{dA}	$\mu_H^{\max}$	$\mu_A^{\max}$
°C	kg N-NO ₃ /kg d.o.m.·d	kg N-NH ₄ /kg d.o.m.·d	kg d.o.m./ kg N-NO ₃	kg d.o.m./ kg N-NH ₄	d ⁻¹	d ⁻¹	d ⁻¹	d ⁻¹
10	0.62	0.54	1.88	0.26	0.09	0.004	1.16	0.14
13	0.93	0.69	1.78	0.26	0.10	0.005	1.66	0.18
16	1.21	0.72	1.86	0.26	0.11	0.007	2.26	0.19
19	1.26	0.69	1.85	0.26	0.11	0.006	2.34	0.18
22	0.73	0.71	2.15	0.27	0.12	0.005	1.56	0.19
25	0.39	0.78	2.30	0.28	0.13	0.005	0.89	0.22
28	0,36	0.74	2.35	0.28	0.13	0.005	0.85	0.21
31	0.40	0.61	2.23	0.27	0.11	0.003	0.89	0.16
34	1,13	0.61	1,91	0.26	0.10	0.004	2.16	0.16
37	0.47	0.65	2.29	0.28	0.13	0.005	1.07	0.18

4. DISCUSSION

The effect of the biological processes can be evaluated through the analysis of the wastewater treatment expressed by the degree of component removal (in %) or on the basis of a change of the value kinetic parameters. At present, the dependencies determined for the enzymatic reactions are assumed for the purpose of description of the biochemical reactions taking place in the biological wastewater treatment processes. In the model of enzymatic reactions from which, among other things, the Monod equation and equation (6) follow, it is assumed that the biochemical processes are simple reactions catalysed by enzymes. The fact that the relevant transformations may occur only inside the cellular

structures of microorganisms, and thus, beyond the analysed solution (the living environment of the microorganisms) is not taken into account.

The presented results of tests and the determined dependencies of the kinetic coefficients on the temperature take into consideration both the species composition and the quantity of microorganisms, as above all, the temperature, considering the lack of inhibitors, determines the development of microorganisms.

The optimal function by means of which it is possible to describe the changes in the determined kinetic parameters of the nitrification and denitrification processes together with an increase in temperature, is the polynomial. The statistical studies of the dependencies between the variables demonstrated that within the tested temperature range, it is the sixth order polynomial. The degree of fitting of the determined functions expressed in percentage by means of correlation coefficient R^2 (specifying the dependency between the measuring values and their equivalents on the best fit curve) reached values within the range between 96 and 99%. Such a correlation coefficient proved the significant compliance of the best fit curves (sixth-order polynomial) with the course of the experimentally determined functions. However, on the basis of the obtained results, it is not possible to determine unambiguously the physical sense of the respective constants of this polynomial. The description of the determined dependencies of the kinetic coefficients on temperature by means of the exponential function in the form of:

$$k_2 = k_1 \cdot \theta^{(T_2 - T_1)} \quad (6)$$

The degree of fitting of the determined functions, expressed by means of correlation coefficient R^2 was assumed as the criterion of selection of the temperature ranges, in which the dependencies of the studied kinetic parameters on the temperature can be described by equation (6). In most cases, it reached the values ranging from 80% to 99% (the degree of fitting was lower for three functions and amounted to 0.65, 0.76 and 0.78). Such a degree of correlation proves the great compliance of the best fit curves with the course of the experimentally determined functions.

Table 5 specifies temperature coefficient values Θ for the nitrification and denitrification processes in separated temperature ranges, as well as the values of the degree of fitting of the determined functions to the value of the experimentally determined parameters.

Table 5. Temperature coefficient values for the nitrification and denitrification processes

No.	parameter ⁽¹⁾	temperature range of using the equation	temperature coefficient Θ	the degree of fit the appointed function to the experimental curves, R^2
1	$\mu_A^{\max}$	10-25°C	1.02	0.76
		25-34°C	0.96	0.89
2	$\mu_H^{\max}$	10-19°C	1.08	0.91
		19-28°C	0.89	0.93
		28-37°C	1.17	0.78
3	$q_A^{\max}$	10-25°C	1.02	0.65
		25-34°C	0.97	0.81
4	$q_H^{\max}$	10-19°C	1.09	0.89
		19-28°C	0.86	0.93
		28-37°C	1.21	0.82
5	k_{dA}	10-16°C	1.10	0.99
		16-31°C	0.96	0.80
		31-37°C	1.09	0.99
6	k_{dH}	10-28°C	1.02	0.97

		28-34°C	0.95	0.92
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353 ⁽¹⁾ Kinetic parameters in the determined temperature ranges must be calculated on the basis of the
 354 following equation: $k_2 = k_1 \cdot \Theta^{(T_2 - T_1)}$, assuming values k_1 and t_1 from the temperature range of the equation
 355 application.

356

357 Temperature coefficient values Θ are different in various temperature ranges, but they also
 358 depend on the method of wastewater treatment. While analysing the collected literature data
 359 (Tables 1 and 2), it can be noticed that most of the authors provide different values of this
 360 coefficient as well as very broad and diversified temperature ranges for their application, e.g.
 361 Streeter and Phelps 2-40°C ($\Theta = 1.047$), Randall 5-45°C ($\Theta = 1.05$) and Malina 4-31°C (Θ
 362 $= 1.0$) [16]. The different temperature coefficient values for the same process are given
 363 depending on the wastewater treatment conditions:

- 364 - for wastewater treatment in the activated sludge process at $BTS < 0.5 \text{ kg BOD}_5/\text{kg of}$
 365 $d.o.m. 1.0 \div 1.04$ [12],
- 366 - for the nitrification process 1.12 [2], 1.103 [13] i 1.08-1.1 [26],
- 367 - for the denitrification process, the range of values from 1.06 to 1.13 [3] and from 1.14 to
 368 1.16 [26].

369 In these cases, the temperature ranges for their application are not specified and the same
 370 temperature coefficient values are used to determine the values of different kinetic
 371 parameters.

372 The analysis of experimentally determined temperature coefficient values Θ (Table 5) allows
 373 a conclusion to be drawn that they assume different values for different temperature ranges
 374 and for respective kinetic parameters. For instance, according to the literature data, value Θ
 375 for $\mu_A^{\max}$, within the temperature range between 10 and 37°C amounts to 1.103 [11], 1.08-
 376 1.1 [26] or 1.12 [2]. It follows from the conducted tests that coefficient value Θ is not a
 377 constant value, independent of the temperature within the range between 10 and 37°C. Its
 378 value, in the separated temperature ranges amounted to: 1.02 (10-25°C) and 0.96 (25-34°C)
 379 (Table 5). The determined value of the temperature coefficient within the temperature range
 380 between 10 and 25°C was lower than the one given in literature by 0.06 [25], and within the
 381 temperature range between 25 and 37°C, it was lower by 0.12. Similar changes in the value
 382 of temperature coefficients were confirmed for the respective analysed kinetic coefficients of
 383 the nitrification and denitrification processes.

384 Figure 2 presents the experimental curve that depicts the changes in the value of the
 385 maximum growth rate for the nitrificants in the temperature function determined on the basis
 386 of tests, as well as the theoretical curves determined on the basis of equation (6). The
 387 following values were assumed for the calculations:

- 388 - variant I: temperature coefficient Θ equal to 1.08, maximum nitrificant growth rate
 389 $\mu_A^{\max 20^\circ\text{C}} = 0.3 \text{ d}^{-1}$ [26],
- 390 - variant II: temperature coefficient Θ equal to 1.103, maximum nitrificant growth rate
 391 $\mu_A^{\max 20^\circ\text{C}} = 0.6 \text{ d}^{-1}$ [2].

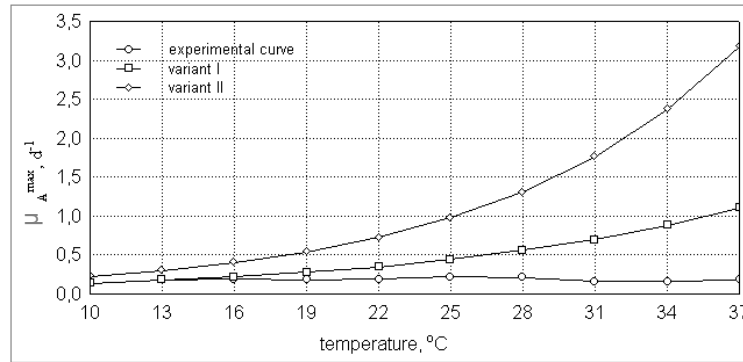


Fig. 2. Changes in parameter value $\mu_A^{\max}$

While comparing the above curves, which describe the changes in the value of the same parameter in the temperature function, the occurrence of the correlation between experimentally obtained values $\mu_A^{\max}$ and those determined on the basis of equation (6) was confirmed only within the temperature range from 10 to 16°C. Within this temperature range, the course of changes in values $\mu_A^{\max}$ determined in an experiment was practically the same as the one calculated theoretically on the basis of the parameters assumed in variant I. The values of maximum nitrificant growth rate calculated in variant II were higher than those determined in the experiment. In this area (standard temperatures for municipal sewage), value $\mu_A^{\max}$ increased exponentially together with an increase in temperature. Within higher temperatures, the experimental curve is significantly different from the curves determined on the basis of equation (6). The theoretical curves do not reflect the occurrence of areas of lower activity of the selected bacterial cultures. In case of formulation of equations, a tacit assumption was made that the activity of bacterial cultures increases together with the temperature or at least remains constant, which does not reflect the reality. It can be concluded that equation (6) is applicable to a limited extent and may be used in a strictly specified range of low temperatures (up to about 16°C).

4. CONCLUSION

While analysing the results of the studies and the conducted computational simulations, it may be noticed that the integration of removal of carbon and nitrogen compounds from the wastewater takes place in the process of wastewater treatment by means of the low-loaded activated sludge.

It can be concluded that the determined values of kinetic coefficients were conditioned by the variable activity of the bacteria at different temperatures (activity of relative psychrophiles at the temperature between 20 and 32°C) and did not have the form of the monotonic exponential function. Above the temperature of 16°C, the curve representing the course of changes in the value of parameter $\mu_A^{\max}$, determined on the basis of the results of the studies, deviated from the hypothetical curve determined on the basis of equation (6). The equation does not reflect the occurrence of temperature ranges with a higher or lower activity of microorganisms of the activated sludge sufficiently. The temperatures were determined within the range between 10 and 37°C, and coefficients Θ related to these temperature ranges do not depend on the temperature set within these ranges. Their values in these ranges were specified for the analysed kinetic parameters of transformations of the nitrogen compounds in the activated sludge process.

The temperature coefficient value is taken into account during the dimensioning of the activated sludge chambers and affects their computational volume. The correct assumption

of values Θ may impact a decrease in investment and operational costs of process facilities of wastewater treatment plants. This problem is of great significance, particularly in the case of technology of sewage treatment with an enhanced temperature and in warm climate.

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503 ABBREVIATIONS

- 504
 505 A - Arrhenius coefficient
 506 K_{O_2} , K_{NH_4} , K_{NO_3} , K_F - saturation constant
 507 K_{dA} and K_{dH} - biomass self-oxidisation coefficient
 508 E - activation energy
 509 S - substrates concentration
 510 U - substrate uptake rate
 511 X_H - heterotrophic biomass
 512 X_A - autotrophic biomass
 513 X_i - inactive part of active sludge mass
 514 X_r - recycled sludge concentration
 515 X_e - concentration of a total suspension in sewage outflow
 516 Y - efficiency of microorganism growth
 517 Y_A and Y_H - nitrificant and denitrificant efficiency growth
 518 Q - sewage inflow
 519 Q_w - recycled sludge
 520 Q_e - sewage outflow
 521 q_A^{max} and q_H^{max} - maximum substrate uptake rate
 522 V_k - volume of bioreactor
 523 HRT - hydraulic retention time
 524 SRT - age of activated sludge
 525 Θ - temperature coefficient
 526 μ_A^{max} and μ_H^{max} - maximum nitrificant and denitrificant growth rate
 527 η_D - share of denitrificants in the biomass of heterotrophies
 528 ρ - load of activated sewage sludge
 529 $[kg\ d.o.m. \cdot d]$ - kg dry organic matter · day