1. Vitalii YAROPUD, 2. Ihor KUPCHUK, 3. Serhiy BURLAKA, 4. Volodymyr RUTKEVYCH

Vinnytsia National Agrarian University

ORCID: 1. 0000-0003-0502-1356; 2. 0000-0002-2973-6914; 3. 0000-0002-4079-4867; 4. 0000-0002-6366-7772.

doi:10.15199/48.2023.09.12

Results of numerical modeling of three-pipe heat exchanger for livestock premises

***Abstract**. Developed a three-pipe heat recovery system containing three coaxially installed pipes (inner, middle and outer), a condensate drain pipe that passes through the outer pipe and is located at the bottom of the middle pipe, an exhaust shaft that passes through the outer pipe, supply and discharge air filter, which is additionally equipped with an ultraviolet lamp. As a result of numerical modeling of the heat recovery device, the distribution of the temperature and vector velocity fields is established.*

***Streszczenie**. Opracował trójrurowy system odzysku ciepła składający się z trzech współosiowo zainstalowanych rur (wewnętrznej, środkowej i zewnętrznej), rury spustowej kondensatu, która przechodzi przez rurę zewnętrzną i znajduje się na dole rury środkowej, szybu wylotowego, który przechodzi przez rurę zewnętrzną rurowy, filtr powietrza nawiewanego i wylotowego, który dodatkowo wyposażony jest w lampę ultrafioletową. W wyniku modelowania numerycznego urządzenia do odzysku ciepła ustala się rozkład pól temperatury i prędkości wektorowych. (**Wyniki modelowania numerycznego trójrurowego wymiennika ciepła dla pomieszczeń inwentarskich**))*

Key words: microclimate, livestock premises, ventilation, heat utilizer, automation, parameters, researches, dependencies.
Słowa kluczowe: mikroklimat, pomieszczenia inwentarskie, wentylacja, użytkownik ciepła, automatyka, parametry, badania, zależności.

Introduction

Much of the year, and according to some technologies – throughout the year, most farm animals stay indoors [1-4]. In this connection, it is necessary to generate in livestock facilities the microclimate that would foster animals' and poultry's physiology and have a positive impact on their condition, health, productivity and product quality [2, 5].

Livestock premises microclimate is the state of environment formed as a result of animals' activity under conditions of certain technology. The main microclimate parameters include: temperature T; relative air humidity W,%; chemical composition of air (content of carbon dioxide CO2, ammonia NH3, hydrogen sulfide H2S); presence of dust (mechanical pollution) and microorganisms (biological pollution) in the air; speed v, m/s, and air flow direction; lighting [2, 6]. Air regime gets disturbed during animals' respiration (release of heat, moisture, carbon dioxide, etc.), and as a result of evaporation from manure. Among the main factors of pollution mostly affecting animals' development are gases (carbon dioxide, ammonia, hydrogen sulfide), and such factors as moisture and heat [7-9].

Taking into account process conditions of air in livestock premises (significant dust – up to 6 mg/m3, high humidity – up to 80%, presence of high concentrations of aggressive components – ammonia up to 20 mg/m3, hydrogen sulfide – up to 10 mg/m3, carbon dioxide – up to 0.28%) [8, 10], and it was found as a result of analysis of heat exchanger structures [11, 12] that sanitary-hygienic and operational parameters, high energy efficiency and low cost of installation, the most suitable for ventilation systems are shell-and-tube heat exchangers of pipe-in-pipe type.

To maintain microclimate in livestock facilities, structural-and-technological diagram of three-pipe concentric heat exchanger has been developed [13, 14].

Analysis of Recent Research and Publications

Known exhaust air heat recovery device [15] includes heat exchangers placed inside housing, and fans. The device is equipped with supply air inlet pipe and cooled air outlet pipe, with both pipes being installed inside the wall of the premises, which makes it necessary to make two holes therein. This device's disadvantage lies in a low efficiency of utilization of exhaust air's heat, significant weight and overall size, and in the need in additional conditions disrupting the integrity of buildings' walls.

Known tubular recuperator of ventilation air heat on counterflows [16] contains internal, middle and insulated outer pipes, channel electric heater, condensate drain pipe, exhaust shaft, supply and exhaust fans. This equipment's disadvantage lies in the lack of elements for cleaning the supply air from dust, insects, fur and other small particles being constantly present in the air, which, in turn, significantly affects the condition, health, productivity and quality of livestock products.

The three-pipe heat exchanger unit implements the technological process as follows [17]. Supply (cold) air is attracted by supply fan 7, having pre-passed through air filter 9, and then injected through inner tube 1 through channel electric heater 4 and ultraviolet lamp 10, which cleans it from bacteria and harmful microorganisms. With the help of fan 8, exhaust (warm) air from the premises is fed into the space between pipes 1 and 2. Air flows in the opposite direction: exhaust air exits to external environment from exhaust shaft 6, with supply air rotating and continuing to move in the opposite direction in the space between pipes 2 and 3. The opposite direction of supply and exhaust air flow increases the energy efficiency of the heat exchanger unit and allows increasing the uniformity of air temperature distributed along the length of the heat exchanger unit. In such a manner goes the process of heat exchange between supply and exhaust air through the walls of pipes 1 and 2, so that supply air is heated to a certain value. Condensate formed by exhaust air cooling on the outer surface of pipe 1 and the inner surface of pipe 2 is discharged through tube 5.

The use of an ultraviolet lamp raises the technological efficiency of three-pipe heat exchanger, as it protects livestock premises against bacteria and harmful microorganisms.

Presentation of Basic Research results.

Numerical simulations of operational process of developed heat exchanger are carried out using Star CCM + software package.

The following continuum grid models were selected: multifaceted cell generator, surface grid generator and cell extruder. The basic cell size was 0.001 m, with the maximum size ratio of connected grid edges being 1.3. The general view of heat exchanger's calculated grid is presented in fig. 1.

The following ones were selected as physical models of dry and wet channels: three-dimensional one, Euler multiphase model, the method of separate flow and VOF bulk liquid, the model of phase interaction, the model of separate multiphase temperature [18]. The flow is subject to Navier-Stokes equation [19] and k-ε turbulence model [20, 21]. Euler phases were as follows: air and water [22]. The air phase was subordinated to the models of real gas MASVP-PR97 (steam) and turbulent flow. The water phase was subject to models of van der Waals's real gas and turbulent flow [23].

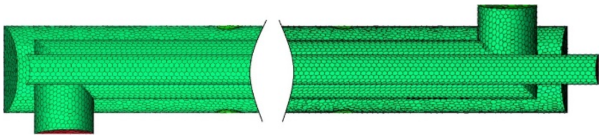

Fig. 1. General view of developed heat exchanger unit's calculated grid

The following ones were selected as physical models of heat exchanger's walls: three-dimensional model of solid material, constant density and the power model of separate solid body [24].

A stationary solver was chosen. The number of internal inertia equaled to 10. Heat exchanger's geometric dimensions are presented in table 1.

Table 1. Geometric dimensions of developed heat exchanger unit

Element	Parameter
Direct three-pipe module	material – polyethylene; length – 8 m; outer pipe diameter – 0.4 m; middle pipe diameter – 0.274 m; inner tube diameter – 0.138 m; pipe wall thickness – 0.0005 m
Corner modules	material – polyethylene; angle – 90°; pipe wall thickness – 0.0005 m

At the inlet to the heat exchanger, air flow was equal to Q_1 = Q3 = 0.14 m3/s, the temperature was t_1 = 30 ° C, t2 = 0 ° C. Thermal insulation was installed around the heat exchanger unit, i.e. no heat exchange with environment occurred.

As a result of simulations, temperature field distribution in the heat exchanger unit was obtained (Fig. 3).

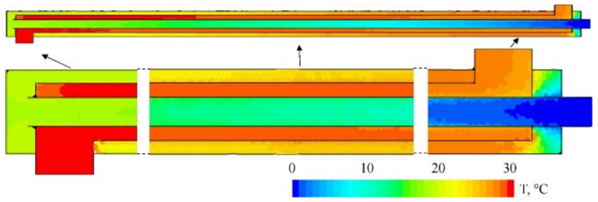

Fig. 3. Temperature field distribution in the heat exchanger unit

Air flows' temperature distribution along the length of the heat exchanger unit is shown in Fig. 4. According to fig. 4, heat exchanger ensures temperature gradient in the range from 11.6 to 15.7°C. The average temperature is 13.7°C.

The vector field of velocities was generated to visualize the process of air flow movement in the heat exchanger unit (Fig. 5).

To optimize the design and operating parameters of three-pipe concentric heat exchanger, let us use the model generated in Star CCM + software package.

Variation of design and mode parameters of three-pipe concentric heat exchanger unit was carried out within:

- the length of the heat exchanger's outer tube L = 5-30 m;
- the radius of the heat exchanger's outer tube r_3 = 0.25-1.00 m;
- volumetric air flow rate V = 0.14-1.4 m^3/s;
- ambient temperature T_c = 0-10°C.

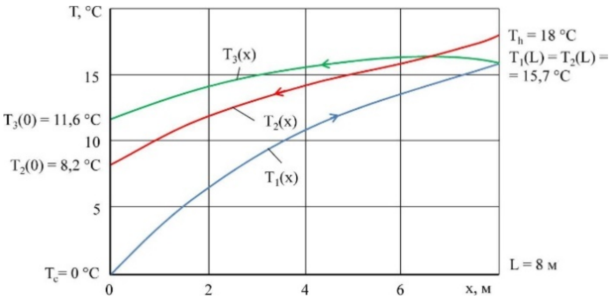

Fig. 4. Air flows' temperature distribution along the length of three-pipe heat exchanger

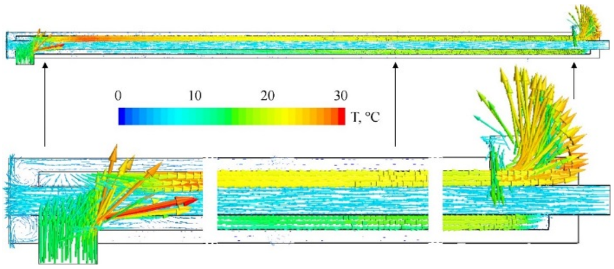

Fig. 5. Vector velocity field distribution in the heat exchanger unit

Useful heat output of heat exchanger unit ΔN, which is determined using Star CCM + software package, was chosen as the optimization criterion.

Step-by-step sorting [25, 26] of each of the above parameters made it possible to obtain graphical dependences of their impact on the heat exchanger unit's useful heat output (Fig. 6-8).

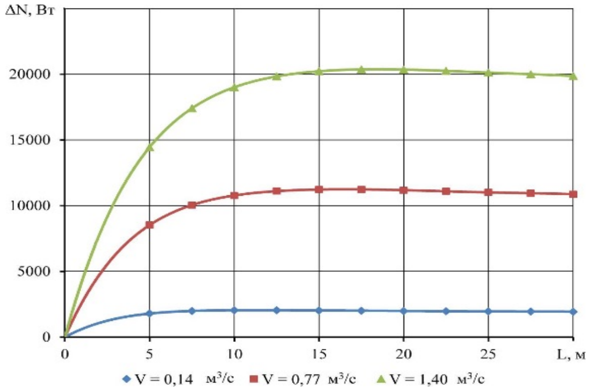

Fig. 6. Dependence between useful heat output of heat exchanger unit ΔN and the length of its outer tube L and volumetric air flow V at a fixed value of r_3 =1 m, Tc = 0°C

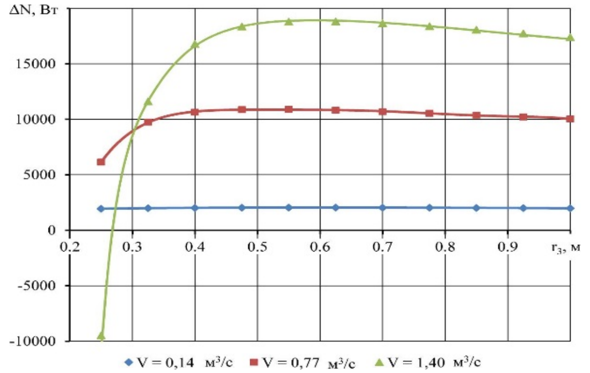

Fig. 7. Dependence between useful heat output of heat exchanger unit ΔN and the radius of its outer tube r_3 and volumetric air flow V at a fixed value of L =7.5 m, Tc = 0 ° C

Figure 6 shows that useful heat output increases with the heat exchanger's length to the maximum value, then decreasing slightly, i.e. the optimum is observed. This optimum occurs due to increase of pneumatic losses in the air flow through the pipeline of great length.

According to Figure 7, with a small value of the heat exchanger's external air duct radius, a negative value of useful heat output caused by high pneumatic losses is observed. However, as the radius of the external air duct increases, the optimum of useful heat output appears.

The dependence between useful heat output of the heat exchanger unit and ambient temperature (Fig. 8) is linear. As the ambient temperature increases, the heat exchanger's useful heat output decreases.

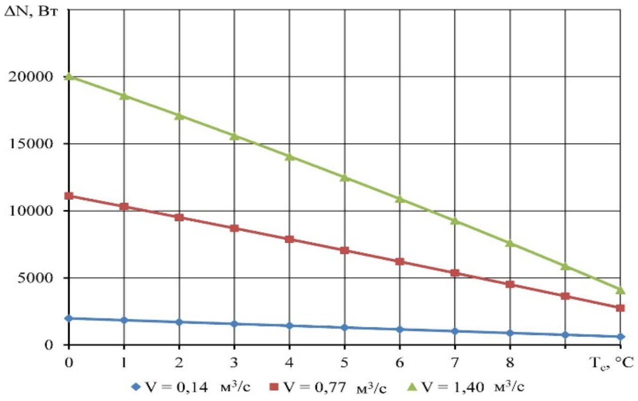

Fig. 8. Dependence between useful heat output of heat exchanger unit ΔN and ambient temperature T_c and air volume flow V at a fixed value of L =7.5 m, r_3 = 0.7

To optimize design-and-mode parameters, the following system of equations was generated [27]:

$$\begin{cases} \Delta N \to \max, \\ L \to \min, \\ r_3 \to \min. \end{cases} \quad (1)$$

Given the ambient temperature conditions T_c =0°C under different volumetric air flow rates V, the solution of the system of equations (1) is presented by the data summarized in table 2.

Table 2. Optimal design-and-mode parameters of three-pipe concentric heat exchanger

V, m³/s	L, m	r₃, m	ΔN, W
0.14	5.8	0.2	1906
0.27	7.74	0.24	3551
0.39	9.46	0.3	5222
0.52	11.43	0.35	6976
0.64	13.19	0.39	8583
0.77	15.13	0.43	10315
0.9	16.99	0.47	12071
1.02	18.85	0.53	13866
1.15	20.71	0.55	15503
1.27	22.53	0.62	17380
1.4	24.39	0.66	19179

By approximating table 2 data, we obtain the dependences between design parameters of heat exchanger system and volumetric flow rate of the air passing through it under the condition of the greatest useful heat output:

$$r_3 = 0{,}3619 \cdot V + 0{,}1523, \quad (2)$$

$$L = 14{,}776 \cdot V + 3{,}7335, \quad (3)$$

$$\Delta N = 13713 \cdot V - 144{,}92. \quad (4)$$

Graphical interpretation of dependencies (2) - (4) is presented in Figures 9-11.

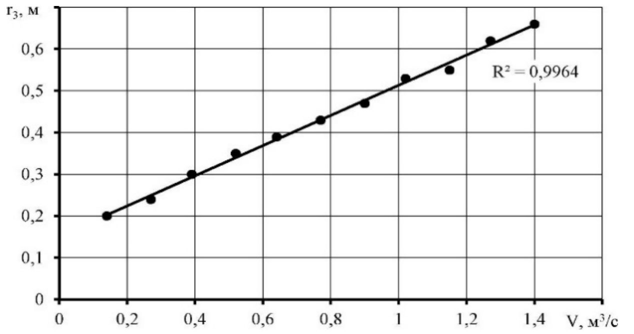

Fig. 9. Dependence between heat exchanger radius r_3 and volumetric flow rate of air V passing through under the condition of the greatest useful heat output

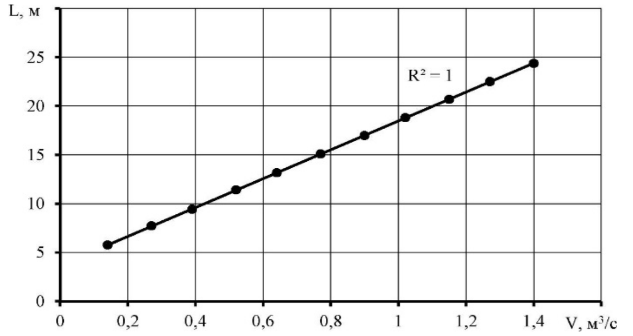

Fig. 10. Dependence between heat exchanger's length L and volumetric flow rate of air V passing through under the condition of the greatest useful heat output

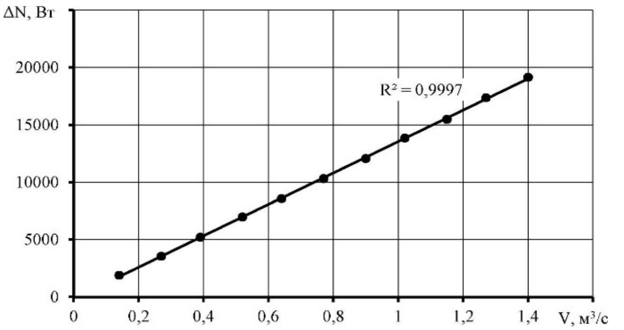

Fig. 11. Dependence between useful thermal power ΔN and volumetric flow rate of air V passing through the heat exchanger unit

Conclusions

Developed was a three-pipe heat exchanger containing three coaxially installed pipes (an inner, a middle and an outer ones), a condensate drain pipe that passes through the outer pipe and is located at the bottom of the middle pipe, an exhaust shaft that passes through the outer pipe, supply and discharge air filter, which is additionally equipped with an ultraviolet lamp.

As a result of heat exchanger's numerical simulation, established was the distribution of temperature and vector velocity fields. The analysis of results of theoretical studies of heat transfer process in design-and-process diagrams of three-pipe concentric heat exchanger showed that it ensures the temperature gradient in the range from 11.6 to 15.7°C (an average value being 13.7°C).

Optimization of results of theoretical research allowed us determining the dependences between the heat exchanger design parameters (length L and radii r_1, r_2, r3 of air ducts) and volumetric flow of air passing through it under the condition of the greatest useful heat output: L = 14,776 · V + 3,7335, r_1 = 0.3619 · V + 0.1523, r_1 = 0.343 · r_3, r_2 = 0.686 · r_3.

Funding

This research was supported and funded by the Ministry of Education and Science of Ukraine under grant № 0121U108589.

Authors: *YAROPUD Vitalii – PhD in Engineering, Associate Professor, Dean of the Faculty of Engineering and Technology, Vinnytsia National Agrarian University (21008, 3 Sonyachna str., Vinnytsia, Ukraine), e-mail: yaropud77@gmail.com; KUPCHUK Ihor – PhD in Engineering, Associate Professor, Deputy Dean for Scientific Research, Faculty of Engineering and Technology, Vinnytsia National Agrarian University (21008, 3 Sonyachna str., Vinnytsia, Ukraine), e-mail: kupchuk.igor@i.ua; BURLAKA Serhiy – PhD in Engineering, Senior Lecturer, Faculty of Engineering and Technology, Vinnytsia National Agrarian University (21008, 3 Sonyachna str., Vinnytsia, Ukraine), e-mail: ipserhiy@gmail.com; RUTKEVICH Volodymyr – PhD in Engineering, Associate Professor, Faculty of Engineering and Technology, Vinnytsia National Agrarian University (21008, 3 Sonyachna str., Vinnytsia, Ukraine), e-mail: v_rut@ukr.net.*

REFERENCES

[1]. Prishlyak V. M., Yaropud V. M. Substantiation of constructive parameters of recuperative heat utilizers for livestock premises. *Collection of scientific works of Vinnytsia National Agrarian University. Series: Technical Sciences*. 85 (2014), Iss. 2, 102-112.

[2]. Poberezhets Ju., Chudak R., Kupchuk, I., Yaropud V., Rutkevych V. Effect of probiotic supplement on nutrient digestibility and production traits on broiler chicken. *Agraarteadus*. 32 (2021), nr. 2, 296-302. https://doi.org/10.15159/jas.21.28

[3]. Kaletnik G.M., Yaropud V.M. Theoretical research of pneumatic losses of air heat exchanger of side-evaporating type of livestock premises. *Machinery & Energetics. Journal of Rural Production Research*. 12 (2021), nr. 4, 35-41.

[4]. Kaletnik G.M., Yaropud V.M. Physical and mathematical model of the ventilation system for injecting clean air in livestock premises. *Engineering, energy, transport of agro-industrial complex*. 114 (2021), nr. 3, 4-15. https://doi.org/10.37128/2520-6168-2021-3-1

[5]. Kovlevsky I. A. The microclimate of livestock buildings. *Bulletin of the National Academy of Sciences of Belarus. Series of agricultural sciences*. 5 (2005), 157–158.

[6]. Yaropud V.M., Aliyev E.B. The results of the inspection of the state of the microclimate in the pigsty with a negative pressure ventilation system. *Engineering, energy, transport of agro-industrial complex*. 113 (2021), nr. 2, 168-177.

[7]. Hygiene of farm animals. Book 1. General zoohygiene. Edited by A. F. Kuznetsova and M. V. Demchuk. *Agropromizdat*. (1991), 200 p.

[8]. Zaitsev A. M., Zhiltsov V. I., Shavrov A. V. Microclimate of livestock complexes. *Agropromizdat*. (1986),192 p.

[9]. Gunko, I., Hraniak, V., Yaropud, V., Kupchuk, I., Rutkevych, V. Optical sensor of harmful air impurity concentration. *Przegląd Elektrotechniczny*. 97 (2021), nr. 7, 76-79. https://doi.org/10.15199/48.2021.07.15

[10]. Gusev A. E., Mityukov N. V., Busygina E. L. Expediency of heat exchangers in the ventilation system. *International Journal of Experimental Education*. 8 (2012), 63-64.

[11]. Vatin N. I., Smotrakova M. V. Feasibility study for the use of ventilation systems with rotary heat recovery: monograph. (2003), 75 p.

[12]. Nimich G. V., Mikhailov V. A., Bondar E. S. Modern ventilation and air conditioning systems. Publishing house «Avanpost-Prim». (2003), 626 p.

[13]. Yaropud V., Hunko I., Aliiev E., Kupchuk I. Justification of the mechatronic system for pigsty microclimate maintenance. *Agraarteadus*. 32 (2021), nr. 2, 212–218. https://doi.org/10.15159/jas.21.21

[14]. Yaropud, V. Analytical Study of the Automatic Ventilation System for the Intake of Polluted Air from the Pigsty. *Scientific horizons*. 24 (2021), nr. 3, 19-27.

[15]. Baron V. G., Gershkovich V. G. Exhaust air heat recovery device: US Pat. 11134 Ukraine: 7F24F7 / 007 No u 2005 04888; stated 23.05.2005; publ. 15.12.2005, Bull. № 12

[16]. Yaropud V.M., Babin I.A. Three-pipe heat recovery unit: US Pat. 126074 Ukraine: IPC (2018.01) F24F 5/00 No u 2017 11085; stated 13.11.2017; publ. 11.06.2018, Bull. № 11

[17]. Prishlyak V. M., Yaropud V. M., Babin I. A. Three-pipe heat recovery unit: US Pat. 133549 Ukraine: IPC F24F 3/052 (2006.01); stated 11.19.2018; publ. 10.04.2019, Bull. № 7.

[18]. Kuznietsova I., Bandura V., Paziuk V., Tokarchuk O., Kupchuk I. Application of the differential scanning calorimetry method in the study of the tomato fruits drying process. *Agraarteadus*. 31 (2020), nr. 2, 173–180. https://doi.org/10.15159/jas.20.14

[19]. Shtuts A., Kolisnyk M., Vydmysh A., Voznyak O., Baraban S., Kulakov P. Improvement of stamping by rolling processes of pipe and cylindrical blades on experimental research. *Key Engineering Materials*. 844 (2020), 168–181. https://doi.org/10.4028/www.scientific.net/kem.844.168

[20]. Yaropud V., Honcharuk I., Datsiuk D., Aliiev E. The model for random packaging of small-seeded crops' seeds in the reservoir of selection seeder's sowing unit. *Agraarteadus*. 33 (2022), nr. (1), 199-208. https://doi.org/10.15159/jas.22.08

[21]. Shevchenko I., Aliiev E., Viselga G., Kaminski J. Modeling separation process for sunflower seed mixture on vibro-pneumatic separators. *Mechanika*. 27 (2021), nr. 4, 311-320. https://doi.org/10.5755/j02.mech.27647

[22]. Paziuk V., Vyshnevskiy V., Tokarchuk O., Kupchuk I. Substantiation of the energy efficient schedules of drying grain seeds. *Bulletin of the Transilvania University of Braşov, Series II: Forestry, Wood Industry, Agricultural Food Engineering.* 63 (2021), nr. 14, 137–146. https://doi.org/10.31926/but.fwiafe.2021.14.63.2.13

[23]. Kupchuk I., Burlaka S., Galushchak A., Yemchyk T., Galushchak D., Prysiazhniuk Yu. Research of autonomous generator indicators with the dynamically changing component of a two-fuel mixture. *Polityka Energetyczna*. 25 (2022), nr. 2, 147–162. https://doi.org/10.33223/epj/150746

[24]. Rutkevych V., Kupchuk I., Yaropud V., Hraniak V., Burlaka S. Numerical simulation of the liquid distribution problem by an adaptive flow distributor. *Przegląd Elektrotechniczny*. 98 (2022), nr. 2, 64-69. https://doi.org/10.15199/48.2022.02.13

[25]. Gunko I., Babyn I, Aliiev E., Yaropud V., Hrytsun A. Research into operating modes of the air injector of the milking parlor flushing system. *UPB Scientific bulletin, Series D: Mechanical Engineering,* 83 (2021), nr. 2, 297-310.

[26]. Kupchuk I., Yaropud V., Hraniak V., Poberezhets Ju., Tokarchuk O., Hontar V., Didyk A. Multicriteria compromise optimization of feed grain grinding process. *Przegląd Elektrotechniczny*. 97 (2021), nr. 11, 179-183. https://doi.org/10.15199/48.2021.11.33

[27]. Yaropud V., Kupchuk I., Burlaka S., Poberezhets Ju., Babyn I. Experimental studies of design-and-technological parameters of heat exchanger. *Przegląd Elektrotechniczny*. 98 (2022), nr. 10, 57-60. https://doi.org/10.15199/48.2022.10.10