

UDC 621

ENHANCING THE EFFICIENCY OF THE TURBOGENERATOR COOLING SYSTEM THROUGH THE USE OF FINNED TUBES IN THE GAS COOLER

Bohdan K. Shestak

Bogdan.Shestak@gmail.com

ORCID: 0009-0002-0659-5394

National Aerospace University
"Kharkiv Aviation Institute"

17, Vadyma Manka str., Kharkiv, 61070, Ukraine

The reliability of a high-power turbogenerator largely depends on its cooling system. The trouble-free and efficient operation of this system, in particular the gas cooler, is a problem that has not been fully resolved as of now. A modernized design of a gas cooler for a 325 MW turbogenerator, featuring high-finned bimetallic tubes, is proposed in the paper. To substantiate the efficiency of such a design and determine the heat transfer reserve of the gas cooler, its thermal state was calculated. The obtained results showed that the water overheating in the gas cooler is 5 °C. At the same time, one section of the gas cooler provides heat loss removal of 1266 kW at a hydrogen flow rate of 6.66 m³/s and a cooling water flow rate of 200 m³/s, which meets the requirements for this gas cooler.

Keywords: turbogenerator, gas cooler, finned tubes, thermal calculation, criterion equations.

Introduction

The cooling system of a hydrogen-cooled turbogenerator is technologically and structurally complex. The service life of the units of other turbogenerator systems and ensuring its trouble-free operation largely depend on its efficiency and reliability. The tendency to increase the power of modern turbogenerators necessitates the introduction of more efficient design solutions into cooling systems.

A synchronous three-phase hydrogen-cooled turbogenerator is designed to generate electrical energy when directly connected to a steam turbine (Fig. 1). The main structural elements of the turbogenerator are given in the papers [1–3].

Cooling of turbogenerators with a capacity of 200–350 MW is typically performed using hydrogen circulating in a



Fig. 1. General view of the turbogenerator

closed loop by means of a centrifugal compressor. The parameters of the cooling system must comply with the requirements of DSTU (State Standard of Ukraine) EN 60034-6:2019 [4]. The overall design of the turbogenerator and its cooling system must ensure effective cooling of structural components [5], as well as maintain the temperature rise of the windings, stator core, and heated hydrogen within the permissible limits for the specified insulation class in accordance with DSTU EN 60034-1:2016 [6], during nominal operation of the turbogenerator.

To cool hydrogen, gas coolers are built into a special box under the stator housing of the turbogenerator. Their performance is an important factor in the turbogenerator cooling system, and their optimal design can affect the overall efficiency, which is explained by pronounced changes in the thermophysical properties of the cooling substances under operating conditions.

In addition, the reliable operation of the cooling system is one of the main factors that guarantees the trouble-free operation of the turbogenerator as a whole. Its malfunction can lead to the failure of the turbogenerator and, as a result, long and costly repairs.

The problem of ensuring the required level of temperature parameters of the structural elements of turbogenerators when increasing their power during the modernization process is considered in this paper. An essential condition for modernization is to increase the efficiency of the turbogenerator cooling system

This work is licensed under a Creative Commons Attribution 4.0 International License.

© Bohdan K. Shestak, 2025

while maintaining the overall parameters of the gas coolers and ensuring their required strength. Existing gas cooler designs do not satisfy these conditions [7].

Let's analyze modern methods of designing gas coolers, set out in separate papers.

Thus, in [8] the authors evaluated the design of a gas cooler with finned tubes. Based on the model, an assessment of different numbers of rows, lengths and diameters of tubes at different ambient temperatures was made to determine the most suitable design in terms of pressure losses and ensuring the required heat exchange area for the selected operating conditions.

In [9] the authors simulated and evaluated the thermohydraulic characteristics of a gas cooler with finned tubes using a distributed modeling approach with the ε -NTU method. The results of the study showed that due to an increase in the mass flow rate of the working fluid and a decrease in the diameters of the tubes, the performance of gas coolers increased.

The authors of [10] analyzed the performance of gas coolers with finned tubes and different inlet air flow patterns using CFD methods. The modeling results showed that different types of inlet flow velocity profiles of the cooling gas significantly affect the performance of the gas cooler.

In [11], the influence of the geometric parameters of gas coolers on the system performance was studied. Parametric analysis confirmed the effective increase in heat transfer with an increase in the heat transfer area of the gas cooler. However, the optimal cooling gas discharge pressure decreases. Other system components remain unchanged.

In [12, 13], methods for calculating real gases for centrifugal compressors are presented. They include the use of several different polytropic path equations, as well as several numerical integration methods.

The use of flat tubes in the design of gas coolers was considered by the authors in [14]. The study found that changing the cross-sectional configuration of the tubes is an effective approach to increase the thermal performance of the gas cooler, which leads to a significant increase in the heat transfer coefficient.

In the abovementioned papers, the research of cooling systems is based on existing refrigerants such as R404A, R134A or R407A. However, their main drawback is the lack of calculations when using hydrogen as a cooling gas with increased operating pressure. Without additional research, these solutions cannot be scientifically substantiated and implemented on turbogenerators operating with an excess hydrogen pressure of 450 kPa. The reason for this is the need to use fully assembled turbogenerators with different designs of gas coolers.

Experimental values of the cooling gas parameters are used in the presented study.

The purpose of the study is to scientifically substantiate the provision of the necessary cooling parameters of the turbogenerator by the proposed design of the gas cooler. To achieve this goal, an analytical thermal calculation was performed using mathematical models based on the basic equations of thermodynamics and gas dynamics, taking into account the principles of the composition of engineering alloys. The combination of brass and aluminum as the primary materials for the cooling tube design enabled an increase in the gas cooler's efficiency while maintaining overall dimensions, due to the enhanced effective finned surface area, optimized fin pitch, and staggered tube arrangement.

To achieve the goal, the following tasks were set:

- to develop of a gas cooler design using a high-finned bimetallic tube design;
- to conduct a study of the efficiency of the gas cooler design with given geometric parameters of the tubes.

Design of gas coolers of the turbogenerators

A general view of the turbogenerator gas cooler is shown in Fig. 2.

The detailed design of the gas cooler is shown in Fig. 3. It includes a tube bundle (a system of finned tubes), a housing and water compartments [15, 16]. The tubes are hermetically connected to the end plates. This prevents cooling water from penetrating the hydrogen flow. Covers with inlet and outlet pipes designed for water supply are attached to the plates. The principle of operation is as follows: hot hydrogen (after passing through the heated structural elements of the operating turbogenerator) comes into contact with the surface of the tubes through which cooling water circulates. After passing through the gas coolers, cold hydrogen enters the turbogenerator again.

The main materials of the housing and tubes can be different, depending on the installation conditions and cooling water (fresh, mineralized or sea water). The material of the housing and covers is stainless or carbon steel with a polymer coating. The material of the tube sheets is brass (or a metal or engineering

alloy similar to its properties). The material of the cooling tubes is stainless or carbon steel, copper alloys, aluminum, etc. The coating of the gas cooler must ensure a long service life (at least 40 years) and have chemical resistance to hydrocarbons, solvents, acids, salts, alkalis, etc.

The studies presented in [17, 18] provide scientific justification for the use of tubes with expanded surfaces or fins distributed along their length in the design of gas coolers of modern turbogenerators (Fig. 4). Due to this, the effective surface area for heat exchange processes is significantly increased. Such modernized gas coolers are actively used in repairs and modernization of turbogenerators to increase the efficiency of the cooling system.

The general geometry of a high-finned tube is shown in Fig. 5.

Based on the results of the research presented in [19] and the analysis of the experience of gas coolers production, it can be concluded that the design of the high-finned tubes is the most effective for use in the production of gas coolers for large and medium-power turbogenerators.



Fig. 2. General view of the turbogenerator gas cooler



Fig. 4. General view of the finned tubes of the gas cooler

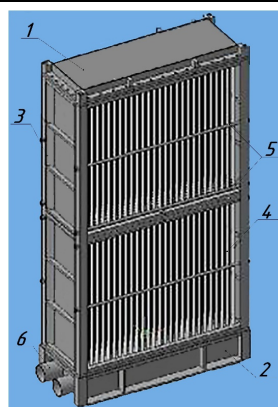


Fig. 3. Design of the turbogenerator gas cooler:

1 – top cover; 2 – bottom cover; 3 – frames;
4 – cooling tubes; 5 – tie rods; 6 – water drain/supply point

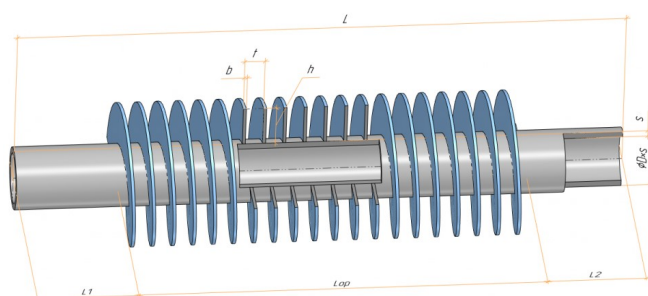


Fig. 5. General geometry of a high-finned tube

Analytical calculation of the thermal state of a gas cooler

The purpose of the calculation is to determine the heat transfer margin of the gas cooler, which incorporates high-finned tubes of the proposed design, intended for a 325 MW turbogenerator.

To improve the operational characteristics, a bimetallic tube structure is used – a brass tube with aluminum fins – which provides the necessary protection of the tube material against corrosion. An important factor when using a bimetallic design of finned tubes is to ensure the maximum possible contact between the coolants (water-hydrogen).

During the proposed analytical calculation, the heat flux through the finned tube wall was determined. For this, the geometric dimensions of the tube, tube sheet and coolant parameters were given. During the calculation, criterion equations and dependencies, according to which the parameters for further three-dimensional calculation can be described, were determined.

The design parameters of the tubes and tube sheet are shown in Figs. 6, 7. Other necessary initial data are presented in Table 1.

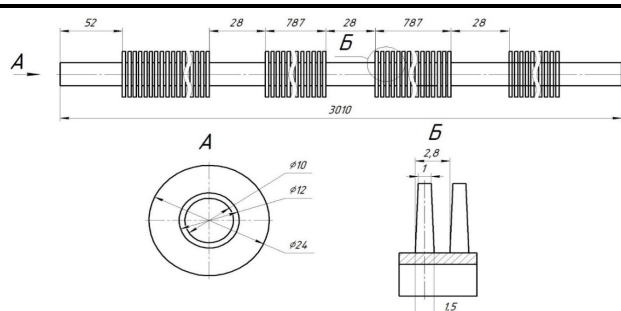


Fig. 6. Tube parameters for gas cooler calculation

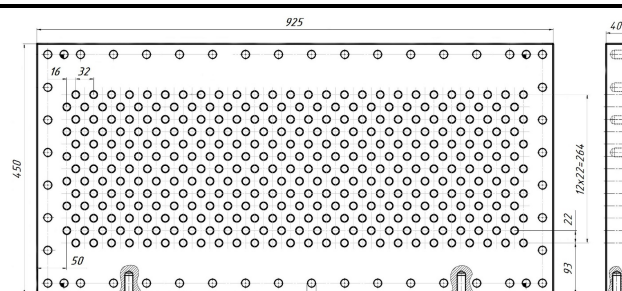


Fig. 7. Tube sheet parameters for gas cooler calculation

Table 1. Calculation output data

Inner tube diameter d_i , m	0.01
Outer tube diameter d , m	0.012
Outer finning diameter D , m	0.024
Full length of the tube l , m	3.01
Effective tube length l_{ef} , m	2.84
Heat transfer surface of 1 m of gas-washed tube f_a , m ²	0.258
Heat transfer surface of 1 m of water-washed tube f_{wash} , m ²	0,0314
Number of tubes in a row n , pcs	26
Number of rows in a section m , pcs	13
Number of tubes in the section n_t , pcs	338
Number of cooler sections N , pcs	3
Distance between tubes in a row S_1 , m	0.032
Row spacing S_2 , m	0.022
Live cross-sectional area of 1 m ² of cooler F_1 , m ²	0.518
Finning pitch S_f , m	0.0028
Finning height h_f , m	0.006
Finning surface area of 1 m tube f_f , m ²	0.269
Tube cross-sectional area f_w , m ²	0.000079
Outer fin thickness, m	0.001
Inner fin thickness, m	0.0015

Number of fins per 1 m of tube n_f , pcs	357.1
Finning coefficient	7.6
Tube material	brass
Fins material	aluminum
Thermal conductivity of the fins material λ_a , kW/m°C	0.236
Temperature of gas leaving the cooler T_a , °C	40
Temperature of water entering the cooler T_w , °C	36
Hydrogen consumption Q_a , m ³ /s	23
Water consumption Q_w , m ³ /h	600
Number of hydrogen courses q_a	2
Number of water courses q_w	1
Absolute pressure of hydrogen P_a , kPa	450
Hydrogen density ρ_a , kg/m ³	0.3623
Water density ρ_w , kg/m ³	995
Allocated losses P , kW	3798
Specific heat coefficient of hydrogen C_p , kJ/(kg·°C)	14.27
Number of sections connected in series by water q_{nw}	1

A diagram of heat transfer through a wall with straight trapezoidal fins is shown in Fig. 8.

The calculation method is given in detail in the studies [20, 21, 22]. Some of the criterion equations necessary for the calculation are presented below.

Nusselt criterion for staggered bundles of finned tubes with perpendicular flow of a gas medium around them. The average value for the bundle as a whole is calculated by the formula

$$Nu = 0.36 \cdot C_z \cdot C_s \cdot \psi^{-0.5} \cdot Re^n \cdot Pr^{0.33},$$

where C_z and C_s are bundle geometry parameters; ψ is the tube finning factor; Re is the Reynolds number; Pr is the Prandtl number.

The finning efficiency is calculated by the formula

$$\eta = 1 - \frac{\psi - 1}{\psi} (1 - \eta_f),$$

where ψ is the finning factor; η_f is the fin efficiency parameter.

The finning ratio is calculated by the formula

$$\psi = \frac{F_f + F_{wall}}{F_{base} + F_{wall}},$$

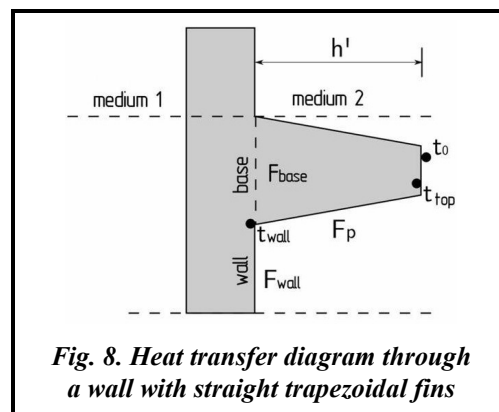


Fig. 8. Heat transfer diagram through a wall with straight trapezoidal fins

where F_f is the finning area; F_{wall} is the area of the part of the finned side that is not covered by the bases of the finning elements; F_{base} is the area of the part of the finned side covered by the bases of the finning elements.

The results of the proposed calculation of the gas cooler based on the above data are given in Table 2.

Table 2. Results of analytical calculation of gas cooler

Heat removal surface of the cooler F_a , m	825.9	Drop in water pressure in the cooler H_w , Pa	25017.2
Narrow cross-section of the cooler S_a , m	1.892	Specific heat capacity of water at 20 °C, kJ/(kg·K)	4.183
Hydrogen overheating in the generator ΔT_a , °C	31.94	Overheating of water in the cooler ΔT_w , grad	5.475
Average hydrogen temperature $T_a^{average}$, °C	64.0	Average water temperature $T_w^{average}$, grad	44.738
Kinematic viscosity coefficient of hydrogen ν at $T_a^{average}$, m ² /s	1.35×10^{-4}	Kinematic viscosity coefficient of water ν_w , m ² /s	6.55×10^{-7}
Thermal conductivity coefficient of hydrogen λ , kW/(m·°C)	1.94×10^{-4}	Prandtl number Pr_w	6.06
Hydrogen velocity in a narrow cross-section V_a , m/s	12.16	Thermal conductivity coefficient λ_w , kW/(m·°C)	0.000636
Reynolds number for hydrogen flow Re	1080.8	Reynolds number for water Re_w	31967
Euler number for hydrogen flow Eu	9.7	Internal heat transfer coefficient α_{int} , kW/(m ² ·°C)	12.08
Hydrogen pressure drop in the cooler H_a , Pa	921.4	Relative heat transfer coefficient K , kW/(m ² ·°C)	0.53
Nusselt number Nu	12.5	Average logarithmic temperature difference in counterflow ΔT , grad	15.69
Convective heat transfer coefficient α , kW/(m ² ·°C)	0.866	Heat load of the cooler K_1 , kW/(m ² ·°C)	0.293
Thermal resistance coefficient of finning E	0.573	Heat transfer reserve M , %	45.4
Finning efficiency coefficient η	0.975		
Reduced heat transfer coefficient $\alpha_{reduced}$, kW/(m ² ·°C)	1.911		
Water cooler tube cross-section F_w , m ²	0.080		
Water velocity in pipes V_w , m/s	2.094		

A detailed analysis of the data of the conducted study allows to conclude that the optimal ratio of the working surface planes is 1 to 8. Further changes in the geometry and type of fins do not lead to a change in the heat transfer margin by more than 5%.

From the above, it follows that the use of a high-finned bimetallic tube structure with the main geometric parameters given in Table 1 was an acceptable solution. With these parameters, it was possible to provide the necessary areas of the water-hydrogen heat-transfer surfaces (90 m² for water and 743 m² for hydrogen) (Fig. 6).

Conclusions

1. As a result of the research, a new gas cooler design, which provides the necessary heat removal efficiency when increasing the turbogenerator power to 325 MW, was developed. A distinctive feature of the proposed gas cooler design is the use of high-finned bimetallic tubes with specified geometric parameters.

2. The efficiency of the gas cooler design with the specified geometric parameters of the tubes was studied and a scientific justification for ensuring the required efficiency of the proposed gas cooler design was provided. According to the analytical calculation of the thermal state of the gas cooler, the water overheating in the gas cooler is 5 °C. One section of the gas cooler provides heat loss removal of 1266 kW at a hydrogen flow rate of 6.66 m³/s and a cooling water flow rate of 200 m³/s. The obtained results satisfy the design requirements.

The main result of the study was confirmation of the high efficiency of using high-finned tubes in the design of the gas cooler of a high-power turbogenerator.

A further direction of the study will be to use the results obtained using a numerical model to assess the possibility of changing the design of the gas cooler in order to determine the optimal parameters of the turbogenerator cooling system as a whole. The results obtained using the analytical model will be compared with the three-dimensional calculation data using the k- ϵ turbulence model to validate and quantify the magnitude of the deviation between the three-dimensional modeling data and the analytical data.

References

1. Kerszenbaum, I. & Klempner, G. (2018). Generator design and construction. In: Kerszenbaum, I. & Klempner, G. (eds). Handbook of Large Turbo-Generator Operation and Maintenance. Chapter 2, pp. 53–168. <https://doi.org/10.1002/9781119390718.ch2>.
2. Miction, M., Calverley, S. D., Clark, R. E., Howe, D., Chambers, J. D. A., Sykes, P. A., Dickinson, P. G., McClelland, M., Johnstone, G., Quinn, R., & Morris, G. (2007). Modelling and testing of a turbo-generator system for exhaust gas energy recovery. Proceedings of *IEEE Vehicle Power and Propulsion Conference* (Arlington, TX, USA), pp. 544–550. <https://doi.org/10.1109/VPPC.2007.4544184>.
3. Miction, M., Calverley, S. D., Clark, R. E., Howe, D., McClelland, M., & Sykes, P. (2006). Switched reluctance turbo-generator for exhaust gas energy recovery. Proceedings of *12th International Power Electronics and Motion Control Conference* (Portoroz, Slovenia), pp. 1801–1807. <https://doi.org/10.1109/EPEPMC.2006.4778667>.
4. (1991). IEC 60034-6:1991. Rotating electrical machines – Part 6: Methods of cooling (IC Code). International Standard, 39 p.
5. Yaichenia, V. V. (2018). *Avtomatyzatsiia systemy okhlozhennia turbogenerators TVF-125-2U3* [Automation of the cooling system of the turbogenerator TVF-125-2U3]: master's thesis: 151 Automation and computer-integrated technologies / National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, 89 p. (in Ukrainian). <https://ela.kpi.ua/handle/123456789/28999>.
6. (2017). EN 60034-1:2010; EN 60034-1:2010/AC:2010 Rotating electrical machines – Part 1: Rating and performance. International Standard.
7. Minko, A. N. (2012). *Optimal'naya geometriya i massogabaritnyye parametry konstruksii korpusa statora turbogeneratorov s vozduшной sistemoy okhlazhdeniya* [Optimal geometry and mass-dimensional parameters of the stator housing design of turbogenerators with an air cooling system]. *Energoberezeniye. Energetika. Energoaudit – Energy saving. Power engineering. Energy audit*, no. 01 (95), pp. 33–39 (in Russian).
8. Alexopoulos, C., Aljolani, O., Heberle, F., Roumpedakis, T. C., Brüggemann, D., & Karellas, S. (2020). Design evaluation for a finned-tube CO₂ gas cooler in residential applications. *Energies*, vol. 13, iss. 10, article 2428. <https://doi.org/10.3390/en13102428>.
9. Chai, L., Tsamos, K. M., & Tassou, S. A. (2020). Modelling and evaluation of the thermohydraulic performance of finned-tube supercritical carbon dioxide gas coolers. *Energies*, vol. 13, iss. 5, article 1031. <https://doi.org/10.3390/en13051031>.
10. Zhang, X., Ge, Y., & Sun, J. (2020). CFD performance analysis of finned-tube CO₂ gas coolers with various inlet air flow patterns. *Energy and Built Environment*, vol. 1, iss. 3, pp. 233–241. <https://doi.org/10.1016/j.enbenv.2020.02.004>.
11. Wang, S., He, Y., Tuo, H., Cao, F., & Xing, Z. (2013). Effect of heat transfer area and refrigerant mass flux in a gas cooler on heating performance of air-source transcritical CO₂ heat pump water heater system. *Energy and Buildings*, vol. 67, pp. 1–10. <https://doi.org/10.1016/j.enbuild.2013.07.078>.
12. Taher, M. & Evans, B. F. (2020). Using a cubic polynomial temperature-entropy constant efficiency path for centrifugal compressor polytropic performance evaluation. <http://dx.doi.org/10.13140/RG.2.2.23470.54083/1>.
13. Evans, B. F. & Huble, S. (2017). Centrifugal compressor performance: Making enlightened analysis decisions. Proceedings of the *46th Turbomachinery Symposium* (Houston, TX, USA, 11–14 December 2017), 55 p. <https://core.ac.uk/reader/187128036>.
14. Khoshvaght-Aliabadi, M., Ghodrati, P., Rashidi, M. M., & Kang, Y. T. (2024). Structural analysis and optimization of flattened tube gas cooler for transcritical CO₂ heat pump systems. *Energy*, vol. 307, article 132588. <https://doi.org/10.1016/j.energy.2024.132588>.
15. Kuzmin, V. V., Shevchenko, V. V., & Minko, A. N. (2011). *Optimizatsiya massy i razmerov elementov neaktivnoy zony turbogeneratorov s vozduшной sistemoy okhlazhdeniya* [Optimization of mass and dimensions of elements of the inactive zone of turbogenerators with an air-cooled system]. *Vestnik KrNU imeni Mikhaïla Ostrogradskogo – Transactions of Kremenichuk Mykhailo Ostrohradskyi National University*, iss. 6/2011 (71), part 1, pp. 100–104 (in Russian).
16. Hattori, K., Ide, K., Goto, F., Semba, A., & Watanabe, T. (2002). Sophisticated design of turbine generator with inner cooler ventilation system. *Hitachi Review*, vol. 51, no. 5, pp. 148–152.
17. Ge, Y. T. & Cropper, R. T. (2009). Simulation and performance evaluation of finned-tube CO₂ gas coolers for refrigeration systems. *Applied Thermal Engineering*, vol. 29, iss. 5–6, pp. 957–965. <https://doi.org/10.1016/j.applthermaleng.2008.05.013>.
18. Zhang, X. & Ge, Y. T. (2021). The effect of heat conduction through fins on the performance of finned-tube CO₂ supercritical gas coolers. *International Journal of Heat and Mass Transfer*, vol. 181, article 121908. <https://doi.org/10.1016/j.ijheatmasstransfer.2021.121908>.

19. Jadhav, N. P., Deshmukh, S., & Lele, M. M. (2012). Numerical simulation of fin and tube gas cooler for trans-critical CO₂ air conditioning system. *International Journal of Engineering Research & Technology (IJERT)*, vol. 1, iss. 10, 8 p.
20. Maiorino, A., Aprea, C., & Del Duca, M. G. (2021). A flexible top-down numerical modeling of an air-cooled finned-tube CO₂ trans-critical gas cooler. *Energies*, vol. 14, iss. 22, article 7607. <https://doi.org/10.3390/en14227607>.
21. Chen, Y. & Lundqvist, P. (2006). Analysis of supercritical carbon dioxide heat exchangers in cooling process. *Proceedings of International Refrigeration and Air Conditioning Conference*, paper 765.
22. Anderson, D., Tannehill, J. C., Pletcher, R. H., Munipalli, R., & Shankar, V. (2020). *Computational Fluid Mechanics and Heat Transfer*. 4th Edition. CRC Press, 974 p. <https://doi.org/10.1201/9781351124027>.

Received 25 June 2025

Accepted 20 August 2025

Підвищення ефективності системи охолодження турбогенератора шляхом використання в газоохолоджувачі оребрених трубок

Б. К. Шестак

Національний аерокосмічний університет «Харківський авіаційний інститут»,
61070, Україна, м. Харків, вул. Вадима Манька, 17

Надійність турбогенератора великої потужності багато в чому залежить від його системи охолодження. Безаварійна й ефективна робота цієї системи, зокрема газоохолоджувача, є проблемою, яка не повністю вирішена на теперішній час. У статті запропоновано модернізовану конструкцію газоохолоджувача для турбогенератора потужністю 325 МВт, в якому використовуються біметалеві трубки з високим оребренням. Для обґрунтування ефективності такої конструкції та визначення запасу теплопередачі газоохолоджувача проведено розрахунок його теплового стану. Отримані результати показали, що перегрів води в газоохолоджувачі становить 5 °С. При цьому одна секція газоохолоджувача забезпечує відведення теплових втрат у 1266 кВт при витратах водню 6,66 м³/с і охолоджуючої води 200 м³/с, що задовольняє вимогам до цього газоохолоджувача.

Ключові слова: турбогенератор, газоохолоджувач, оребрені трубки, тепловий розрахунок, критеріальні рівняння.

Література

1. Kerszenbaum I., Klempner G. Generator design and construction. In: Kerszenbaum, I. & Klempner, G. (eds). *Handbook of Large Turbo-Generator Operation and Maintenance*. 2018. Chapter 2. P. 53–168. <https://doi.org/10.1002/9781119390718.ch2>.
2. Miction M., Calverley S. D., Clark R. E., Howe D., Chambers J. D. A., Sykes P. A., Dickinson P. G., McClelland M., Johnstone G., Quinn R., Morris G. Modelling and testing of a turbo-generator system for exhaust gas energy recovery. *Proceedings of 2007 IEEE Vehicle Power and Propulsion Conference* (Arlington, TX, USA). 2007. P. 544–550. <https://doi.org/10.1109/VPPC.2007.4544184>.
3. Miction M., Calverley S. D., Clark R. E., Howe D., McClelland M., Sykes P. Switched reluctance turbo-generator for exhaust gas energy recovery. *Proceedings of 12th International Power Electronics and Motion Control Conference* (Portoroz, Slovenia). 2006. P. 1801–1807. <https://doi.org/10.1109/EPEPEMC.2006.4778667>.
4. ДСТУ EN 60034-6:2019 Машини електричні обертові. Частина 6. Методи охолодження (ІС-код) (EN 60034-6:1993, IDT; ІЕС 60034-6:1991, IDT) / ДП «Український науково-дослідний та навчальний центр проблем стандартизації, сертифікації та якості» (ДП «УкрНДНЦ»). Київ, 2019. https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=89126
5. Яйченя В. В. Автоматизація системи охолодження турбогенератора ТВФ-125-2У3: магістерська дис.: 151 Автоматизація та комп'ютерно-інтегровані технології / КПІ ім. Ігоря Сікорського, Київ, 2018. 89 с. <https://ela.kpi.ua/handle/123456789/28999>.
6. ДСТУ ІЕС 60034-1:2016 Машини електричні обертові. Частина 1. Номінальні та робочі характеристики EN 60034-1:2010; EN 60034-1:2010/АС:2010, IDT) / ДП «Український науково-дослідний та навчальний центр проблем стандартизації, сертифікації та якості» (ДП «УкрНДНЦ»). Київ, 2018. https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=68104.

7. Минко А. Н. Оптимальная геометрия и массогабаритные параметры конструкции корпуса статора турбогенераторов с воздушной системой охлаждения. *Энергосбережение. Энергетика. Энергоаудит*. 2012. № 01 (95). С. 33–39. <https://repository.kpi.kharkov.ua/server/api/core/bitstreams/10bab92d-75b0-44eb-9068-60e0b9427b73/content>.
8. Alexopoulos C., Aljolani O., Heberle F., Roumpedakis T. C., Brüggemann D., Karellas S. Design evaluation for a finned-tube CO₂ gas cooler in residential applications. *Energies*. 2020. Vol. 13. Iss. 10. Article 2428. <https://doi.org/10.3390/en13102428>.
9. Chai L., Tsamos K. M., Tassou S. A. Modelling and evaluation of the thermohydraulic performance of finned-tube supercritical carbon dioxide gas coolers. *Energies*. 2020. Vol. 13. Iss. 5. Article 1031. <https://doi.org/10.3390/en13051031>.
10. Zhang X., Ge Y., Sun J. CFD performance analysis of finned-tube CO₂ gas coolers with various inlet air flow patterns. *Energy and Built Environment*. 2020. Vol. 1. Iss. 3. P. 233–241. <https://doi.org/10.1016/j.enbenv.2020.02.004>.
11. Wang S., He Y., Tuo H., Cao F., Xing Z. Effect of heat transfer area and refrigerant mass flux in a gas cooler on heating performance of air-source transcritical CO₂ heat pump water heater system. *Energy and Buildings*. 2013. Vol. 67. P. 1–10. <https://doi.org/10.1016/j.enbuild.2013.07.078>.
12. Taher M., Evans B. F. (2020). Using a cubic polynomial temperature-entropy constant efficiency path for centrifugal compressor polytropic performance evaluation. <http://dx.doi.org/10.13140/RG.2.2.23470.54083/1>.
13. Evans B. F., Huble S. Centrifugal compressor performance: Making enlightened analysis decisions. *Proceedings of the 46th Turbomachinery Symposium* (Houston, TX, USA, 11–14 December 2017). 2017. 55 p. <https://core.ac.uk/reader/187128036>.
14. Khoshvaght-Aliabadi M., Ghodrati P., Rashidi M. M., Kang Y. T. Structural analysis and optimization of flat-tened tube gas cooler for transcritical CO₂ heat pump systems. *Energy*. 2024. Vol. 307. Article 132588. <https://doi.org/10.1016/j.energy.2024.132588>.
15. Кузьмин В. В., Шевченко В. В., Минко А. Н. Оптимизация массы и размеров элементов неактивной зоны турбогенераторов с воздушной системой охлаждения. *Вестник КрНУ имени Михаила Остроградского*. 2011. Вып. 6/2011 (71). Ч. 1. С. 100–104.
16. Hattori K., Ide K., Goto F., Semba A., Watanabe T. Sophisticated design of turbine generator with inner cooler ventilation system. *Hitachi Review*. 2002. Vol. 51. No. 5. P. 148–152.
17. Ge Y. T., Cropper R. T. Simulation and performance evaluation of finned-tube CO₂ gas coolers for refrigeration systems. *Applied Thermal Engineering*. 2009. Vol. 29. Iss. 5–6. P. 957–965. <https://doi.org/10.1016/j.applthermaleng.2008.05.013>.
18. Zhang X., Ge Y. T. The effect of heat conduction through fins on the performance of finned-tube CO₂ supercritical gas coolers. *International Journal of Heat and Mass Transfer*. 2021. Vol. 181. Article 121908. <https://doi.org/10.1016/j.ijheatmasstransfer.2021.121908>.
19. Jadhav N. P., Deshmukh S., Lele M. M. Numerical simulation of fin and tube gas cooler for transcritical CO₂ air conditioning system. *International Journal of Engineering Research & Technology (IJERT)*. 2012. Vol. 1. Iss. 10. 8 p.
20. Maiorino A., Aprea C., Del Duca M. G. A flexible top-down numerical modeling of an air-cooled finned-tube CO₂ trans-critical gas cooler. *Energies*. 2021. Vol. 14. Iss. 22. Article 7607. <https://doi.org/10.3390/en14227607>.
21. Chen Y., Lundqvist P. Analysis of supercritical carbon dioxide heat exchangers in cooling process. *Proceedings of International Refrigeration and Air Conditioning Conference*. 2006. Paper 765.
22. Anderson D., Tannehill J. C., Pletcher R. H., Munipalli R., Shankar V. *Computational Fluid Mechanics and Heat Transfer*. 4th Edition. CRC Press, 2020. 974 p. <https://doi.org/10.1201/9781351124027>.