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MATHEMATICAL MODELING OF COMFORTABLE CONDITIONS OF CONVECTIVE HEAT EXCHANGE OF HUMANS AND ENVIRONMENT

Estimating environmental characteristics and determining comfortable conditions is a rather complex task that requires powerful mathematical and computer equipment. The purpose of the article is to build a mathematical model and determine the comfortable conditions of convective heat transfer of man and the environment by temperature in the city of Mykolaiv. The article "Mathematical modeling of comfortable conditions of convective heat exchange of humans and the environment" presents experimental studies of the evaluation of the comfortable conditions of convective heat exchange of the human body and the surrounding environment based on mathematical calculations allow to clearly outline the comfort zones in the cold period of the year. The basis of the research is the mathematical modeling of the comfortable conditions of the human body, which is based on the use of the developed algorithm, the basis of which is the synthesis of two software products. The ability to import data made a significant impact on the synthesized work of the programs, which made it possible to transfer the calculations without loss of content without loss of time. Optimal solutions identified during the creation of the algorithm allowed to create a method of mathematical modeling of the comfortable conditions of the human body.

The heat exchange between the human body and the temperature of the atmospheric air is estimated. The graphical dependence of the change of convective heat exchange on the atmospheric air temperature is constructed. An approximation of the curve on the basis of which the derivative of the function is determined. The levels of comfort of convective heat exchange of man with the environment are presented. The optimal temperature conditions for the human body in the cold period of the year are substantiated.

The normal temperature threshold is 1.5-0.5 °C, where the human body is in a comfortable state and there is moderate heat transfer. For the middle level, the temperature is determined in the range of 2.0-1.49 and 0.49-0 °C, where the increase in heat transfer begins due to the increase in atmospheric air temperature, which leads to sweating. Lowering the temperature, in turn, leads to heat release from the body to warm up.

Key words: *mathematical modeling, convective heat transfer, approximation, analytical differentiation, comfort zones, algorithm.*

Оцінювання характеристик навколишнього середовища та визначення комфортних умов є досить складним завданням, яке потребує потужного математичного та комп'ютерного обладнання. Метою статті є побудова математичної моделі та визначення комфортних умов конвективного теплообміну людини та навколишнього середовища за температурою в місті Миколаєві. У статті «Математичне моделювання комфортних умов конвективного теплообміну людини та навколішнього середовища» представлено експериментальні дослідження оцінки комфортних умов конвективного теплообміну організму людини та навколишнього середовища на основі математичних розрахунків, які дозволяють чітко окреслити зони комфорту в холодний період року.

Основою дослідження є математичне моделювання комфортних станів організму людини, яке базується на використанні розробленого алгоритму, основою якого є синтез двох програмних продуктів. Можливість імпорту даних значно вплинула на синтезовану роботу програм, що дозволило передавати розрахунки без втрати вмісту без втрати часу. Оптимальні рішення, виявлені при створенні алгоритму, дозволили створити метод математичного моделювання комфортних станів організму людини.

Оцінено теплообмін між тілом людини і температурою атмосферного повітря. Побудовано графічну залежність зміни конвективного теплообміну від температури атмосферного повітря. Апроксимація кривої, на основі якої визначається похідна функції. Наведено рівні комфортності конвективного теплообміну людини з

навколишнім середовищем. Обґрунтовано оптимальні температурні умови для організму людини в холодний період року.

Нормальним температурним порогом є 1,5-0,5 °С, при якому організм людини перебуває в комфортному стані і є помірна тепловіддача. Для середнього рівня температура визначається в межах 2,0-1,49 і 0,49-0 °С, де починається збільшення тепловіддачі за рахунок підвищення температури атмосферного повітря, що призводить до потовиділення. Зниження температури, у свою чергу, призводить до виділення тепла з організму для зігрівання.

Ключові слова: *математичне моделювання, конвективний теплообмін, апроксимація, аналітична диференціація, зони комфорту, алгоритм.*

Introduction

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An important factor in the normal functioning of the body is the release of heat into the environment.

Body temperature during any external processes is maintained only when there is a balance in heat production and heat transfer of the body. The heat exchange of the human body with the environment is due to thermal conductivity, convection, radiation and evaporation.

The heat balance maintained by the body can be disturbed and lead to hypothermia or overheating of the body, which in turn causes loss of ability to work, consciousness or even death.

Interpretation of the concept of "comfort" is quite conditional and controversial in our time. Basically, this concept is considered as a set of conditions, circumstances that affect normal well-being, mood, which depends on such conditions.

Comfort of environmental conditions for the human body, the concept is narrower and applies to environmental factors that affect the state of the human body.

The authors [12] presented a model that allows to predict the comfortable state of a person in different temperature ranges. She studied the comfortable state of a person in the thermal regime of the room [11], where a mathematical model was proposed and analytical expressions were obtained, which allow to determine the irradiation coefficients and assess the heat exchange of a person with the internal environment. A significant contribution to the study of human heat exchange was made [9], which published the results of theoretical studies related to the heat exchange of the human body and the parameters of the microclimate of the room.

The purpose of the article is to build a mathematical model and determine the comfortable conditions of convective heat transfer of man and the environment by temperature in the city of Mykolaiv.

Experimental researches

Maintaining an acceptable state of health, well-being and ability to work directly depends on the thermal comfort of the environment. It is the heat exchange of the human body and the environment can be assessed by convective heat transfer, determined by the Newton-Richman (formula 1):

$g_k = \alpha_k F_e (t_{sur} - t_a)$, *where:* (1)

t_{sur} – human body surface temperature,

t_a – atmospheric temperature,

F_e – effective surface of the human body, taken 1.8 m^2,

α_k – heat transfer coefficient, taken 4.06 $\frac{\text{W}}{\text{m}^2\cdot\text{deg}}$.

The surface temperature of the human body was measured with a non-contact thermometer at the time of entry into the room.

Temperature indicators of atmospheric air are taken for the five-day period in December of the city of Mykolaiv (table 1).

Table 1

Convective heat transfer at these temperatures

Atmospheric temperature, °C	Heat transfer coefficient, $\frac{\text{W}}{\text{m}^2\cdot\text{deg}}$	Effective surface of the human body, m^2	Human body surface temperature, °C	Convective heat transfer, Joule
-3,0	4,06	1,8	32,3	257,97
-2,0			29,6	230,93
0,0			28,3	206,82
0,0			28,3	206,82
2,0			30,3	206,82

In the MS Excel program, it is possible to build environmental characteristics (EC) created on the basis of a selection of tabular data. The approximation of the built environmental characteristics is created using the functional menu built into the program. For a more detailed evaluation of EC, the software components cannot provide the definition of the coefficients, which shows the accuracy of the approximation of the functions and the corresponding level, which is associated with the trend line describing the corresponding function [6].

The environment of the mathematical processor MathCad to a greater extent makes it possible to qualitatively process EC. Using the data import functions, the graphical differences obtained in MS Excel can be transferred to MathCad with further evaluation. Level import allows you to differentiate them and build derivatives on the basis of the received differentials with the subsequent determination of the comfort zone. In addition, the high-quality solution of mathematical expressions carried out in MathCad allows you to quickly and clearly process large volumes of data, which are used a lot of time in MS Excel in their work.

The process of differentiation is performed in the mathematical processor MathCad, which is connected with its automated process. The resulting equation, which was imported from MS Excel, is calculated using a special function button that allows you to calculate the input. MS Excel allows differentiation only manually using built-in functions.

The calculations carried out in the above programs made it possible to develop a clear algorithm for mathematical modeling of human comfort zones. By combining the functionality of the MathCad and MS Excel programs, it is guaranteed to set the comfort zone for environmental characteristics, which gives a complete picture of the impact of the factor on the living organism.

The first stage is the determination of the indicator and the corresponding operating factor. Based on the construction of ecological characteristics, for their further processing, it is necessary to choose environmental parameters as the active factor. These can be: atmospheric air temperature, relative humidity, wind speed, solar radiation, etc. In this case, the object is a living organism, namely a person.

The human body must have a quantitative assessment, that is, it must be calculated using certain numerical values – indicators. Such indicators include: the temperature of the human body, blood pressure, pulse, the amount of heat released, etc. It is important to assess the degree of influence of this or that factor on the indicator, this allows more accurate derivation of environmental safety indices in future processes. The next step is to enter the data bank into the MS Excel spreadsheet. The accuracy of the obtained studies depends on this stage, due to the volume of experimental data, the greater their amount, the more accurate the approximation of EC.

In the algorithm, which is presented in the figure, all the processes of mathematical modeling of human comfort zones are specified, which shows the entire calculation work from beginning to end [1]. All it work is based on mathematical calculations of various nature (fig. 1).

The presented algorithm can be improved by increasing the active factors, which gives a more accurate assessment when determining comfortable conditions for the human body. The introduction of one more active factor will allow us to build and evaluate three-factor environmental characteristics. This will make it possible to comprehensively evaluate, define, characterize and result of the conducted research.

Optimization of computer and mathematical equipment will contribute to increasing the level of accuracy of performed calculations. The possibility of using more advanced programs that will allow you to perform calculations not in several software environments, but in one. Construction of graphical dependencies in mathematical processors operating in automatic mode, due to the introduction of coded processes into the program environment. First of all, the use of software products that allow you to automatically evaluate the function and its derivative, in order to highlight the comfort zones of the ecological characteristics and give a better picture of the experiment [7, 8, 10].

The method of mathematical modeling of human comfort zones, which is presented in the form of an algorithm, allows you to quickly and qualitatively assess environmental characteristics using any amount of information. The computer and mathematical base of which allows to increase the level of accuracy of experimental studies, thanks to automated evaluation methods, which are more perfect compared to manual calculations.

Today, there are no analogues among similar methods and algorithms for mathematical modeling of human comfort zones.

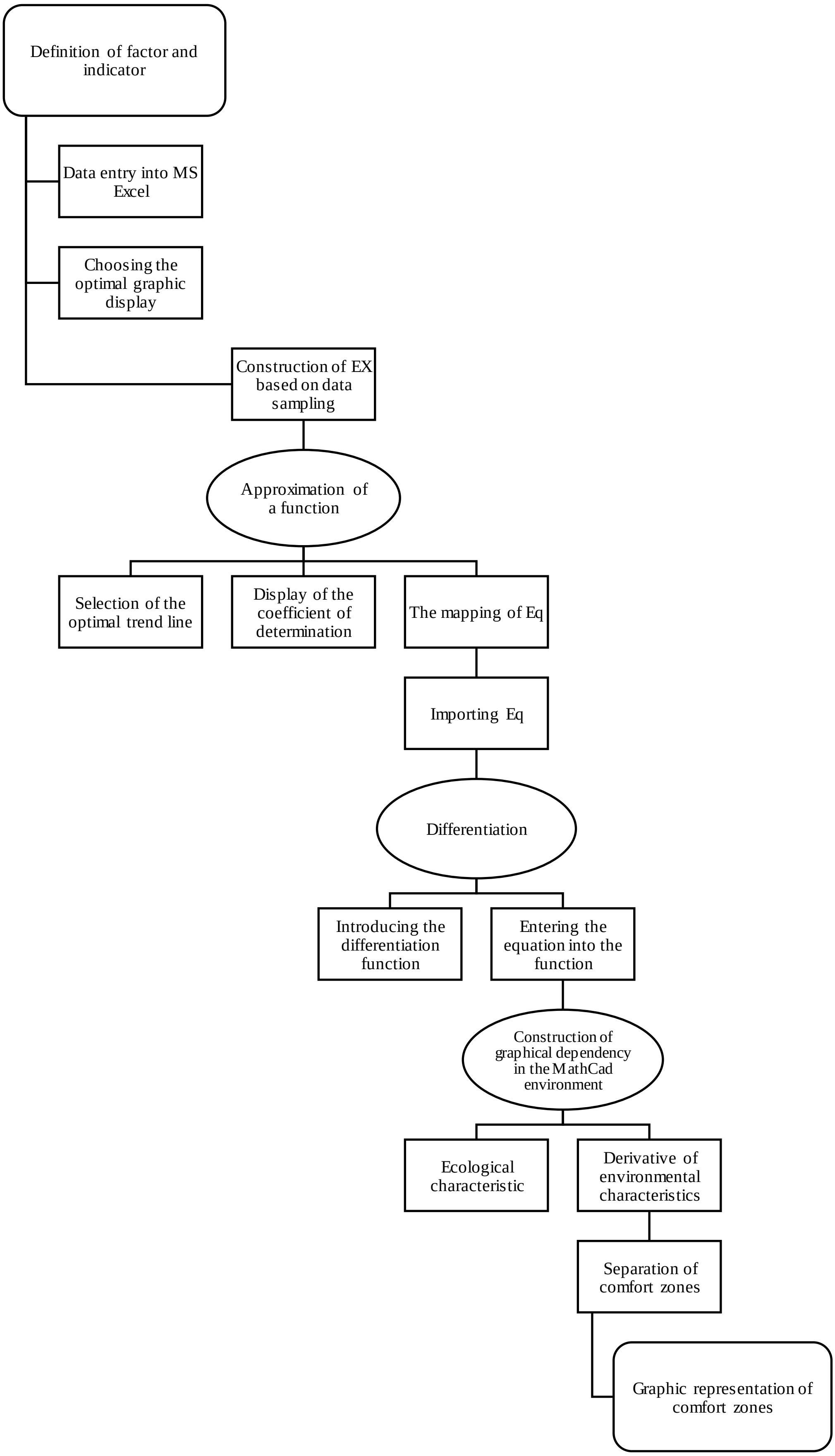

Fig. 1. Algorithm of mathematical modeling of human comfort zones

Results and discussion

First of all, the choice of the optimal graphic display is made, which allows to describe the received EC in more detail. Assessing the two-factor environmental performance, the best solution is to depict it using the MS Excel component "Chart" and select "Point with smooth curves", it allows you to get high quality and detailed display.

Graphic dependence (fig. 2) allows to estimate the heat exchange between the human body and the temperature of the atmospheric air. The constructed curve gives a clear picture of the reaction of the organism (convective heat transfer) to meteorological changes - the temperature of atmospheric air. Finding the derivative of this function, will determine the comfort zones of convective heat transfer of man and the environment [2].

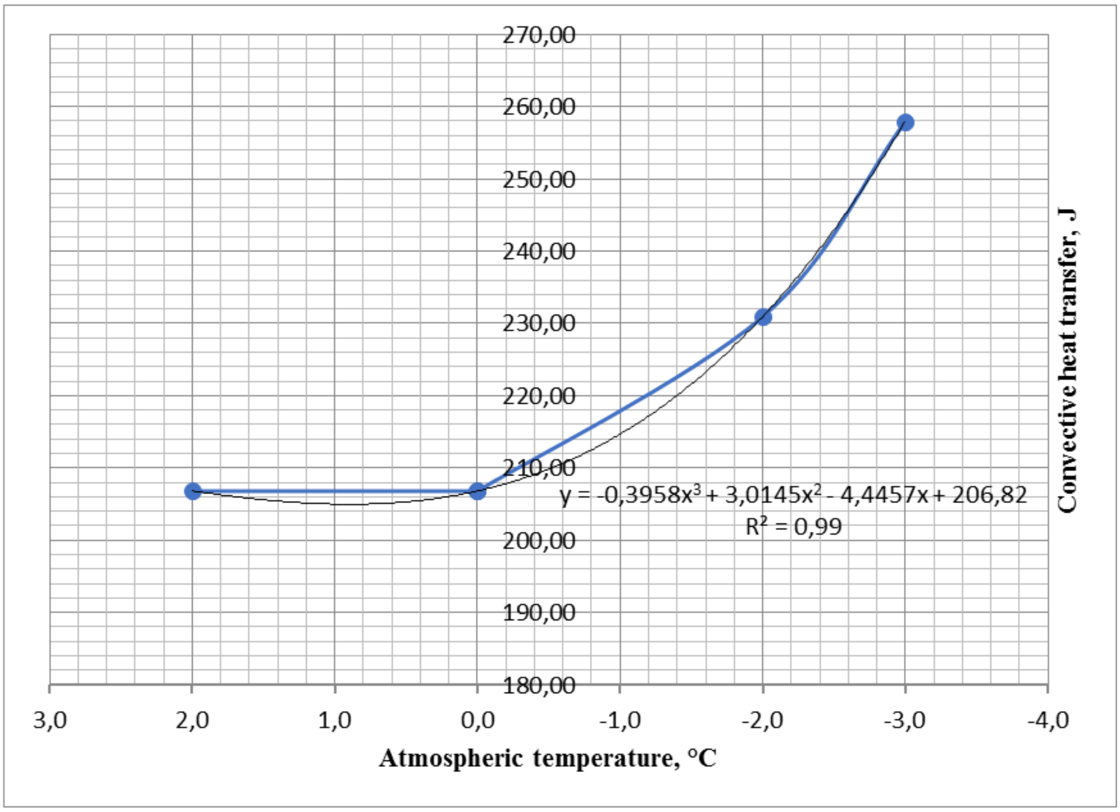

Fig. 2. Dependence of changes in human convective heat transfer on atmospheric air temperature

Approximation of the function in the environment of MS Excel allowed to determine the equation of the function and the coefficient of determination, which is equal to $R^2 = 0.99$. The obtained polynomial of the third degree was transferred to the environment of the mathematical processor MathCad, where analytical differentiation was performed and the derivative was constructed (formula 1,2).

Using the functions of the MathCad mathematical processor, analytical differentiation of this curve was performed and comfort zones were determined accordingly (fig. 3).

$$f(x) = -0.3958x^3 + 3.0145x^2 - 4.4457x + 206.82 \quad (2)$$

$$\frac{dy}{dx}f(x) = -1.1874x^2 + 6.029x - 4.4457 \quad (3)$$

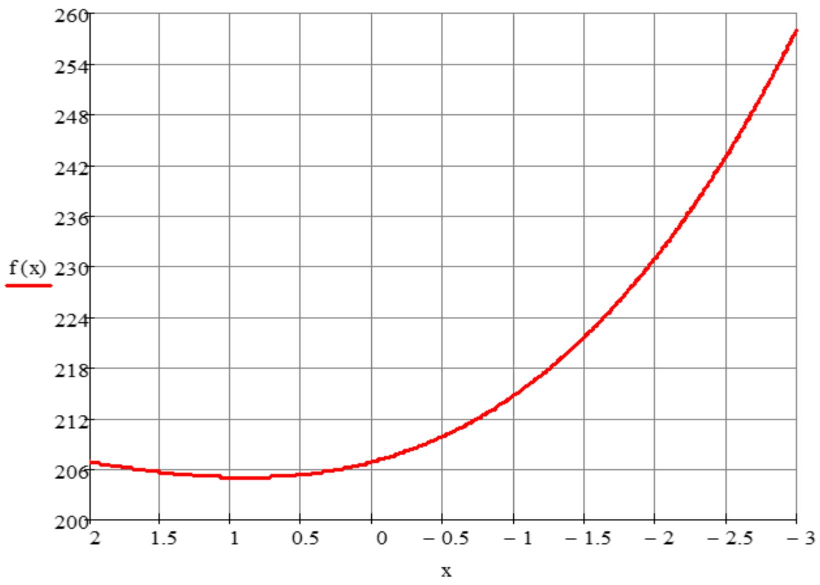

Fig. 3. Dependence of changes in human convective heat transfer on atmospheric air temperature in MathCad environment

The process of differentiation is reduced to automated calculation in the mathematical processor MathCad. By pressing the corresponding function button, which is located in the panel "Calculation", we create the basis for the calculation. Then we copy the equation in the field of differentiation and get the answer as a derivative (each expression must have a name, this allows the program to determine a particular expression according to its name) (fig. 4,5).

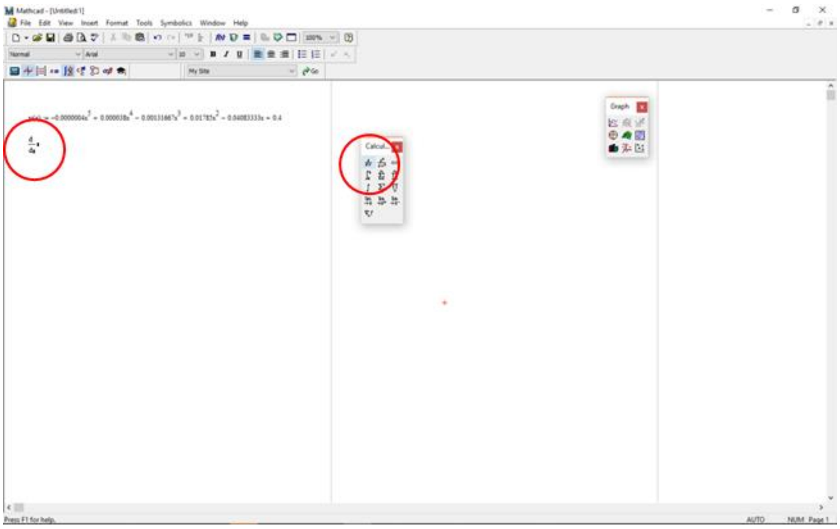

Fig. 4. The differentiation process in MathCad

Each level of comfort is clearly traced by the nature of the change in the derivative function of the dependence of convective human heat exchange on atmospheric air temperature.

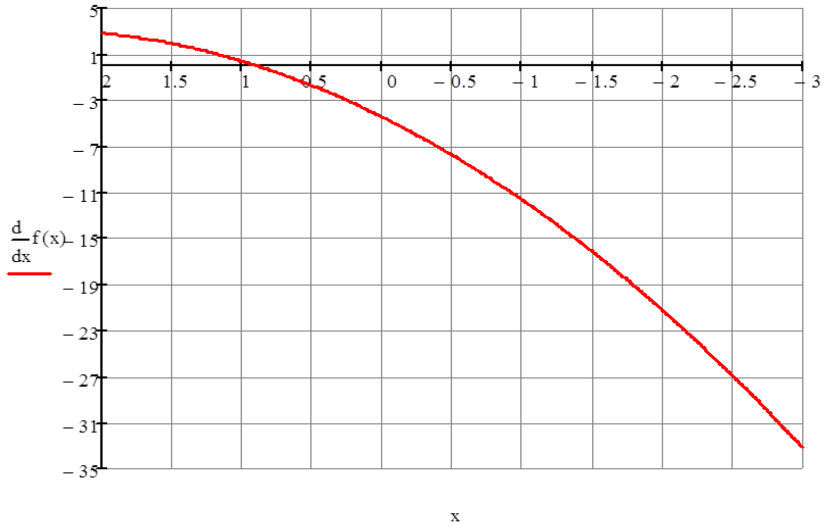

Fig. 5. Derivative functions in the MathCad environment

Graphic dependencies are built on the basis of the received expressions. Select the menu item “Add” and click on the line “Charts”, where in the list click on “X-Y chart”. After that, an empty graph field appears on the workspace, in which the name of the function to which our equation belongs is written along the ordinate axis, and the name related to the sample of values in x is written along the abscissa axis, given that the function and its derivative have the same values of x, it makes sense to build graphical dependencies in one graphic field) [4, 5]. Therefore, it is possible to enter both the function equation and the derivative equation in the field, and to leave x unchanged, but more detailed for the assessment of comfort are graphical dependencies, which are built separately from each other. This allows to clearly and qualitatively characterizing the trend of change of the derivative during the assessment of comfort zones EC.

The separation of comfort zones is based on a graphical dependence, which consists of a function and its derivative. After analyzing the nature of the derivative change, we can distinguish comfort zones: the optimal zone, the middle and low comfort zone. According to these zones, you can select the gradation for each of the developed levels [3].

Based on the constructed derivative, on its basis a graph is constructed with selected comfort zones, where green indicates the optimum zone, yellow - medium, red - low comfort zone.

Normal heat exchange of the organism and the environment is determined by the comfort levels of the constructed derivative (fig. 6):

optimal (comfortable) condition - 1.5-0.5 ° C;

moderate condition - 2-1.49 and 0.49-0 ° C;

uncomfortable state - 0,1 - (- 3) ° C.

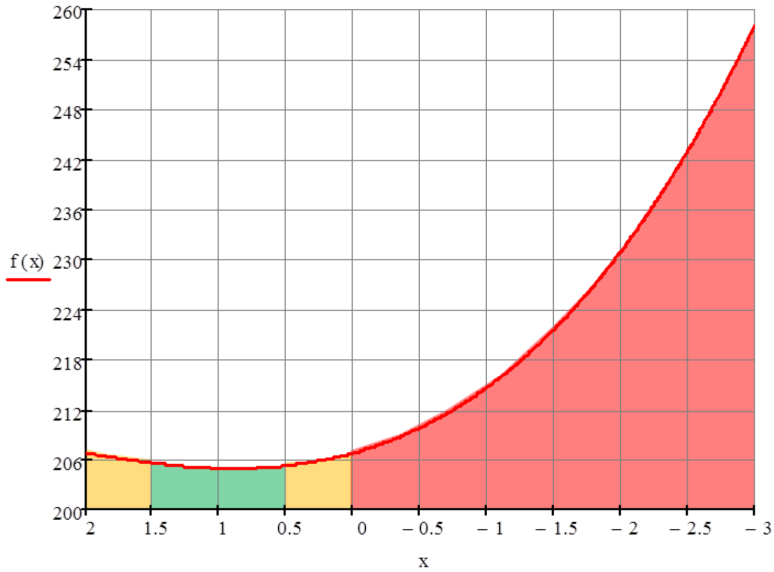

Fig. 6. Comfort levels of convective heat exchange of a person with the environment

Certain levels of comfort of convective heat exchange of the person with environment allow to estimate optimum temperature conditions for a human body in the cold period of year.

Optimization of computer and mathematical apparatus will help increase the level of accuracy of calculations. Ability to use more advanced programs that will perform calculations not in several software environments, but in one. Construction of graphic dependencies in mathematical processors operating in automatic mode, due to the introduction of coded processes in the program environment. First of all, the use of software products that allow you to automatically evaluate the function and its derivative, in order to identify comfort zones of environmental characteristics and give a better picture of the experiment.

The presented algorithm can be improved by increasing the operating factors, which gives a more accurate assessment when determining the comfortable conditions for the human body. The introduction of another active factor will build and assess the three-factor environmental characteristics. This will allow a comprehensive assessment, determination, characterization and results of research.

Conclusions

At subzero temperatures, the human body begins to give off heat (energy), where there is an increase in values along the y-axis. The normal temperature threshold is 1.5-0.5 °C, where the human body is in a comfortable state and there is moderate heat transfer. For the middle level, the temperature is determined in the range of 2.0-1.49 and 0.49-0 °C, where the increase in heat transfer begins due to the increase in atmospheric air temperature, which leads to sweating. Lowering the temperature, in turn, leads to heat release from the body to warm up.

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