ANALYSIS OF CRITICAL RADIUS OF INSULATION FOR HORIZONTAL PIPES

Daria Vakulenko[1], Viktor Mileikovskyi[1], Tetiana Tkachenko[1], Adam Ujma[2], Viktoriia Konovaliuk[1]
[1]Kyiv National University of Construction and Architecture, Ukraine;
[2]Czestochowa University of Technology, Poland
vakulenko_di@knuba.edu.ua, mileikovskyi@gmail.com, ttv13ttv@gmail.com,
adam.ujma@pcz.pl, coppoca@gmail.com

Abstract. Thermal insulation of pipelines is used in different industries including agricultural technologies. Energy efficiency depends on heat losses, which, in turn, are limited by heat insulation. Decentralized ventilation is effective in rural low-rise buildings. One such device used is a regenerative ventilator like Blauberg Vento or Vents TwinFresh. There is a task to improve the efficiency of its operation. Investigation of heat recovery processes in thin ducts is taking place. Experimental uncertainty decreases with better heat insulation of the experimental setup. But in heat transfer literature, there is a notion of the critical radius of insulation. More the insulation radius should decrease its effectiveness due to the development of the outer surface. In the theory, the heat transfer coefficient of the outer surface is assumed to be constant. In this study, laminar convective flow around the outer horizontal cylindrical insulation surface of a large thickness is considered. The formula of the average heat transfer coefficient is used that takes into account the Grashof number. While the insulation thickness is increased, the surface temperature and the heat transfer coefficient are decreased. The function of thermal resistance dependence on the outer diameter related to the inner one and its derivative have been analysed. As a result, an asymptotic increase of thermal resistance was observed without extremums. So, there are no critical diameters if the insulation is so large to obtain laminar convective flow. The maximum radius of thermal insulation should be determined not as critical, but as expedient. Thus, it can provide 5-20% lower heat transfer resistance than the asymptotic one. The radius of thermal pipe insulation of technological devices should be accepted based on technical and economic justification.

Keywords: critical radius of insulation, heat transfer coefficient, Nusselt number, energy efficiency.

Introduction

The heat losses problem appears in different technical branches from precise measurement systems to construction [1-4]. Insulating materials are widely used in various fields of knowledge [3-6]. There is a variety of insulating materials depending on the field of their application. Heat-insulated pipelines are widely used in agricultural technologies. Insulation increases the energy efficiency of various systems, including engineering networks of rural buildings and parts of agricultural devices and machines. Ideal insulation [7] is a very helpful concept in some theoretical cases but it cannot be achieved in practice. Analysis of heat insulation of buildings [8-12] can show very large external sizes of insulation. Sometimes, the sizes of thermal insulation of optical elements [13] and pipes [14-16] are small. And the insulation is efficient in both cases.

Using decentralized ventilation in rural low-rise buildings is highly efficient and provides normalized microclimate parameters [17-20]. This type of ventilation has a large number of advantages. They take up relatively little space and minimize interference in the interior of buildings. One such device is a regenerative ventilator like Blauberg Vento or Vents TwinFresh, which operates periodically on the air supply and exhaust. This device in the cooling period can be more efficient than a recuperative one used on vertically greened walls for the cooling effect [21] and sanitation abilities [22-24] cooling the inlet air because the plants will not cause significant air recirculation. In these conditions, the device will be protected against solar radiation cheaper than using green roofs or terraces [25-26]. In addition, air distribution is very important in energy performance [27-31]. The importance rises at variable air volume ventilation [32-37]. The device has no simultaneously operated neighbouring air inlet and outlet comparably with a recuperative one, which avoids the exhausting inlet air compared with a recuperative analogue. The study of such device requires improving the efficiency of its operation [17, 20]. The efficiency depends on the efficiency of the regenerative heat exchanger. In the Vents TwinFresh ventilator, it consists of thin channels. Therefore, the task of heat exchange research in thin pipes arises. The experimental investigation needs a correct thickness of pipe heat insulation. Better heat insulation of the experimental setup decreases experimental uncertainty. In the literature, it is suggested to apply the concept of the critical radius of insulation. The scientific novelty of the work is disproof of the critical radius concept as the global maximum of the insulation effectiveness, which is obtained using a constant heat transfer coefficient, that contradicts the well-known experimental and theoretical

DOI: 10.22616/ERDev.2023.22.TF178

data, for example [38]. If the extremum exists, it is local. Overcoming the critical radius raises the energy efficiency and decreases laboratory test errors due to heat losses, which is the aim of the work.

Materials and methods

The laminar natural convection along a horizontal cylinder of external diameter d, m, can be described by the dependence [38] of the Nusselt number Nu_x by the heat transfer coefficient α_x, $W \cdot m^{-2} \cdot K^{-1}$, and the thermal conductivity of air λ_{air}, $W \cdot m^{-1} \cdot K^{-1}$ along the contour of the cylinder on the Grashof number Gr_x by the curvilinear coordinate x, m, counted from the front critical point along the contour of the cylinder using (Fig. 1) a function $f(\varphi)$ that depends on the central angle φ from the front critical point:

$$Nu_x = \alpha_x \cdot d/\lambda_{air} = 0.604 \cdot f(\varphi) \cdot Gr_x^{1/4} \cdot (x/d)^{1/4}. \quad (1)$$

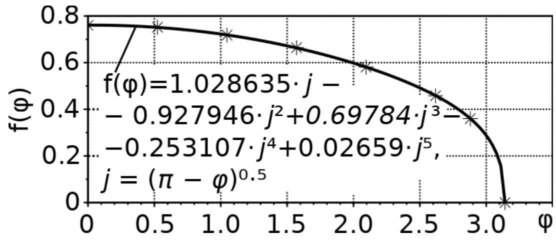

Fig. 1. **Function $f(\varphi)$:** asterisks – the data [38];
line – approximation with the deviation ± 0.001

The degree of the polynomial (Fig. 1) and the number of digits in its coefficients have been automatically chosen using the authors' library for SciLab. It has a function to enumerate the degree from zero until enough deviation will be obtained. After that, it tries to exclude each coefficient and re-regress the data to eliminate unnecessary ones. Finally, it truncates the trailing digits until the precision is kept. The polynomial has different signs, so at some values of j, the senior ranks are destroyed by subtracting. This causes a lot of digits after the decimal separator.

If the air has the temperature coefficient of volumetric expansion β, K^{-1}, and the kinematic coefficient of viscosity ν, $m^2 \cdot s^{-1}$, if the acceleration of gravity is g, $m \cdot s^{-2}$, and if the temperature, K, of the surface and ambience, corresponding to T_{surf} and T_{ext}, the Grashof number along the contour of the cylinder is $Gr_x = g \cdot \beta \cdot x^3 \cdot (T_{surf} - T_{ext})/\nu^2$. Using the dependence of the curvilinear coordinate on the central angle and diameter, the curvilinear coordinate $x = \varphi \cdot d/2$, m. After transformations of expression (1) substituting the Grashof number:

$$\alpha_x \cdot d/\lambda_{air} = 0.604 \cdot f(\varphi) \cdot \varphi \cdot \left(g \cdot \beta \cdot d^3 \cdot (T_{surf} - T_{ext})/(16 \cdot \nu^2)\right)^{1/4}. \quad (2)$$

The averaging of equation (2) in the work [38] gives the average heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$,

$$\alpha = 0.372 \cdot \left(g \cdot (T_{surf} - T_{ext})/(T_{ext} \cdot \nu^2 \cdot d)\right)^{1/4} \cdot \lambda_{air}. \quad (3)$$

Thermal resistance of a heat-insulated cylinder, R_ℓ, $m^2 \cdot K \cdot W^{-1}$, including linear resistance of the inner side $R_{\ell o}$, $m^2 \cdot K \cdot W^{-1}$, using thermal conductivity of the insulation material λ_{ins}, $W \cdot m^{-1} \cdot K^{-1}$, and internal diameter of the insulation d_0, m,

$$R_\ell = R_{\ell o} + \left(\ln(d/d_0)/(2 \cdot \pi \cdot \lambda_{ins})\right) + \left(1/(\pi \cdot d \cdot \alpha)\right), \quad (4)$$

Taking into account the heat transfer equation [39, 40] and (4):

$$(T_{int} - T_{surf})^4 = 0.372^4 \cdot (R_{\ell o} + \ln((d/d_0)/2 \cdot \lambda_{ins})))^4 \cdot (g \cdot d^3/\nu^2) \cdot \lambda_{air}^4 \cdot (T_{surf} - T_{ext})^5/T_{ext} \quad (5)$$

To simplify the analysis, let us introduce a complex of parameters. A dimensionless parameter

$$A = 0.372^4 \cdot (R_{\ell o} + \ln((d/d_0)/2 \cdot \lambda_{ins})))^4 \cdot \lambda_{air}^4 \cdot g \cdot d^3/\nu^2 \quad (6)$$

Relative overtemperatures of the inner and outer insulation surfaces above the external air temperature, corresponding,

$$\Delta\tilde{T}_{int} = (T_{int} - T_{ext})/T_{ext}; \; \Delta\tilde{T}_{surf} = (T_{surf} - T_{ext})/T_{ext} \quad (7)$$

A dimensionless parameter

$$\tilde{B} = (g \cdot d_o^3/\nu^2) \cdot (\lambda_{air}/\lambda_{ins})^4 \quad (8)$$

A derivative of the parameter *A*

$$\tilde{A} = dA/dt\,\tilde{d}, \quad (9)$$

where the relative outer insulation diameter, m, related to the inner one, m, is

$$\tilde{d} = d/d_0. \quad (10)$$

The dimensionless thermal resistance of all layers under the thermal insulation including the internal heat transfer:

$$\tilde{R}_{\ell o} = 2 \cdot R_{\ell o} \cdot \lambda_{ins}. \quad (11)$$

Equations (4) and (5) will be treated as an implicit function of *d*. Using the parameters (6)-(11),

$$\tilde{R}_{\ell} = \tilde{R}_{\ell o} + (\ln \tilde{d}/(2\pi)) + 1/(0.372 \cdot \pi \cdot (\tilde{B} \cdot \tilde{d}^3 \cdot \Delta\tilde{T}_{surf})^{0.25}), \quad (12)$$

$$\frac{dR_{\ell}}{d\tilde{d}} = \left(1 - \frac{3\Delta\tilde{T}_{surf} + \tilde{d} \cdot d\Delta\tilde{T}_{surf} d\tilde{d}}{0.744 \cdot \tilde{B}^{0.25} \cdot \tilde{d}^{3/4} \cdot \Delta\tilde{T}_{surf}^{\ 1.25}}\right) / \left(2 \cdot \pi \cdot \tilde{d}\right). \quad (13)$$

A derivative for the relative surface overtemperature

$$\frac{d\Delta\tilde{T}_{surf}}{d\tilde{d}} = -\frac{0.186^4 \cdot \tilde{B} \cdot \tilde{d}^2 \cdot \left(2 \cdot \pi \cdot \tilde{R}_{\ell o} + \ln \tilde{d}\right)^3 \cdot \Delta\tilde{T}^5{}_{surf}}{4 \cdot \left(\Delta\tilde{T}_{int} - \Delta\tilde{T}_{surf}\right)^3 + 5 \cdot \tilde{A} \cdot \Delta\tilde{T}_{surf}^{\ 4}} \cdot \left(3 \cdot \left(2 \cdot \pi \cdot \tilde{R}_{\ell o} + \ln \tilde{d}\right)\right) + 4 \quad (14)$$

The software for calculation expressions (12)-(14) has been made in the Scilab Algebra open-source system to determine the design and thermophysical features of a prototype horizontal pipe with an insulation cover. The relative outer insulation diameter $\tilde{d}$ = (1…100), m. The ambient air temperature T_{ext} = 293.15 K. Temperature difference between internal and external environments ΔT_{int} = 20 K. The heat transfer coefficient of the pipe material is large enough, so considering the heat transfer resistance $R_{\ell o}$ as near to zero. The gravity acceleration is $g = 9.81$ m·s^{-2}. The pipe diameter $d_0 = 0.01$ m. The kinematic coefficient of viscosity $\nu = 15.06 \cdot 10^{-6}$ m^2·s^{-1}. Thermal conductivity of air $\lambda_{air} = 0.024$ W·m^{-1}·K^{-1}. The material of insulation is an NBR/PVC-based closed cell with thermal conductivity $\lambda_{ins} = 0.035$ W·m^{-1}·K^{-1}.

Results and discussion

As a result, the total dimensionless heat transfer resistance coefficient (Fig. 2a) and the temperature on the outer surface (Fig. 2b) of the thermal insulation were obtained. To approve the derivative (14), it has been approximated by finite differences (Fig. 2c). The deviation is 0.0012. In addition, the outer temperature and its derivative have been built (Fig. 2d). The thermal resistance monotonically increases increasing the heat insulation diameter.

The insulation can be enlarged until enough small overtemperature on the outer surface to achieve the laminar flow. It is possible to additionally enlarge it more and more for better energy efficiency and laboratory test accuracy.

It can be explained as the concept of the critical radius is based on a constant outer heat transfer coefficient. But enlarging the insulation causes the decrease of the overtemperature lowering the coefficient significantly.

No critical but expedient diameter should be used after the rise of energy efficiency is not considerable. The authors have experience using insulation by foam rubber many times over the critical diameter to test the heat transfer in small-diameter channels. Also, the large sizes of building insulation confirm the results. In rural development, the results can increase the energy efficiency of machines and devices that use insulated pipes or vessels with hot or cold substances.

Based on the results of this work, a new experimental stand for the future research of regenerators in decentralised ventilators was re-designed, which allows for decreasing the uncertainty approx. twice.

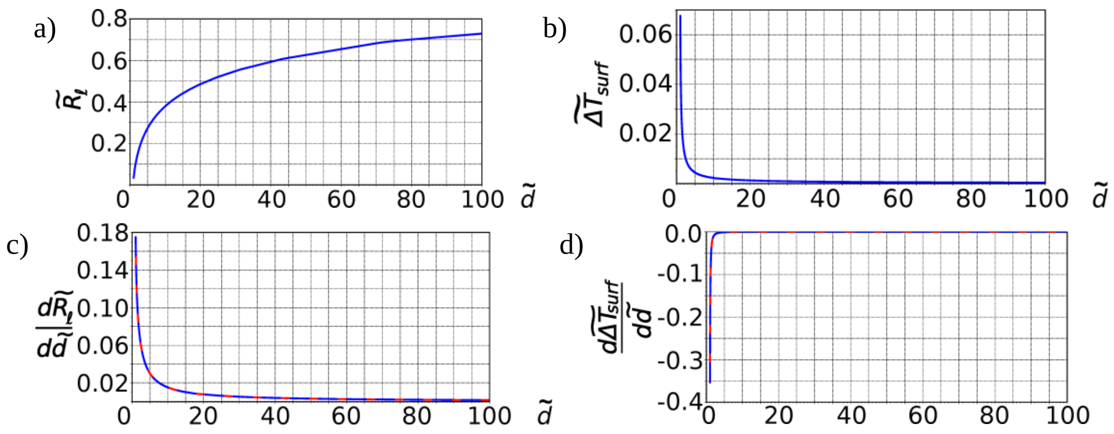

Fig. 2. **Results:** a – total dimensionless heat transfer resistance coefficient; b – temperature on the outer surface of the thermal insulation; c – derivative of thermal resistance; d – derivative of the outer surface temperature: red – derivative; blue – finite differences approximation

Conclusions

1. The laminar thermogravitational flow can be achieved around the thermal insulation of a horizontal pipe by enough increasing the diameter of the insulation. The thermal resistance will rise with the insulation radius.
2. The concept of the critical diameter was disproved. This can be explained as the concept of the critical radius is based on a constant outer heat transfer coefficient. But enlarging the insulation causes a decrease in the overtemperature of the outer surface lowering the coefficient significantly.
3. It is necessary to use not the critical but the expedient diameter after the rise of energy efficiency is not considerable.
4. The possibility to overcome the critical diameter allows for raising the energy efficiency of the apparatus, including rural machines and technological equipment.

Acknowledgements

We express our gratitude to Vents (Ukraine) for their assistance in carrying out the research. The work is also invested by state grant 0223U000498 "Creating perspective technologies of forming the safe building environment combining "green structures", phytodesign, and engineering systems".

Author contributions

Conceptualization, D. V. and V. M; methodology, D. V. and V. M., software, D. V. and V. M., validation, D. V., V. M., and V. K., formal analysis, D. V. and V. M.., investigation, D. V. V. M. and T. T., writing – original draft preparation, D. V., writing – review and editing, V. M., V. K. and T. T., project administration, T. T., A.U., funding acquisition, T.T., V.M. All authors have read and agreed to the published version of the manuscript.

References

[1] Skliarov V. Computational modeling of colorimetric primary transducer for metrological assurance in additive manufacturing. Proc. SPIE 10602, Smart Structures and NDE for Industry 4.0, 106020S (27 March 2018)

[2] Jurczak M.A., Skotnicka-Siepsiak A., Comparing the efficiency of evacuated tube and flat-plate solar collectors in real installation conditions. Construction of Optimized Energy Potential (CoOEP), Vol. 9, No 2/2020, pp. 31-38, DOI: 10.17512/bozpe.2020.2.04

[3] Senchuk M., Khovanskyi K. Опалення виробничих приміщень зі змінним тепловим режимом (Heating of industrial rooms with varying thermal conditions). Ventyliatsiia, osvitlennia ta teplohazopostachannia, iss. 19, 2016, pp. 55-64 (In Ukrainian)

[4] Szafranko E., Methodology for assessment of the cost effectiveness of simple energy efficient investments. Construction of Optimized Energy Potential (CoOEP), Vol. 9, No 2/2020, pp. 111-119.

[5] Skliarov V., Neyezhmakov P., Prokopov A. Verification and analysis of FEM for measurement of temperature distribution through the multilayer wall. Proc. SPIE 10959, Metrology, Inspection, and Process Control for Microlithography XXXIII, 109592Y (26 March 2019)

[6] Skliarov V., Zalohin M. and Fil S. Modeling and evaluation of the energy saving under the improvements of the calibrators of temperature using by finite element method. International Congress of Metrology, (2017) 08006

[7] Petrash V., Khomenko A., Polomannyy O., Visotska M., Integration of ground and ventilation air energy for heating buildings. Construction of Optimized Energy Potential (CoOEP), Vol. 10, No 1/2021, pp. 7-17

[8] Brycht N., Heat loss through cylindrical and spherical building partitions, Construction of Optimized Energy Potential (CoOEP), Vol. 9, No 1/2020, pp. 119-126

[9] Kizyeyev M., Soroka V., Dovbenko V., Novytska O., Protsenko S. Energy Auditing, Certification and Thermo-modernization of NUWEE Buildings, Construction of Optimized Energy Potential (CoOEP), Vol. 9, No 2/2020, pp. 103-110

[10] Zhelykh V., Furdas Y., The optimal insulation thickness determined for modular buildings according to multi-criteria analysis. Construction of Optimized Energy Potential (CoOEP), Vol. 10, No 1/2021, pp. 43-51

[11] Respondek Z., Condensation of water vapor on the external surfaces of building envelopes. Construction of Optimized Energy Potential (CoOEP), Vol. 10, No 1/2021, pp. 119-126

[12] Savchenko O., Lis A., Economic indicators of a heating system of a building in Ukraine and Poland, Construction of Optimized Energy Potential (CoOEP), Vol. 9, No 2/2020, pp. 97-102

[13] Lu P., Gao T., Chen Q., Ren X., Energy Saving Thermal Management of Space Remote Sensor and Validation. Energies, Vol. 16, Iss. 2, 2023, 864.

[14] Gerdes J.-N., Munder M., Sauer A., Evaluation of technical and economic potential of waste heat distribution networks in industrial sites. Energy Reports, Vol. 9, Sup. 3, 2023, pp. 219-226.

[15] Aranda-Arizmendi A., Rodríguez-Vázquez M., Jiménez-Xamán C. M., Romero R. J., Montiel-González M. Parametric Study of the Ground-Air Heat Exchanger (GAHE): Effect of Burial Depth and Insulation Length. Fluids, Vol. 8, Iss. 2, 2023, 40

[16] Yang Y., Zhu H., Zhou C., Zou Y. A novel insulation design for high-temperature pipe penetrating the walls of molten salt reactor cavity. Case Studies in Thermal Engineering, Vol. 36, 2022, 102189

[17] Mileikovskyi V., Vakulenko D., Simulation of the efficiency of improved regenerative decentralised ventilators Vents TwinFresh, Construction of Optimized Energy Potential (CoOEP), Vol. 9, No 1/2020, 61-67, DOI: 10.17512/bozpe.2020.1.07

[18] Filis V, Kolarik J, Smith KM. The impact of wind pressure and stack effect on the performance of room ventilation units with heat recovery. Energy and Buildings. 2021;234:110689. doi: 10.1016/j.enbuild.2020.110689

[19] Pekdogan T., Tokuç A., Ezan M.A., Ba ̧saran T. Experimental Investigation of a Decentralized Heat Recovery Ventilation System. J. Build. Eng. 2021, 35, 102009.

[20] Вакуленко Д, Мілейковський В. Моделювання ефективності теплоутилізації регенеративного провітрювача за різними підходами (Simulation the effectiveness of heat recovery of the regenerative ventilator using different approaches). Ventyliatsiia, osvitlennia ta teplohazopostachannia, iss. 41, 2022, pp. 32-38 (In Ukrainian)

[21] Tkachenko T., Mileikovskyi V. Methodology of thermal resistance and cooling effect testing of green roofs. Songklanakarin Journal of Science and Technology, Vol. 42, 2020, pp. 50-56.

[22] Tkachenko, T., Mileikovskyi, V. Increasing indoor air quality by a natural sanitizing interior. 1st International Symposium of Earth, Energy, Environmental Science and Sustainable Development, JESSD 2020, November 25, 2020, Jakarta, Indonesia. E3S Web of Conferences, vol. 211, 2020, article no 02015.

[23] Tkachenko T., Mileikovskyi V., Dziubenko V., Tkachenko O. Improvement of the safety of multi-floor housing. Innovative Technology in Architecture and Design (ITAD 2020), May 21-22, 2020, Kharkiv, Ukraine. IOP Conference Series: Materials Science and Engineering, vol. 907, 2020, article no. 012064.

[24] Tkachenko T., Mileikovskyi V. Solution of sick building syndrome problem using indoor plants. Environmental Innovations: Advances in Engineering, Technology and Management, EIAETM,

September 23-27, 2019, online. Procedia Environmental Science, Engineering and Management, vol. 6, pp.405-411

[25] Tkachenko T., Mileikovskyi V. Assessment of Light Transmission for Comfort and Energy Efficient Insolation by “Green Structures”. 19th International Conference on Geometry and Graphics, ICGG 2020, January 18-22, 2021, São Paulo, Brazil. Advances in Intelligent Systems and Computing, vol. 1296, pp. 139-151.

[26] Tkachenko T., Mileikovskyi V. Geometric basis of the use of “green constructions” for sun protection of glazing. 18th International Conference on Geometry and Graphics, ICGG 2018, 3-7 August, 2018, Milan, Italy. Advances in Intelligent Systems and Computing, vol. 809, 2019, pp. 1096-1107.

[27] Voznyak O., Savchenko O., Spodyniuk N., Sukholova I., Kasynets M., Dovbush O. Improving of ventilation efficiency at air distribution by the swirled air jets. Pollack Periodica., vol. 17, 2022, pp. 123-127

[28] Voznyak O., Spodyniuk N., Savchenko O., Dovbush O., Kasynets M., Datsko O. Analysis of air jets velocity attenuation at special initial conditions. Diagnostyka, vol. 23, 2022, article no 2022308.

[29] Voznyak O., Savchenko O., Spodyniuk N. Sukholova, I., Kasynets M., Dovbush Oleksandra. Air distribution efficiency improving in the premises by rectangular air streams. Pollack Periodica., vol. 17, 2022, pp. 111-116

[30] Zhelykh, V., Voznyak, O., Yurkevych, Y., Sukholova, I., Dovbush, O. Enhancing of energetic and economic efficiency of air distribution by swirled-compact air jets. Production Engineering Archives, vol. 27, 2022, pp.171-175

[31] Kapalo P., Sedláková, A., Košičanová D., Voznyak O., Lojkovics J., Siroczki P. Effect of ventilation on indoor environmental quality in buildings. 9th International Conference on Environmental Engineering, ICEE 2014, May 22-23, 2014, Vilnius, Lithuania. article no. 146072

[32] Voznyak, O., Sukholova, I., Myroniuk, K. Research of device for air distribution with swirl and spread air jets at variable mode. Eastern-European Journal of Enterprise Technologies, vol. 6, 2015, pp.15-23

[33] Voznyak, O., Korbut, V., Davydenko, B., Sukholova, I. Air Distribution Efficiency in a Room by a Two-Flow Device. Lecture Notes in Civil Engineering, vol. 47, 2020, pp. 526-533

[34] Voznyak O., Spodyniuk N., Sukholova I., Dovbush O., Kasynets M., Datsko O. Diagnosis of damage to the ventilation system. Diagnostyka, vol. 22, 2021, pp. 91-99.

[35] Myroniuk K., Voznyak O., Savchenko O., Kasynets M. Mathematical Modeling of an Air Flow Leakage with the Jets Interaction at the Variable Mode. 3rd International Scientific Conference EcoComfort and Current Issues of Civil Engineering, EcoComfort 2022, September, 14-16, 2022, Lviv, Ukraine. Lecture Notes in Civil Engineering, vol. 290, 2023, pp. 289-298

[36] Voznyak O., Yurkevych Y., Sukholova I., Myroniuk K. Mathematical Modeling of Air Distribution in a Non-stationary Mode by Swirled-Compact Air Jets. EcoComfort 2022, September, 14-16, 2022, Lviv, Ukraine. Lecture Notes in Civil Engineering, vol. 290, 2023, pp. 432-440.

[37] Voznyak O., Myroniuk K., Spodyniuk N., Sukholova I., Dovbush O., Kasynets M. Air distribution in the room by swirl compact air jets at variable mode. Pollack Periodica., vol. 17, 2022, pp. 117-122

[38] Кулінченко В. Р., Ткаченко С. Й. Теплопередача з елементами масообміну (теорія і практика процесу) (Heat transfer with mass transfer elements (theory and practice of the process)). Київ. Фенікс. 2014. 917 с. (In Ukrainian).

[39] Zhang Q, Sun Y, Yang J. Bio-heat transfer analysis based on fractional derivative and memory-dependent derivative heat conduction models. Case Studies Thermal Engineering 2021; 27: pp. 101-211. DOI: 10.1016/j.csite.2021.101211

[40] Sun L, Fu B, Wei M, Zhang S. Analysis of Enhanced Heat Transfer Characteristics of Coaxial Borehole Heat Exchanger. Processes. 2022; 10(10):2057. DOI: 10.3390/pr10102057