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RESEARCH RESULTS OF THE CYBER-PHYSICAL SYSTEM ON ONLINE-MONITORING OF AIR HUMIDITY IN GREENHOUSES GROWING AREA

Relevance. *Nowadays, one of the global world problems, which has been increasing significantly recently, is the need to ensure of food-security and year-round availability of food products for people in different countries of the world. This problem requires a comprehensive solution via generating a scientifically based approach in various directions, that stimulate the optimization of long-term sustainability of agricultural production, including through rational use of resources and work planning during the cultivation, storage and transportation of agricultural products. Therefore, the scientific and applied problem of this article is relevant and consists in the development of the theory of cyber-physical systems construction for agrotechnical purpose due to the substantiation of computer-oriented methods and models of comprehensive aggregation and intellectual transformation of distributed measurement data of the air humidity of industrial greenhouses growing areas. The* ***main purpose*** *of the article is the development of scientific approaches to further modernization of Industry 4.0 systems for agrotechnical purposes due to the substantiation of the structural and algorithmic organization of the cyber-physical system on non-destructive online monitoring of air humidity of industrial greenhouses growing areas. The* ***research object*** *is non-stationary processes of aggregation, transmission and interpretation of distributed measurement data of the air humidity of industrial greenhouses growing areas. The* ***research subject*** *is methods and technologies on non-destructive online monitoring of the air humidity of industrial greenhouses growing areas.* ***Conclusions.*** *The important scientific and applied task of the development of scientific approaches to the further modernization of Industry 4.0 systems for agrotechnical purpose has been solved due to the substantiation of the structural and algorithmic organization of the cyber-physical system on non-destructive online monitoring of the air humidity of industrial greenhouses growing areas.*

Key words: *cyber-physical system, monitoring, humidity, greenhouse, growing area, structural-algorithmic organization.*

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РЕЗУЛЬТАТИ ДОСЛІДЖЕНЬ КІБЕРФІЗИЧНОЇ СИСТЕМИ ОНЛАЙН-МОНІТОРИНГУ ВОЛОГОСТІ ПОВІТРЯ ЗОНИ ВИРОЩУВАННЯ ТЕПЛИЦЬ

Актуальність. *На сьогоднішній день однією з глобальних світових проблем, яка останнім часом значно посилилась, є необхідність забезпечення продовольчої безпеки та цілорічної доступності населення різних країн світу продуктами харчування. Ця проблема потребує комплексного вирішення шляхом генерування науково обґрунтованого підходу за різними напрямками, що стимулюють оптимізацію довгострокової стійкості сільськогосподарських виробництв, у тому числі, завдяки раціональному використанню ресурсів і плануванню робіт під час вирощування, зберігання й транспортування сільськогосподарської продукції. Отже, науково-прикладна задача, вирішенню якої присвячено цю статтю, є актуальною та полягає в розвитку теорії побудови кіберфізичних систем агротехнічного призначення завдяки обґрунтуванню комп'ютерно-орієнтованих методів і моделей комплексної агрегації та інтелектуальної трансформації розподілених вимірювальних даних щодо вологості повітря зони вирощування промислових теплиць.* ***Основна мета*** *статті полягає в розробці наукових підходів щодо подальшого розвитку систем Industry 4.0 агротехнічного призначення завдяки обґрунтуванню структурно-алгоритмічної організації кіберфізичної системи неруйнівного онлайн-моніторингу вологості повітря зони вирощування промислових теплиць.* ***Об'єктом дослідження*** *є нестаціонарні процеси агрегації, передачі та інтерпретації розподілених вимірювальних даних щодо вологості повітря зони вирощування промислових теплиць.* ***Предметом дослідження*** *є методи та технології неруйнівного онлайн-моніторингу вологості повітря зони вирощування промислових теплиць.* ***Висновки.*** *У результаті досліджень статті було розв'язано важливу науково-прикладну задачу з розробки наукових підходів щодо подальшого розвитку систем Industry 4.0 агротехнічного призначення завдяки обґрунтуванню структурно-алгоритмічної організації кіберфізичної системи неруйнівного онлайн-моніторингу вологості повітря зони вирощування промислових теплиць.*

Ключові слова: *кіберфізична система, моніторинг, вологість, теплиця, зона вирощування, структурно-алгоритмічна організація.*

The relevance of the scientific and applied task of the research. Nowadays, one of the global world problems, which has been increasing significantly recently, is the need to ensure of food-security and year-round availability of food products for people in different countries of the world (Baudoin W. et al, 2017; Berezniak, 2020). This problem requires a comprehensive solution via generating a scientifically based approach in various directions, that stimulate the optimization of long-term sustainability of agricultural production, including through rational use of resources and work planning during the cultivation, storage and transportation of agricultural products. This approach is possible due to the increasing an innovative component of agricultural enterprises through the development and introduction of highly-effective information technologies into their production processes (American Society of Agricultural and Biological Engineers, 2008; Sustainable Development Goals: National Report). Currently, computer-oriented, information and digital technologies are increasingly being used, which causes a continuous search on scientifically based ways of their development. One of such industries, the needs of which require constant modernization through the introduction of highly-effective comprehensive software and hardware solutions of cyber-physical technologies, which combine modern achievements in the field of computer, microprocessor, sensor and infocommunication technologies, is crops cultivation in greenhouse conditions. Since the indicators of quality, volumes and rates of cultivation directly depend on the effectiveness and informativeness of monitoring and control of agrotechnical procedures of the agricultural crops growing, which correlate with trends in ensuring global food-security (Jørgensen, 2018).

Taking into account the well-known solutions of certain problems of software and hardware development of computerized and cyber-physical systems, the theory of comprehensive precision and intellectual monitoring of the analysed physical environments state is under the formation stage (Both et al., 2015). The main issues that require additional development on the basis of well-known theories are as follows: accounting the principles of systematicity and comprehensiveness of collection and processing of distributed measurement data; deepening the theoretical foundations of the substantiation of sensor locations and their network interaction; development of physical and mathematical apparatus of the laboratory monitoring results extrapolation to real objects; account of the measured parameters relationships during the interpretation of the controlled environment integral state. Therefore, the scientific and applied problem of this article is relevant and consists in the development of the theory of cyber-physical systems construction for agrotechnical purpose due to the substantiation of computer-oriented methods and models of comprehensive aggregation and intellectual transformation of distributed measurement data of the air humidity of industrial greenhouses growing areas.

Purpose, object and subject of the research. The main purpose of the article is the development of scientific approaches to further modernization of Industry 4.0 systems for agrotechnical purposes due to the substantiation of the structural and algorithmic organization of the cyber-physical system on non-destructive online monitoring of air humidity of industrial greenhouses growing areas. The research object is non-stationary processes of aggregation, transmission and interpretation of distributed measurement data of the air humidity of industrial greenhouses growing areas. The research subject is methods and technologies on non-destructive online monitoring of the air humidity of industrial greenhouses growing areas.

Critical analysis and logical summarization of the up-to-date scientific publications and technical developments. Solving the scientific and practical problems of development and research of measuring methods and means of air humidity in the growing area is a mandatory condition for substantiating the scientific basis during the introduction of advanced monitoring and adaptive control technologies of the microclimate integral state of industrial greenhouses in order to increasing the rates, volumes and quality of greenhouse crops production.

Continuous non-destructive monitoring of the humidity of the greenhouses physical environments requires special attention, because an excessive level of moisture may cause the diseases appearance and lead to a transpiration decrease. Also, an insufficient humidity may cause hydraulic stress and reduce the intensity of photosynthesis due to a decrease of the carbon dioxide assimilation (Pawlowski, Guzman, Rodriguez, 2009). The research of humidity monitoring means for greenhouse conditions is associated with two main problems: temperature and humidity in greenhouses are inversely proportional factors; most of the modern automatic systems on monitoring and controlling microclimate parameters of greenhouses use the same drive mechanisms for the temperature and humidity regulating. In order to maintain an optimal level of humidity in the regulated range, the temperature value must be set based on the current value of relative humidity. Therefore, the humidity controller must work in the setpoint generator mode with the ability to produce a signal that controls the temperature with sufficient sensitivity in the appropriate operating range (Rodriguez, Guzman, Berenguel, 2008). To date, many scientific works have been devoted to solving the problem of creating and researching highly-effective methods and means of air humidity measuring and monitoring, the main ones of which are listed in Table 1.

Also, a significant number of experimental research results are presented in up-to-date scientific literature, which prove the effectiveness of using the computerized humidity meters of physical environments in greenhouses, the main ones are presented in Table 2.

In the scientific work (Rabbi, Chen, Sethuvenkatraman, 2019), experimental dependences between the optimal values of temperature, air humidity and light intensity for different types of greenhouse crops were established, as shown in Table 3.

The general result of the analysis of well-known technologies of the measurement monitoring of humidification regimes of greenhouses physical environments (Shamshiri, 2007; Matula, Batkova, Legese, 2016; Halim, Hassan, Zakaria, 2016; The Center for Agriculture, Food and the Environment; Korner, Challa, 2003, Asolkar, Bhadade; van Iersel M.W., Chappell M., Lea-Cox J.D., 2013; Rabbi B., Chen Z.-H., Sethuvenkatraman S., 2019) is the substantiation of the need to develop and research cyber-physical subsystems of air humidity in the growing area taking into account the factors of temperature, intensity and spectral composition of lighting, as well as types and vegetation periods of crops in online mode.

Research results. Cyber-physical monitoring of air humidity in the growing area is a dynamic process, the parameters of which are determined by mass transfer phenomena between the greenhouse inside volume and outside environment, as well as physical and biological processes of crops growth (Ben Ali R., Bouadila S., Mami A., 2018, Maher A., Kamel E., Enrico F., 2016; Mostakim N., Mahmud S., Jewel K. A, 2020; Diaz-Florez G., Mendiola-Santibanez J., Solis-Sanchez L., 2019).

On the basis of the information mentioned above, a block-diagram of the monitoring process has been proposed, which describes the parameters influence on the processes of the moisture mass exchange, which is shown in Fig. 1.

Considering the current requirements concerning technological cultivation modes and modern design of greenhouses, the basic equation when building a mathematical model of the air humidity monitoring was obtained (Ben Ali R., Bouadila S., Mami A., 2018, Maher A., Kamel E., Enrico F., 2016; Diaz-Florez G., Mendiola-Santibanez J., Solis-Sanchez L., 2019):

$$\frac{dW_{air\ in}(t)}{dt} = \frac{L_{air\ in}}{\rho_{air} V_g} \begin{pmatrix} C_e\left(P_{air\ out}(t) - P_{air\ in}(t)\right) \\ -\left(W_{air\ in}(t) - W_{air\ out}(t)\right) \end{pmatrix} + Z_{total\ hum}(t), \quad (1)$$

where: $W_{air\ in}$ – relative air humidity of the growing area, %; $W_{air\ out}$ – outside relative air humidity, %; t – time, s; V_g – volume of the greenhouse growing area, m^3; ρ_{air} – air density, kg/m^3; $L_{air\ in}$ – difference between the fresh air flow and the flow of air leaving the greenhouse, m^3/s; C_e – coefficient of the water vapor transfer in air, kg/(m^3·Pa); $P_{air\ out}$ – outside saturated vapor pressure, Pa; $P_{air\ in}$ – inside saturated vapor pressure as a function of air temperature, Pa; $Z_{total\ hum}$ – difference between the

Table 1

Well-known research results on humidity measuring and monitoring of the physical environments of industrial greenhouses

The subject of study	The obtained effect	Source of literature
Modern methods and means of measuring and monitoring of humidity	An analysis of existing technologies on humidity monitoring of greenhouse soil and air was carried out. Approaches to the selection of humidity sensors were substantiated. Dependencies between the optimal temperature and humidity were established. Qualitative indicators of the influence of soil and air moisture on crops growth were determined.	[9]
Functional characteristics of capacitive humidity sensors	The method of calibration of capacitive humidity sensors was substantiated. The main characteristics of the most common humidity sensors were evaluated. Recommendations for the sensors use were substantiated.	[10]
General principles of humidity sensors operation modes	The basic functions of capacitive humidity sensors as a part of greenhouse microclimate monitoring and control systems using Internet of Things technology were substantiated.	[11]
Methods and means of the efficiency increase of humidity control systems	The method of humidity sensors calibration was developed. Dependencies between the optimal temperature and humidity of greenhouses were established. Recommendations for the sensors introduction into real conditions were substantiated.	[12]

Table 2

Results of using the humidity monitoring tools

The subject of study	The obtained effect	Source of literature
Optimization of humidification modes of greenhouses	The empirical relationships between the optimal temperature and humidity in greenhouses were established. Scientific and practical approaches to control of air humidification and soil irrigation systems in greenhouses were developed.	[13]
The effectiveness of humidity monitoring	The indicators dependence of the growing greenhouse crops effectiveness on the humidity and temperature of greenhouses was determined due to the use of simulation methods.	[14]
Forecasting the amount of cultivation taking into account the humidity factor	The computerized technology on remote monitoring of the air humidity level of the growing area was proposed, which takes into account the influence of temperature and humidity on the indicators of the growing greenhouse crops efficiency considering their types.	[15]

Table 3

Recommended parameters of the greenhouse microclimate

Plant types	Air temperature, ºC	Air humidity, %	Illumination intensity (PAR), µmol/(m²·s)
Tomato	from 23 to 27 (day) from 13 to 16 (night)	from 50 to 60	400
Cucumber	from 25 to 30	from 80 to 90	400
Eggplant	from 25 to 28 (day) from 14 to 16 (night)	from 65 to 75	505
Pepper	from 22 to 30 (day) from 14 to 16 (night)	from 60 to 65	505
Lettuce	from 24 to 28 (day) from 13 to 16 (night)	from 65 to 80	from 260 to 290
Strawberry	from 20 to 26 (day) from 13 to 16 (night)	from 50 to 65	from 200 to 400

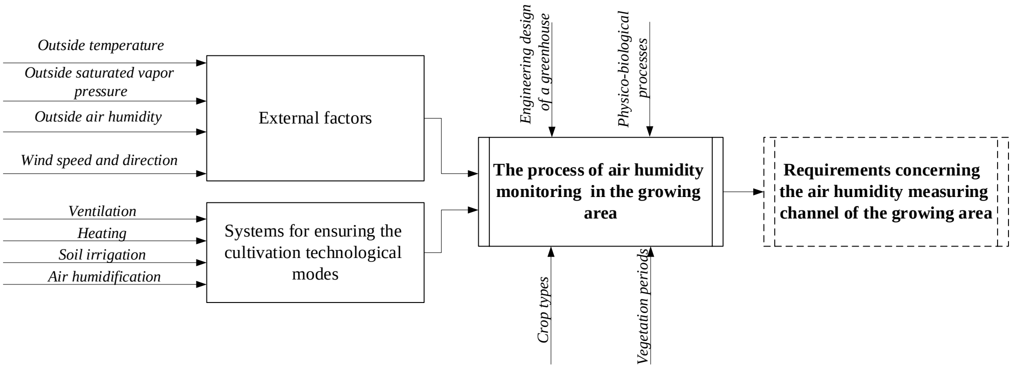


Fig. 1. Block-diagram of greenhouse air humidity monitoring

Table 4

Technological parameters during simulation of air moisture dynamics in the greenhouse growing area

Parameter	Accepted value	Measuring units	Source of literature
Coefficient of the water vapor transfer in air (C_e)	$2.8 \cdot 10^{-8}$	kg/(m³·Pa)	[21]
Air density (ρ_{air})	1.292	kg/m³	[22]
Volume of the greenhouse growing area ($V_g = A_g \cdot h_g / 4$)	1875; 3750	m³	[23]
Air flow speed (v_{air})	1	m/s	[23]

rate of supply and removal of moisture from the growing area, %/s.

When simulating the non-destructive computerized online monitoring of the air humidity of the greenhouse cultivation area, the numerical values of the technological and design parameters were adopted in accordance with Table 4.

When developing the mathematical model of moisture dynamics in the growing area tomato and cucumber were chosen as basic crops with the following typical periods of vegetation: before and during fruiting in autumn-winter and spring-summer growing cycles. The average value of air humidity in the surrounding environment is determined according to the data of the Ukrainian Hydrometeorological Centre: for the autumn-winter cycle – 81 %, for the spring-summer cycle – 65 % in 2022 year.

On the basis of a comparative analysis of the average values of air humidity in the surrounding environment and regulated requirements of air humidity in growing area (VNTP APK–19–07), general requirements for the productivity of air humidification systems of greenhouses were established, namely:

– the additional level of moisture (+) / removal of moisture (–) for cucumbers when autumn-winter growing cycle before fruiting is equal –6 %, during fruiting +9 %; in spring-summer cycle before fruiting is equal +10 %, during fruiting +15 %;

– the additional level of moisture (+) / moisture removal (–) for tomatoes when autumn-winter growing cycle before fruiting is equal –21 %, during fruiting –16 %; during spring-summer cycle before fruiting is equal –5%, during fruiting +5 %.

The obtained simulation results of the moisture dynamics in the air of greenhouses growing area based on the differential equation (1) and the accepted numerical parameters (see Table 4) are shown in Figs. 2 and 3.

Based on the quantitative and qualitative analysis of the research results obtained via the mathematical model of the process on monitoring the air humidity of the growing area (see Figs. 2 and 3), the following results were established:

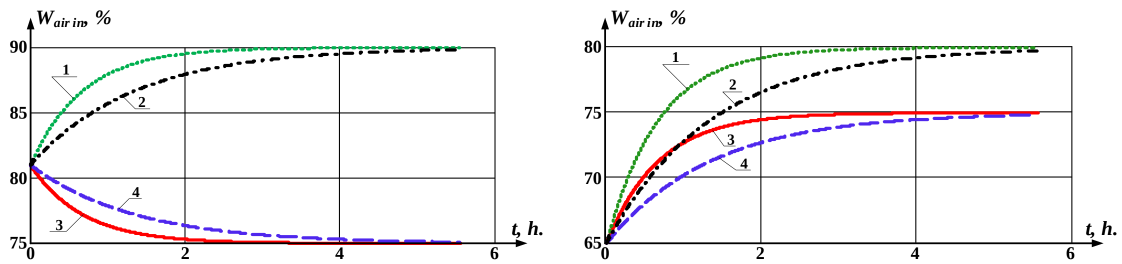
– the time range of reaching the regulated stable value of air humidity in the growing area depends on the greenhouses volume, the types and vegetation periods as well as the seasonal cycle of growing and varies in the range from 1.5 h to 2 h at the nominal productivity of humidification and ventilation systems;

– an account of significant number of the outside parameters, constructive characteristics of greenhouses and physical and biological processes of growing greenhouse crops, as well as the presence of non-linear functional relationships between the air humidity and available level of the soil moisture and air temperature of the growing area necessitates the creating a subsystem on monitoring of the growing greenhouse crops humidity regimes on the basis of adaptive algorithms of information transformation using the mathematical apparatus of fuzzy logic theory.

On the basis of research carried out on the development of the mathematical model of the air humidity computerized monitoring in greenhouses, the functional block-diagram of procedures of the measurement data aggregation and processing regarding the greenhouse cultivation humidity regime was specified (see Fig. 4).

The following notations are shown in Fig. 4: $P_{air\ in}$ – inside saturated vapor pressure; $P_{air\ out}$ – outside saturated vapor pressure; $W_{air\ in}$ – inside relative air humidity; $W_{air\ out}$ – outside relative air humidity; $v_{air\ out}$ – speed of outside air flows; $D_{air\ out}$ – direction of outside air flows; r_v – percentage of opening mechanisms of the ventilation system; k_{air} – air exchange rate; CON_{water} – consumption of irrigation solution; CON_{steam} – liquid flow rate on air humidification.

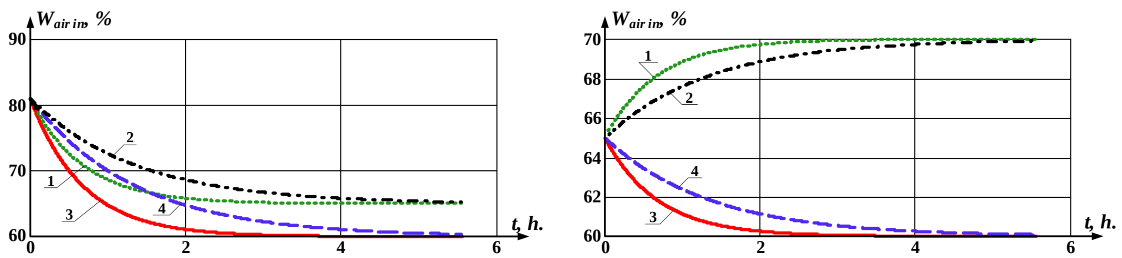
Therefore, the developed functional block-diagram (see Fig. 4) allows to realize an adaptive to types and vegetation periods of crops, precise control of cultivation technological modes, taking



a) autumn-winter growing cycle

b) spring-summer growing cycle

Fig. 2. Simulation results of the air humidity dynamics for cucumbers (*1* – during fruiting, V_g=1875 m³; *2* – during fruiting, V_g=3750 m³; *3* – before fruiting, V_g=1875 m³; *4* – before fruiting, V_g=3750 m³)



a) autumn-winter growing cycle

b) spring-summer growing cycle

Fig. 3. Simulation results of the air humidity dynamics for tomatoes (*1* – during fruiting, V_g=1875 m³; *2* – during fruiting, V_g=3750 m³; *3* – before fruiting, V_g=1875 m³; *4* – before fruiting, V_g=3750 m³)

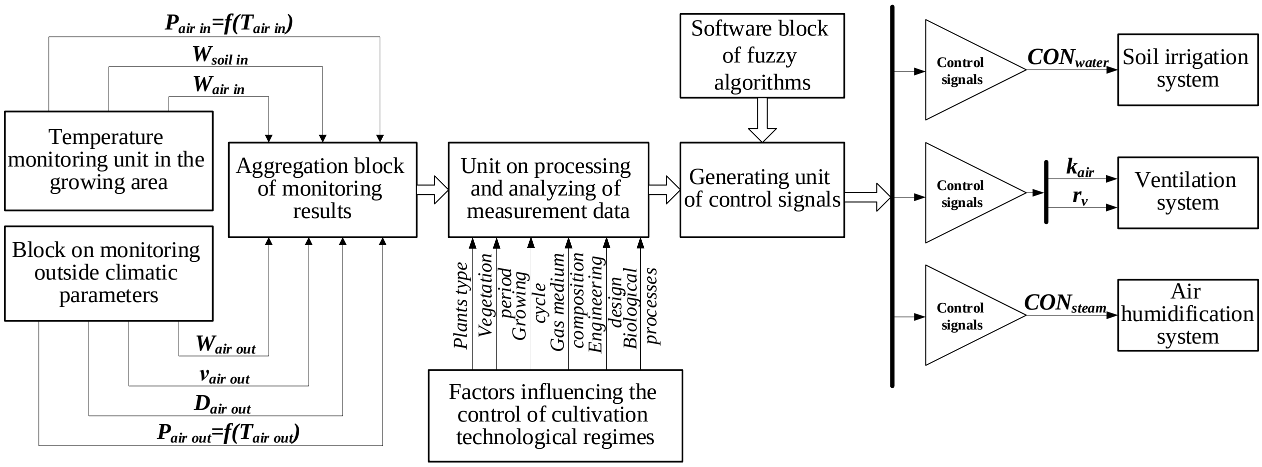


Fig. 4. Improved functional block-diagram of the measurement data aggregation and processing regarding the greenhouse cultivation humidity regime

Fig. 5. Laboratory sample of the computerized greenhouse

into account factors of seasonality and engineering design of greenhouses based on the results of computerized monitoring of the parameters of internal microclimate and external atmospheric parameters in real time mode.

The test results of the implemented cyber-physical air humidity monitoring system (Laktionov I., Vovna O., Berezhnyi M., 2021; Berezhnyi M., Laktionov I., Lebediev V., 2020), which is a functional component of the laboratory sample (see Fig. 5), regarding the assessment of the observations results dynamics of microclimate parameters within the daily cycle of growing when cucumber fruiting are shown in Fig. 6.

The results of experimental tests of the developed hardware and software implementation of the cyber-physical system on online-monitoring of air humidity in the growing area on estimating the average values of the greenhouse microclimate parameters

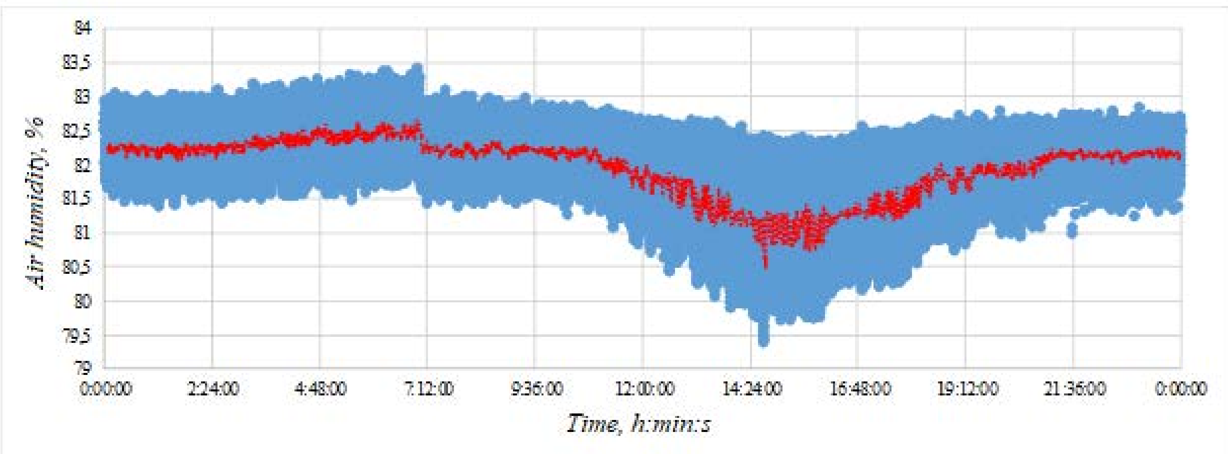


Fig. 6. Air humidity dynamics in the growing area

during the full-cycle of cucumber cultivation (before and during fruiting) are shown in Fig. 7. These results allow to assess the overall dynamics of the measured microclimate parameters of greenhouses. They may also be used by scientists and experts in the area of protected soil vegetable growing during the construction of yield forecasting models, subject to additional interdisciplinary research in the field of computer systems and components and vegetable growing.

As a result of the obtained research results analysis (see Figs. 6 and 7) insignificant average daily dynamics of greenhouse microclimate parameters was established, provided that all measured physical values are within acceptable limits before and during the fruiting of cucumbers with significant dynamics of outside climatic factors. This fact confirms the effectiveness of using the implemented hardware and software components of the cyber-physical system on the non-destructive online monitoring of air humidity in greenhouse growing area.

Priority directions for further research. According to the results of the analysis and substantiation of the main requirements, the future promising directions of research are as follows:

– substantiation of hardware and software components regarding the integration of the developed cyber-physical system into the industrial automation complexes of agrotechnical productions;

– integration of software components implementing the latest world initiatives of distributed intelligent computing;

– development of recommendations on improving the architecture of the investigated cyber-physical system through the long-term experimental tests in real production conditions.

Conclusions. The important scientific and applied task of the development of scientific approaches to the further modernization of Industry 4.0 systems for agrotechnical purpose has been solved due to the substantiation of the structural and algorithmic organization of the cyber-physical system on non-destructive online monitoring of the air humidity of industrial greenhouses growing areas.

The mathematical model of the air humidity monitoring process in the growing area was developed and analysed at the qualitative and quantitative levels. The main results are as follows:

– the time range of reaching the regulated stable value of air humidity in the growing area depends on the greenhouses volume, the types and vegetation periods as well as the seasonal cycle of growing and varies in the range from 1.5 h to 2 h at the nominal productivity of humidification and ventilation systems;

– an account of significant number of the outside parameters, constructive characteristics of greenhouses and physical and biological processes of growing greenhouse crops, as well as the presence of non-linear functional relationships between the air humidity and available level of the soil moisture and air temperature of the growing area necessitates the creating a subsystem on monitoring of the growing greenhouse crops humidity regimes on the basis of adaptive algorithms of information transformation using the mathematical apparatus of fuzzy logic theory.

The hardware and software components of the experimental sample of the cyber-physical air humidity monitoring system, which is a functional component of the laboratory sample, were developed and implemented, which made it possible to carry out laboratory and field tests to assess the main functional, technical and metrological characteristics.

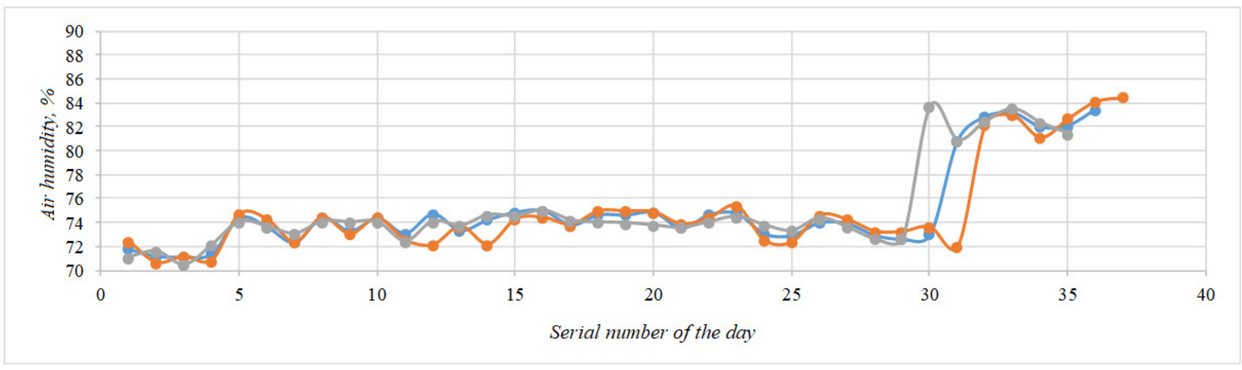


Fig. 7. Average daily values dynamics of air humidity in the growing area (beginning of fruiting 30 – 32 days after sowing)

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