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Study of the influence of external influences on the range of the RFID system

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Abstract. The study is based on the analysis of the phenomena of the direction of electromagnetic radiation through the use of a system of two oscillatory circuits of a reader and an RFID tag. The analysis established the relationship between environmental factors and the range of the RFID system by creating a theoretical model of the phenomenon using partial differential equations of multiple variables and multiple powers. The fact of analysis using a function model for damped electromagnetic periodic oscillations in the zero case has been established. As a result, two formulas were derived that establish the dependence of the range of RFID technology on the temperature and humidity of the environment.

1 Introduction

The RFID system is used in various fields of industry for recording and moving products. In each of these cases, it is important to designate each unit of such products using a specific marking system, which includes the RFID identification system [1-8]. The technology of the marking system is based on the principle of transmitting data with a certain variable amplitude over a distance through the oscillating circuit of the reader - a device for transmitting and reading an electromagnetic signal. Directed electromagnetic radiation is received by an RFID tag or RFID tag, which, using its oscillatory circuit, receives electromagnetic radiation and inputs the data from the memory of the built-in chip into it, after which the signal is sent back. The RFID system can operate in various models using additional energy sources or can do without them. However, when transmitting data, the characteristic of the wave itself is of great importance - the decrease in its energy when passing through a certain medium, which limits the range of the RFID system. During the transmission of information, the electromagnetic signal, which attenuates as it moves away from the reader, is converted at the return stage to have a variable amplitude, remaining at a constant frequency, but the variable amplitude is compensated throughout the entire wave [7-17]. This effect ensures that in the course of research in order to determine the range of RFID technology, we neglect the information that the electromagnetic wave contains [14].

Based on this, further research will be carried out on an electromagnetic wave with certain characteristics without taking into account the information in the amount of several kilobytes that it may contain [13]. Also, based on the above parameters, the scale of action

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of RFID technology in industry is determined, which also leads to the need to work under a wide variety of external weather and natural conditions with varying degrees of ambient temperature, air humidity and other parameters. Taking into account each of the variables is important, which allows us to say that the study of the present effect is relevant.

2 Study

The RFID system uses a system for receiving and transmitting radio waves in the UHF range (860-960 MHz). The wave plays the role of an information carrier between the source and the receiver. In the present study, the electromagnetic wave itself plays an important role, as mentioned above. Consideration of the wave can be carried out according to the use of the method of describing physical phenomena, through differential equations of nth orders with m-variables. It is necessary to derive the corresponding differential equation for the described system.

Note that the equation of any wave is one way or another a solution to a special wave equation, which include plane and spherical waves, among which, taking into account the projections for the electric or magnetic field, electromagnetic fields can also be considered. Let us accept the derivation of the wave differential equation for the model of the simplest plane wave (1).

$$E = E_m e^{-at}\cos(wt - kr + \alpha) \tag{1}$$

The equation descr $E = E_m e^{-at}\cos(wt - kr + \alpha)$ibing this phenomenon can be derived by determining the Laplacian of function (1), that is, the second derivatives with respect to coordinates (2-4), as well as with respect to time (5).

$$\frac{\partial^2 E}{\partial x^2} = -k_x^2 E_m e^{-at}\cos(wt - kr + \alpha) = -k_x^2 E \tag{2}$$

$$\frac{\partial^2 E}{\partial y^2} = -k_y^2 E_m e^{-at}\cos(wt - kr + \alpha) = -k_y^2 E \tag{3}$$

$$\frac{\partial^2 E}{\partial z^2} = -k_z^2 E_m e^{-at}\cos(wt - kr + \alpha) = -k_z^2 E \tag{4}$$

$$\frac{\partial^2 E}{\partial t^2} = -w^2 E_m e^{-at}\cos(wt - kr + \alpha) = -w^2 E \tag{5}$$

As can be seen from the results obtained, the Laplacian of the energy function or the sum of the second derivatives of the function with respect to coordinates is equal to the product of the wave number and the function itself. Taking into account the expression for the wave number and cyclic frequency, according to the resulting relation of equality of the Laplacian function and the product of the function by the square of the cyclic frequency in (5), it is possible to determine a new value for the speed of the electromagnetic wave, which depends on the medium, but for vacuum the value 299,792,458 m/ s, for air with a coefficient of 1.003 – 298,895,770 m/s. Based on the above, we can determine the form of the second-order wave differential equation (6).

$$\frac{\partial^2 E}{\partial x^2}+\frac{\partial^2 E}{\partial y^2}+\frac{\partial^2 E}{\partial z^2}=\Delta E=-\left(k_x^2+k_y^2+k_z^2\right)E=-k^2E=>$$
$$\Rightarrow\begin{pmatrix} k=\frac{2\pi}{\lambda}=\frac{2\pi f}{c}, \\ w=2\pi f, \\ \frac{k^2}{w^2}=\frac{1}{v^2}=>v=\frac{w}{k}=c \end{pmatrix}\Rightarrow \Delta E=\frac{1}{v^2}\frac{\partial^2 E}{\partial t^2} \quad (6)$$

The resulting expression takes into account the dependence on the amount of energy on which the distance depends, since in the energy function there is a time value on which the indicator of the range of the electromagnetic wave depends, that is, reducing its energy level to the minimum value required to launch the RFID tag (7).

$$r=ct(E) \quad (7)$$

Due to this, we can say that there is a certain function of distance (8), which depends on the humidity of the environment, temperature and time during which the electromagnetic wave reaches the RFID tag, which, due to its dependence on energy, satisfies equation (6), which remains to be investigated and withdraw.

$$r(\nu,T,t) \quad (8)$$

The described function is valid and with its help some experiments were carried out, where the dependence on temperature, humidity and the value of the distance function itself was established (Table 1).

Table1. Obtained experimental values.

Temperature, degree	Humidity, %	Distance, sm
16	90	115
12	36	198
10	54	195
3	58	195

Based on the presented Table 1, we can talk about deriving special boundary conditions for function (8) from the presented values (9-16), obtained experimentally.

$$r(90,T,t)=11 \quad (9)$$

$$r(36,T,t)=198 \quad (10)$$

$$r(54,T,t)=195 \quad (11)$$

$$r(58,T,t)=195 \quad (12)$$

$$r(\nu,16,t)=115 \quad (13)$$

$$r(\nu,12,t)=198 \quad (14)$$

$$r(\nu,10,t)=195 \quad (15)$$

$$r(\nu,3,t)=195 \quad (16)$$

In this case, the dependences on environmental temperature and environmental humidity were experimentally established, however, there is the above-mentioned dependence on time in the initial conditions. When its value is zero, obviously, the distance also goes to zero, as can be seen from (17).

$$r(v,T,0)=0 \quad (17)$$

To determine the value of time spent on a relatively maximum distance from those presented - 2 meters, the ratio of this value with the maximum speed of an electromagnetic wave - the speed of light is used, obtaining a value for time (18), at which the function of distance takes on a relatively maximum special value of the function (19), which will subsequently become an approximate value.

$$t_{max}=\frac{d_{max}}{c}=\frac{2}{299\ 792\ 458}=6.67128*10^{-9}\ \text{s} \quad (18)$$

$$r(v,T,6.67128*10^{-9})=r_m \quad (19)$$

Now that equation (6) is given, for function (8) with boundary conditions (9-16) and initial conditions (17, 19), the problem posed will be solved by the Fourier method - separation of variables, from where the solution will be sought in the form (20) , after substituting it, you can come to the form (21), and then, after transformation, come to the first partial value of the solution (22).

$$r(v,T,t)=K(v,T)Q(t) \quad (20)$$

$$\Delta K(v,T)Q(t)=\frac{1}{v^2}K(v,T)Q''(t) \quad (21)$$

$$\frac{\Delta K(v,T)}{K(v,T)}=\frac{Q''(t)}{v^2Q(t)}=-\lambda \quad (22)$$

Based on the presented transformed equality (22), it is possible to obtain two partial differential equations of one and two second-order variables, where the first partial value is chosen negative for a more convenient solution of the resulting partial differential equations. The first equation for the function of time has the form (23), the solution of which is sought in the form (24), after substitution of which, the characteristic form of a second-order differential equation of one variable in partial derivatives appears and the value of the coefficient of the characteristic form, depending on the first partial value (24).

$$Q''(t)+\lambda v^2Q(t)=0 \quad (23)$$

$$Q(t)=e^k \quad (24)$$

$$k^2e^k+\lambda ve^k=0 => k^2+\lambda v^2=0 => k=\pm v\sqrt{\lambda} \quad (25)$$

Based on the obtained values for the coefficient of the characteristic form of the equation, one can obtain the general form of function (26), under which one can substitute the initial conditions (17, 19), obtaining in the first case equation (27), and in the second case immediately when substituting the value from (27), the value of the expression for the second coefficient in the general form of a part of the general function of time (28) in (26).

$$Q(t) = C_1 e^{\sqrt{\lambda} v t} + C_2 e^{-\sqrt{\lambda} v t} \quad (26)$$

$$Q(0) = C_1 + C_2 = 0 => C_1 = -C_2 \quad (27)$$

$$Q(6.67128 * 10^{-9}) = C_1 e^{2\sqrt{\lambda}} + C_2 e^{-2\sqrt{\lambda}} = r_m =>$$

$$=> -C_2 e^{2\sqrt{\lambda}} + C_2 e^{-2\sqrt{\lambda}} = r_m =>$$

$$=> C_2 = \frac{r_m e^{2\sqrt{\lambda}}}{1 - e^{2\sqrt{\lambda}}} \quad (28)$$

Based on the result obtained in (28), it is easy to obtain the value for the first coefficient of the general solution (29) and the general form of the function (30), which, based on the results obtained, can be transformed there.

$$C_1 = -\frac{r_m e^{2\sqrt{\lambda}}}{1 - e^{2\sqrt{\lambda}}} \quad (29)$$

$$Q(t) = C_1 e^{\sqrt{\lambda} v t} + C_2 e^{-\sqrt{\lambda} v t} = -\frac{r_m \left(e^{\sqrt{\lambda}(2+vt)} + e^{\sqrt{\lambda}(2-vt)}\right)}{1 - e^{2\sqrt{\lambda}}} \quad (30)$$

Now, we can move on to the second differential equation starting from (22) with the Laplacian (31), which, taking into account the value of humidity and temperature as function coordinates, can be solved by the method of separation of variables - the Fourier method, taking the form (32) as a solution.

$$\Delta K(\nu, T) + \lambda K(\nu, T) = 0 \quad (31)$$

$$K(\nu, T) = V(\nu) Z(T) \quad (32)$$

After substituting form (32) into equation (31), a new differential equation is obtained from two functions and from two second-order variables in partial derivatives with respect to the coordinates of humidity and temperature (33), which can be transformed to form (34) with the derivation of the second partial the solution value, also taken as a negative value for the best solution of the differential equations arising from the obtained equality.

$$V''(\nu) Z(T) + V(\nu) Z''(T) + \lambda V(\nu) Z(T) = 0 \quad (33)$$

$$\frac{V''(\nu)}{V(\nu)} = -\frac{Z''(T)}{Z(T)} - \lambda = -\lambda_1 \quad (34)$$

The first second-order partial differential equation for the humidity function has the form (35), the solution of which is sought in the form (36), for which the characteristic form (37) is also obtained after substitution with the derivation of the characteristic coefficient, as well as the general form of the humidity function (38).

$$V''(\nu) + \lambda_1 V(\nu) = 0 \tag{35}$$

$$V(\nu) = e^{k_1} \tag{36}$$

$$k_1^2 e^{k_1} + \lambda_1 e^{k_1} = 0 => k_1^2 + \lambda_1 = 0 => k_1 = \pm\sqrt{\lambda_1} \tag{37}$$

$$V(\nu) = C_3 e^{\sqrt{\lambda_1}\nu} + C_4 e^{-\sqrt{\lambda_1}\nu} \tag{38}$$

For the humidity function there are boundary conditions (9-12), with partial substitution of which a system of equations is obtained. It is worth noting that in this case, all 4 equations could play a role, but due to the presence of unknown coefficients of the general form of the humidity function (38) and the partial second value of the solution obtained in (34), only 3 equations are used.

The system of equations for the coefficients is solved by a simple method of deriving one from the other, so already at the second stage of solution, the function for the second coefficient is obtained from the humidity function and at the third stage of solving the system of equations for the first value of the coefficient from the humidity function (39).

$$\begin{cases} V(90) = C_3 e^{90\sqrt{\lambda_1}} + C_4 e^{-90\sqrt{\lambda_1}} = 115 \\ V(36) = C_3 e^{36\sqrt{\lambda_1}} + C_4 e^{-36\sqrt{\lambda_1}} = 198 => \\ V(54) = C_3 e^{54\sqrt{\lambda_1}} + C_4 e^{-54\sqrt{\lambda_1}} = 195 \end{cases}$$

$$=> \begin{cases} C_4 = e^{90\sqrt{\lambda_1}}\left(115 - C_3 e^{90\sqrt{\lambda_1}}\right) \\ C_3 e^{36\sqrt{\lambda_1}} + e^{54\sqrt{\lambda_1}}\left(115 - C_3 e^{90\sqrt{\lambda_1}}\right) = 198 => \\ C_3 e^{54\sqrt{\lambda_1}} + C_4 e^{-54\sqrt{\lambda_1}} = 195 \end{cases}$$

$$=> C_3 = \frac{198 - 115e^{54\sqrt{\lambda_1}}}{e^{36\sqrt{\lambda_1}} - e^{144\sqrt{\lambda_1}}} \tag{39}$$

The resulting forms are substituted into the third equation, obtaining the long expression of equation (40).

$$C_3 e^{54\sqrt{\lambda_1}} + C_4 e^{-54\sqrt{\lambda_1}} = 195 =>$$
$$=> \frac{198 - 115e^{54\sqrt{\lambda_1}}}{e^{36\sqrt{\lambda_1}} - e^{144\sqrt{\lambda_1}}} e^{54\sqrt{\lambda_1}} +$$
$$+e^{90\sqrt{\lambda_1}}\left(115 - \frac{198 - 115e^{54\sqrt{\lambda_1}}}{e^{36\sqrt{\lambda_1}} - e^{144\sqrt{\lambda_1}}} e^{90\sqrt{\lambda_1}}\right) e^{-54\sqrt{\lambda_1}} = 195 \tag{40}$$

The equation itself consists of 2 conditional parts on the left side, each of which can be simplified. Thus, the first term is reduced to a more acceptable form in (41), and the second in (42).

$$\frac{198-115e^{54\sqrt{\lambda_1}}}{e^{36\sqrt{\lambda_1}}-e^{144\sqrt{\lambda_1}}}e^{54\sqrt{\lambda_1}}=\frac{198e^{18\sqrt{\lambda_1}}-115e^{72\sqrt{\lambda_1}}}{1-e^{108\sqrt{\lambda_1}}} \tag{41}$$

$$e^{90\sqrt{\lambda_1}}\left(115-\frac{198-115e^{54\sqrt{\lambda_1}}}{e^{36\sqrt{\lambda_1}}-e^{144\sqrt{\lambda_1}}}e^{90\sqrt{\lambda_1}}\right)e^{-54\sqrt{\lambda_1}}=$$
$$=\left(\frac{115-115e^{108\sqrt{\lambda_1}}-198e^{54\sqrt{\lambda_1}}-115e^{108\sqrt{\lambda_1}}}{1-e^{108\sqrt{\lambda_1}}}\right)e^{-36\sqrt{\lambda_1}}=$$
$$=\frac{115-230e^{108\sqrt{\lambda_1}}-198e^{54\sqrt{\lambda_1}}}{e^{36\sqrt{\lambda_1}}\left(1-e^{108\sqrt{\lambda_1}}\right)} \tag{42}$$

The obtained values are substituted into equation (40), which leads to a transformation of the equation, and by applying the substitution method, the resulting 144-degree equation (43) can be obtained.

$$\frac{198e^{18\sqrt{\lambda_1}}-115e^{72\sqrt{\lambda_1}}}{1-e^{108\sqrt{\lambda_1}}}+\frac{115-230e^{108\sqrt{\lambda_1}}-198e^{54\sqrt{\lambda_1}}}{e^{36\sqrt{\lambda_1}}\left(1-e^{108\sqrt{\lambda_1}}\right)}=195=>$$
$$=>\frac{198e^{54\sqrt{\lambda_1}}-115e^{108\sqrt{\lambda_1}}+115-230e^{108\sqrt{\lambda_1}}-198e^{54\sqrt{\lambda_1}}}{e^{36\sqrt{\lambda_1}}\left(1-e^{108\sqrt{\lambda_1}}\right)}=195=>$$
$$=>-345e^{108\sqrt{\lambda_1}}+115-195e^{36\sqrt{\lambda_1}}-195e^{144\sqrt{\lambda_1}}=0=>\left(e^{\sqrt{\lambda_1}}=x\right)=>$$
$$=>195x^{144}+345x^{108}+195x^{36}-115=0 \tag{43}$$

This equation can be solved graphically and according to the construction of the graph of the function, an elongated paraboloid is obtained that intersects the abscissa axis, that is, with a zero value on the ordinate axis, only with 2 values (44).

$$x_{1,2}=\pm 0.9761 \tag{44}$$

Since the exponential function was used in the substitution, a negative value cannot be accepted, so a positive value is indicated, from which the value for the second partial solution value (45) and the first and second coefficients of the humidity function (46-47) are derived.

$$e^{\sqrt{\lambda_1}}=0.9761=>\lambda_1=(\ln 0.9761)^2=5.85168*10^{-4} \tag{45}$$

$$C_3=\frac{198-115e^{54\sqrt{\lambda_1}}}{e^{36\sqrt{\lambda_1}}-e^{144\sqrt{\lambda_1}}}=$$
$$=\frac{198-115e^{54\sqrt{5.85168*10^{-4}}}}{e^{36\sqrt{5.85168*10^{-4}}}-e^{144\sqrt{5.85168*10^{-4}}}}=7.508802646 \tag{46}$$

$$C_4=e^{90\sqrt{\lambda_1}}\left(115-C_3e^{90\sqrt{\lambda_1}}\right)=$$
$$=e^{90\sqrt{5.85168*10^{-4}}}\left(115-7.508802646e^{90\sqrt{5.85168*10^{-4}}}\right)=$$
$$=430.1568771 \tag{47}$$

Thus, a complete function for the humidity value (48) can be obtained.

$$V(\nu) = 7.508802646e^{\sqrt{5.85168*10^{-4}}\nu} + 430.1568771e^{-\sqrt{5.85168*10^{-4}}\nu} = \\ = 7.508802646e^{0,024190246\nu} + 430.1568771e^{-0,024190246\nu} \tag{48}$$

Returning to the second differential equation for the second-order temperature function in partial derivatives (49), which follows from (34), its solution is also sought similarly to the previous solution in transformed form (50), obtaining a characteristic form, but a different value for the characteristic coefficient (51).

$$-\frac{Z''(T)}{Z(T)} - \lambda = -\lambda_1 => Z''(T) + (\lambda_1 - \lambda)Z(T) = 0 \tag{49}$$

$$Z(T) = e^{k_2} \tag{50}$$

$$k_2^2 e^{k_2} + (\lambda_1 - \lambda)e^{k_2} = 0 => k_2 = \pm\sqrt{\lambda - \lambda_1} \tag{51}$$

By substituting the resulting expressions, a general form is formed for the temperature function (52), and its boundary conditions (13-15) are applied, ideally suited to the general values, forming a system of equations from three variables - the first and second coefficients in the general temperature function (52) and the first partial value of the solution, obtained in (22) and included in this form in (34).

$$Z(T) = C_5 e^{\sqrt{\lambda-\lambda_1}T} + C_6 e^{-\sqrt{\lambda-\lambda_1}T} \tag{52}$$

The resulting system of equations is solved by a similar method by deriving at the first step the expression for the second coefficient in the general temperature equation (53).

$$\begin{cases} Z(16) = C_5 e^{16\sqrt{\lambda-\lambda_1}} + C_6 e^{-16\sqrt{\lambda-\lambda_1}} = 115 \\ Z(12) = C_5 e^{12\sqrt{\lambda-\lambda_1}} + C_6 e^{-12\sqrt{\lambda-\lambda_1}} = 198 \\ Z(10) = C_5 e^{10\sqrt{\lambda-\lambda_1}} + C_6 e^{-10\sqrt{\lambda-\lambda_1}} = 195 \end{cases} => \\ => \begin{cases} C_6 = e^{16\sqrt{\lambda-\lambda_1}}\left(115 - C_5 e^{16\sqrt{\lambda-\lambda_1}}\right) \\ C_5 e^{12\sqrt{\lambda-\lambda_1}} + e^{16\sqrt{\lambda-\lambda_1}}\left(115 - C_5 e^{16\sqrt{\lambda-\lambda_1}}\right)e^{-12\sqrt{\lambda-\lambda_1}} = 198 \\ Z(10) = C_5 e^{10\sqrt{\lambda-\lambda_1}} + C_6 e^{-10\sqrt{\lambda-\lambda_1}} = 195 \end{cases} \tag{53}$$

Then, by substituting the resulting expression, you can solve the second equation of the system, deriving the equation for the first coefficient of the temperature function (54), while making it possible to substitute both values into the third equation, which again transforms into a large equation with two terms on the left side (55).

$$C_5 e^{12\sqrt{\lambda-\lambda_1}} + e^{16\sqrt{\lambda-\lambda_1}}\left(115 - C_5 e^{16\sqrt{\lambda-\lambda_1}}\right)e^{-12\sqrt{\lambda-\lambda_1}} = 198 =>$$

$$=> C_5 = \frac{198 - 115e^{4\sqrt{\lambda-\lambda_1}}}{e^{12\sqrt{\lambda-\lambda_1}} - e^{20\sqrt{\lambda-\lambda_1}}} \quad (54)$$

$$C_5 e^{10\sqrt{\lambda-\lambda_1}} + C_6 e^{-10\sqrt{\lambda-\lambda_1}} = 195 =>$$

$$=> \frac{198 - 115e^{4\sqrt{\lambda-\lambda_1}}}{e^{12\sqrt{\lambda-\lambda_1}} - e^{20\sqrt{\lambda-\lambda_1}}} e^{10\sqrt{\lambda-\lambda_1}} +$$

$$+e^{16\sqrt{\lambda-\lambda_1}}\left(115 - \frac{198 - 115e^{4\sqrt{\lambda-\lambda_1}}}{e^{12\sqrt{\lambda-\lambda_1}} - e^{20\sqrt{\lambda-\lambda_1}}} e^{16\sqrt{\lambda-\lambda_1}}\right)e^{-10\sqrt{\lambda-\lambda_1}} = 195 \quad (55)$$

The first part of (55) can be simplified into (56), and the second into (57), making it possible to put everything together in a general equation, which, after transformations, again reduces to equation (58).

$$\frac{198 - 115e^{4\sqrt{\lambda-\lambda_1}}}{e^{12\sqrt{\lambda-\lambda_1}} - e^{20\sqrt{\lambda-\lambda_1}}} e^{10\sqrt{\lambda-\lambda_1}} = \frac{198 - 115e^{4\sqrt{\lambda-\lambda_1}}}{e^{2\sqrt{\lambda-\lambda_1}}\left(1 - e^{8\sqrt{\lambda-\lambda_1}}\right)} \quad (56)$$

$$e^{16\sqrt{\lambda-\lambda_1}}\left(115 - \frac{198 - 115e^{4\sqrt{\lambda-\lambda_1}}}{e^{12\sqrt{\lambda-\lambda_1}} - e^{20\sqrt{\lambda-\lambda_1}}} e^{16\sqrt{\lambda-\lambda_1}}\right)e^{-10\sqrt{\lambda-\lambda_1}} =$$

$$= \frac{115e^{6\sqrt{\lambda-\lambda_1}} - 230e^{14\sqrt{\lambda-\lambda_1}} - 198e^{10\sqrt{\lambda-\lambda_1}}}{1 - e^{8\sqrt{\lambda-\lambda_1}}} \quad (57)$$

$$\frac{198 - 115e^{4\sqrt{\lambda-\lambda_1}}}{e^{2\sqrt{\lambda-\lambda_1}}\left(1 - e^{8\sqrt{\lambda-\lambda_1}}\right)} + \frac{115e^{6\sqrt{\lambda-\lambda_1}} - 230e^{14\sqrt{\lambda-\lambda_1}} - 198e^{10\sqrt{\lambda-\lambda_1}}}{1 - e^{8\sqrt{\lambda-\lambda_1}}} = 195 =>$$

$$=> 198 - 115e^{4\sqrt{\lambda-\lambda_1}} +$$

$$+\left(115e^{6\sqrt{\lambda-\lambda_1}} - 230e^{14\sqrt{\lambda-\lambda_1}} - 198e^{10\sqrt{\lambda-\lambda_1}}\right)e^{2\sqrt{\lambda-\lambda_1}} =$$

$$= 195e^{2\sqrt{\lambda-\lambda_1}}\left(1 - e^{8\sqrt{\lambda-\lambda_1}}\right) =>$$

$$=> 198 - 115e^{4\sqrt{\lambda-\lambda_1}} + 115e^{8\sqrt{\lambda-\lambda_1}} - 230e^{16\sqrt{\lambda-\lambda_1}} -$$

$$-198e^{12\sqrt{\lambda-\lambda_1}} - 195e^{2\sqrt{\lambda-\lambda_1}} + 195e^{10\sqrt{\lambda-\lambda_1}} = 0 \quad (58)$$

Let us apply the substitution method to equation (58), specifying (59), obtaining a 16-degree equation with even powers of the unknown quantity (60), the solution of which can be found graphically in the form of two opposite values (61).

$$e^{\sqrt{\lambda-\lambda_1}} = y \quad (59)$$

$$230y^{16} + 198y^{12} - 195y^{10} - 115y^{8} + 115y^{4} + 195y^{2} - 198 = 0 \quad (60)$$

$$y = \pm 0.8819 \quad (61)$$

The derived value after substitution determines the first partial value of the solution (62), which after the next substitution determines both the first (63) and second (64) partial values as a function of temperature.

$$e^{\sqrt{\lambda-\lambda_1}} = 0.8819 => \lambda = (\ln 0.8819)^2 + 5.85168 * 10^{-4} = 0.01638 \quad (62)$$

$$C_5 = \frac{198 - 115e^{4\sqrt{\lambda-\lambda_1}}}{e^{12\sqrt{\lambda-\lambda_1}} - e^{20\sqrt{\lambda-\lambda_1}}} = \\ = \frac{198 - 115e^{4\sqrt{0.01638-5.85168*10^{-4}}}}{e^{12\sqrt{0.01638-5.85168*10^{-4}}} - e^{20\sqrt{0.01638-5.85168*10^{-4}}}} = \\ = -1.006656628 \quad (63)$$

$$C_6 = e^{16\sqrt{\lambda-\lambda_1}}\left(115 - C_5 e^{16\sqrt{\lambda-\lambda_1}}\right) = \\ = e^{16\sqrt{0.01638-5.85168*10^{-4}}}\left(115 + 1.006656628e^{16\sqrt{0.01638-5.85168*10^{-4}}}\right) = \\ = 915.1687975 \quad (64)$$

In this way, the complete function of temperature (65) can be obtained for the solution by the Fourier method.

$$Z(T) = -1.006656628e^{0.125677492T} + 915.1687975e^{-0.125677492T} \quad (65)$$

Since the solution was sought by the method of separation of variables and the value for the first partial value of the solution (62) was found, it affects the form of the function of time (30), transforming it to state (66).

$$Q(t) = -\frac{r_m\left(e^{\sqrt{\lambda}(2+vt)} + e^{\sqrt{\lambda}(2-vt)}\right)}{1 - e^{2\sqrt{\lambda}}} = \\ = -\frac{r_m\left(e^{0.127984374(2+vt)} + e^{0.127984374(2-vt)}\right)}{1 - e^{0.255968748}} = \\ = -\frac{2r_m 0, e^{255968748}\cosh(0.127984374vt)}{1 - e^{0.255968748}} \quad (66)$$

As a result, a general function of all the necessary variables and functions is obtained, putting together an expression for the distance from the values of humidity, temperature and time (67).

$$r(v,T,t) = -(7.508802646e^{0,024190246v} + 430.1568771e^{-0,\mathbf{024190246v}}) * \\ * (-1.006656628e^{0.125677492T} + 915.1687975e^{-0.125677492T}) * \\ * \left(\frac{2r_m 0, e^{255968748}\cosh(0.127984374vt)}{1 - e^{0.255968748}}\right) \quad (67)$$

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Expression (67) describes the dependence of the range of the RFID system on humidity, temperature and time. When deriving this expression, only the loss of energy of the electromagnetic wave when passing through the medium was taken into account. But it is known that the processes of receiving and transmitting information between devices are also influenced by external influences on specific receiving and transmission devices. This aspect was not considered in this work.

3 Discussion

To visually express the resulting mathematical model (67), graphical displays of the process are constructed. Thus, one can see the projection of function (67) relative to the dependence of humidity at a temperature of 15 degrees Celsius (Figure 1).

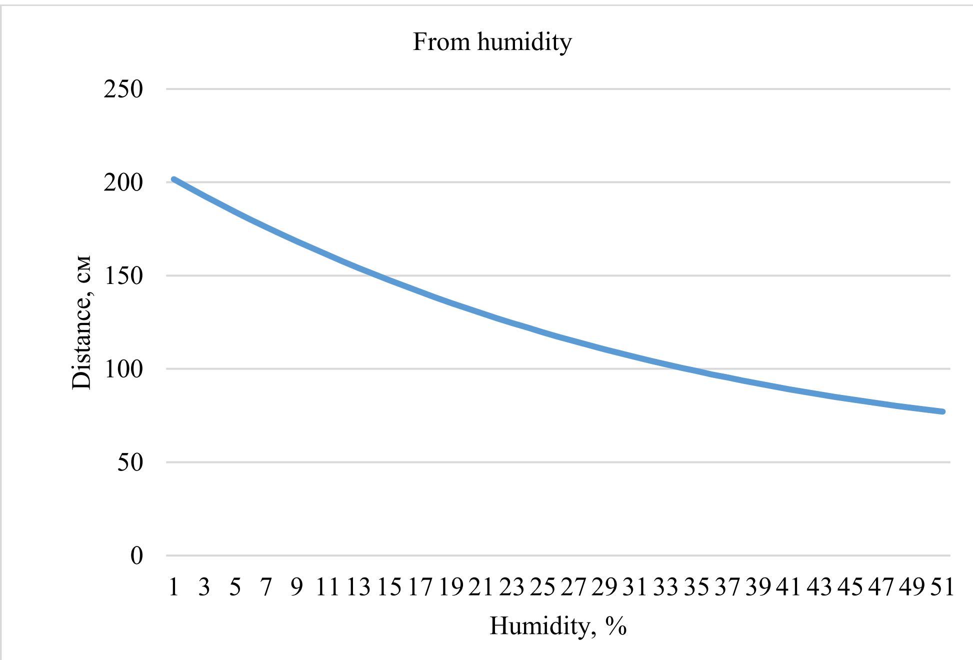

Fig. 1. Graph of range versus humidity.

The graph shows that the range of the RFID system depends on humidity in an exponentially decreasing manner. The dependence on temperature was constructed in a similar way at a humidity level of 55% and the same other parameters (Figure 2).

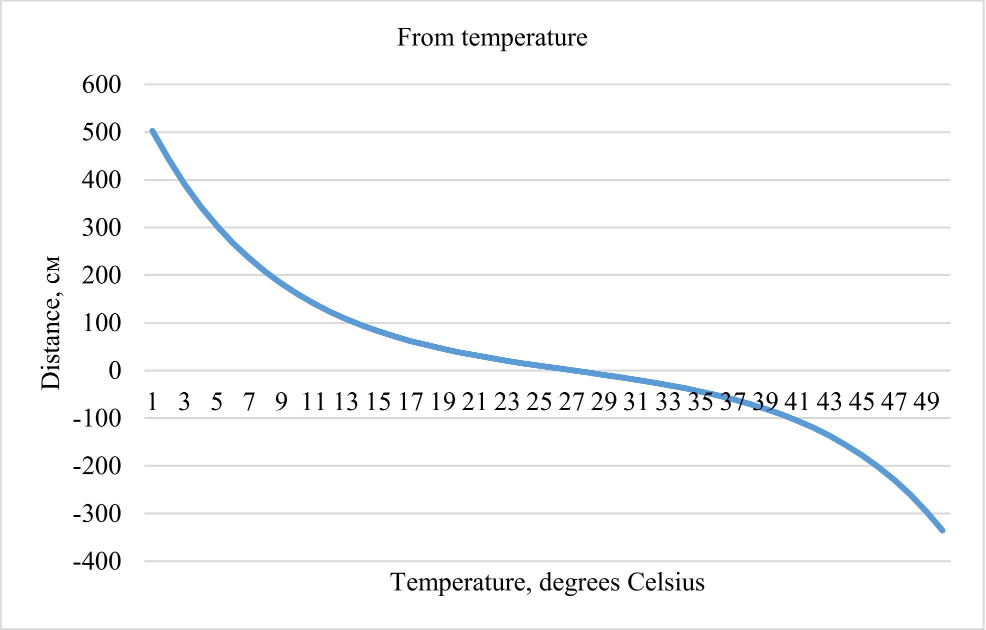

Fig. 2. Range versus temperature graph.

The graph indicates that at low temperatures (from 0^0C to 21^0C) the range of the RFID system depends on temperature in an exponentially decreasing manner, at average temperatures (from 21^0C to 35^0C) the drop tends to be linear, including a critical point at 27.10299^0C, after which there is no dependence of range on temperature, at high temperatures (from 35^0C and above) the graph looks inversely exponential, which indicates that range also does not depend on temperature.

In calculations, the process also depends on the time the pulse is launched along the "receiver-source-receiver" route (67). The graph displays the increase in the range of the RFID system over time, which indicates the reliability of the obtained expression (Figure 3).

 https://doi.org/10.1051/bioconf/202414104024

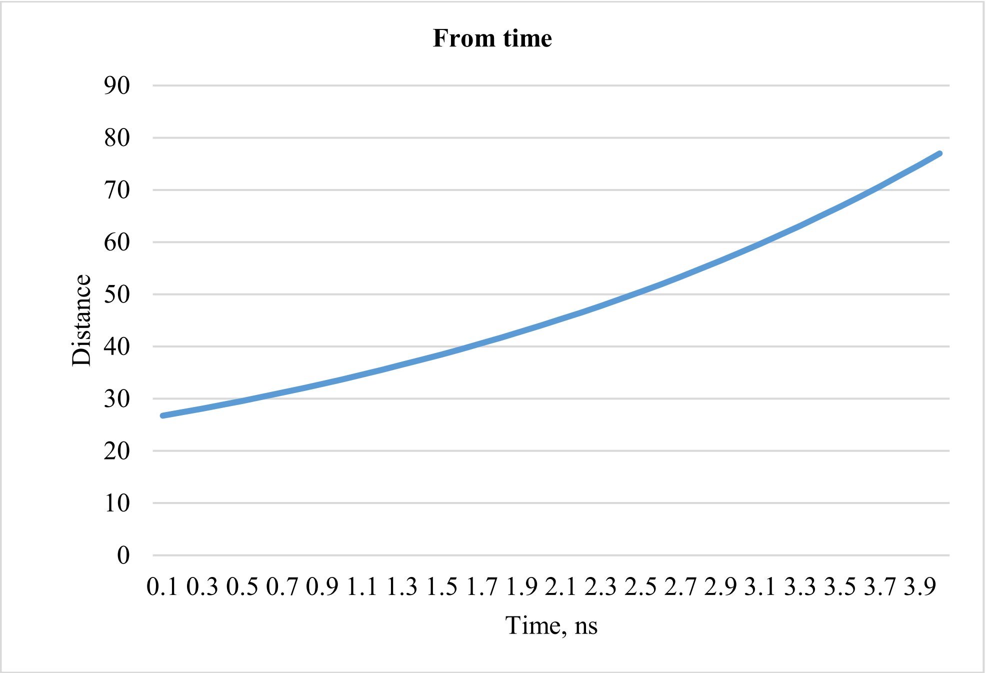

Fig. 3. Graph of distance versus time taken by a wave to travel the distance.

To more clearly express the process, a three-dimensional display of the mathematical model (67) was constructed (Figure 4).

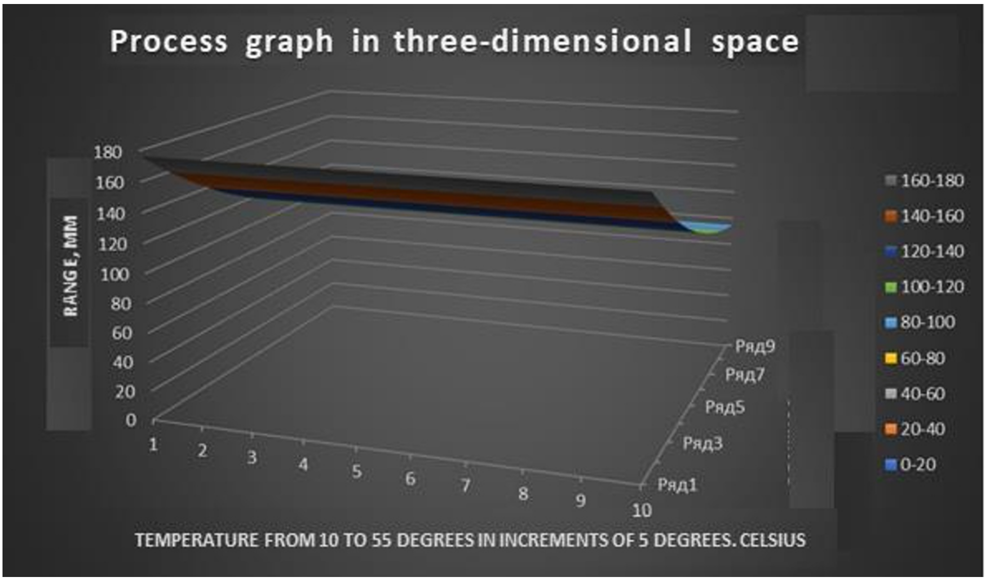

Fig. 4. Process graph in three-dimensional space in the high temperature range.

The graph shows that the range does not depend on temperature (at high temperatures) and decreases exponentially with increasing environmental humidity.

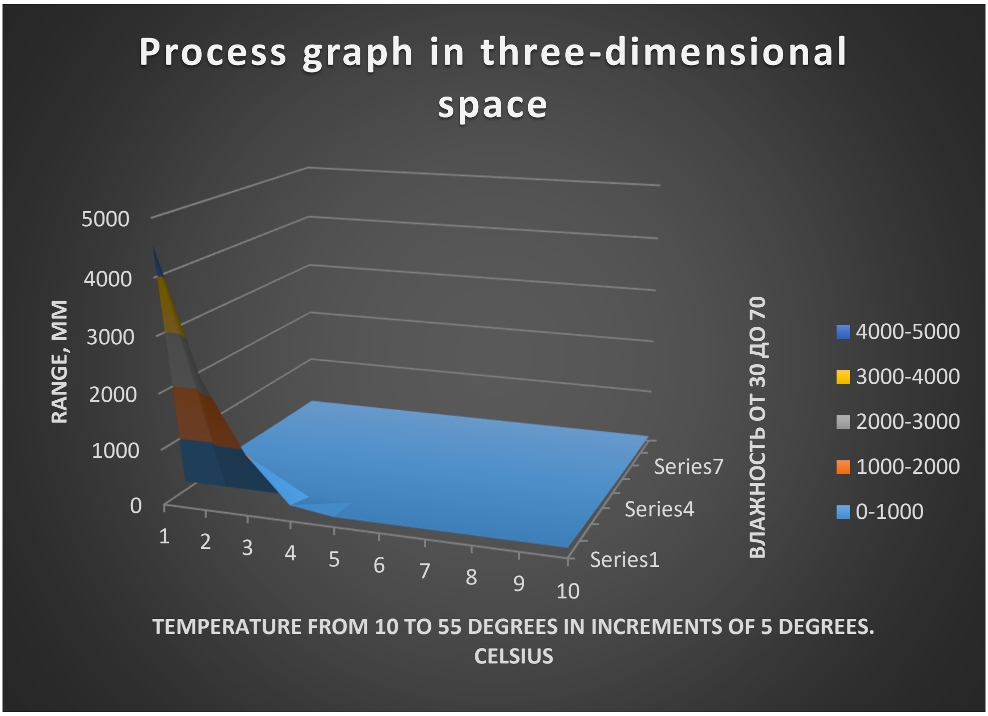

Fig. 5. Process graph in three-dimensional space in the low temperature range.

Figure 5 displays a three-dimensional plot of the process at low temperatures, including the blind zone range.

4 Conclusion

The resulting mathematical model of the process (67) describes the dependence of the range of the RFID system on humidity, temperature and time. When constructing a mathematical model, only the loss of energy of an electromagnetic wave when passing through a medium was taken into account. But it is known that the technology for receiving and transmitting information between special devices is influenced by external influences on specific receiving and transmission devices. However, the contribution of the listed external influences on devices in percentage terms is relatively small. This aspect was not considered in this work. The given graphical displays of the proposed mathematical model correlate with experimental data, which indicates the reliability of the mathematical model.

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