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ECOLOGICAL SUSTAINABILITY OF OPERATION OF AUTONOMOUS LOW-POWER HEAT SUPPLY SYSTEMS

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Abstract.
Introduction. The nameplate data of boiler equipment manufacturers for nominal heat loads are applied when assessing the lifecycle, investigating the environmental impact of autonomous heat supply systems. The actual parameters of energy efficiency, emission of combustion products during the operation of gas boilers depend on many factors. Emission of CO, NOx, CO2-boilers for apartments changes 3-4 times depending on the heat load of the heating period.
Materials and methods. Technical characteristics of energy efficiency, emission of combustion products during the operation of wall-mounted non-condensing and condensing boilers of heat supply systems for the apartments with the area of 400-600 sq.ft. , houses with the area up to 3000 sq.ft during the boiler operation in heat power smooth modulation mode and cycling operation mode were investigated.
Results. During the boiler operation CO, NOx, CO2 emission values change 3-4 times depending on the heat load. During the boiler cyclic operation the parameters of greenhouse gas emission exceed in two times the nameplate data of nominal heat loads.
Discussion. When assessing the influence of operation of gas boilers of autonomous low-power heating systems, the use of nameplate data of technical characteristics for nominal heat loads can result in errors up to 2-3 times. The service life of wall-mounted gas boilers in the conditions of cyclic operation is 7-10 years.
Conclusion. When designing low-power heat supply systems, it makes sense to calculate the system operation stability for different heat loads to check the ecological sustainability. The notion “Ecological sustainability of autonomous heat supply system operation” is introduced.
Keywords: energy efficiency, emission of gases, condensing boiler, non-condensing boiler, ecological sustainability.

1. Introduction.

Heat supply systems – heating and hot water preparation – are the main tools, which allow producing and maintaining temperature-humidity and hygienic modes at human whereabouts. The achievement of high indexes of energy effectiveness of heat supply systems and, as a result, decrease in technogenic impact on the planet natural environment are directly connected with the ability to control the autonomous heat supply system operation parameters: total energy effectiveness of the heat generator, heat transfer medium circulation circuit and heating appliances. Wall-mounted gas boilers are widely used as heat generators for autonomous heat supply systems of the premises with the area up to 3000 square feets or apartments in multistory buildings. The necessity to limit the operational costs and improve ecological sustainability of

the systems becomes particularly urgent due to the rise of prices for energy sources, especially in countries with cold climate. Heating of premises is one of the main factors of environmental impact when using hydrocarbon fuel. In EU-27 countries heating and hot water supply are the main sources of residential energy consumption. Their shares are 70% and 14%, respectively, from the total annual energy consumption [1]. Housing sector plays an important role in energy effectiveness programs and policy of all developed countries, in particular, EU adopted Directive on the Energy Performance of Buildings [2] and international standards [3], [4]. As applicable to thermal generating units of autonomous heat supply systems, several investigations of lifecycle assessment demonstrated in section 2 were carried out, however, when assessing the emission of combustion products and their impact on the atmosphere the values of carbon oxide (CO) and nitrogen oxide (NOx) were taken as the initial values according to the nameplate data of the manufacturers of heat generators for nominal loads. The actual greenhouse gas emissions depend on the heat load mode of the heat supply system operation and heat generator type. The use of the indicated data when assessing the lifecycle for maximum loads leads to errors in the analysis results up to 3-4 times. The service life of wall-mounted gas boilers for autonomous heat supply systems of apartments and individual boilers is much shorter than of floor-mounted boilers. The service life currently declared by manufacturers is 10 years in average. When assessing the lifecycle of heat supply systems with these boilers, the use of longer time periods is not reasonable.

The purpose of this investigation is to define the range of change in ecological impact parameters of non-condensing and condensing wall-mounted gas boilers applied in households with the heated area up to 3000 square feets during the whole heating period of the season.

2. Review of literature on the environmental impact of autonomous domestic heat supply systems.

The method of lifecycle assessment (LCA) of the influence of greenhouse gases during fuel combustion, production and utilization of boilers of autonomous heat supply systems is studied in several researches. Viral P. Shah et al. [5] considered the geographical factor influence and studied three types of domestic heating and cooling systems in combinations (burner-boiler-heat pump-air conditioner) in four places in the United States: Minnesota, Oregon, Pennsylvania, Texas. As applicable to calculating LCA in heating modes, the units with 80% AUEF, which are currently not used for new premises, were considered; the units were assessed for energy effective boilers with 94% AUEF of condensing type. It is indicated in the paper that operational components in the heating mode have the largest share of LCA impacting the environment and the variant “gas boiler-air conditioner” has lower environmental impact level. When assessing the energy effectiveness indexes, the performance standards of equipment manufacturers were used for nominal values of heat loads.

Gajewski, A. et al. [6] investigated ecological characteristics of different heating systems, including condensing boilers when taking into account carbon dioxide gas emission, Koroneos, C.J. et al. [7] studied characteristics of solar water heaters, Laschi, A. [8], Chiesa, M. et al. [9] – production indexes of wooden pellets for heating. In all papers, the emission indexes of gases in LCA for heating equipment were considered for standard nominal operation modes of thermal generating units. The comparison of different types of traditional hydrocarbon fuel for heating premises from the point of ecological impact on the environment indicates the advantage of natural gas (Mahmoud, M. et al.) [10].

G. Vignali [11] compared the lifecycles of non-condensing and condensing wall-mounted gas boilers manufactured by Immergas SpA (Italy).

The analysis was carried out for three climatic regions of Italy. The assessment was made using CML methods and cumulative energy demand (CED) taking into account the categories required by the certification systems "Ecological Product Declaration" (EPD). The analysis results demonstrated that, in average, condensation boilers have the environmental impact by 23% less than non-condensing analogs. This is mainly connected with lower fuel consumption at the operation stage and lower levels of CO and NOx gas emission during fuel combustion. The investigation also shows that mostly the boiler operation stage contributes to environmental impact and in average it accounts for over 90% of the total impact. The comparative researches of energy efficiency and environmental impact of emission gases of autonomous heating systems are the main topic when selecting the equipment due to their large share in total household energy consumption (Ibrahim O. et al.) [12], in particular, in comparison with centralized heat supply systems (Andric I. et al.) [13].

The researches of many authors are dedicated to the investigation of operation of wall-mounted gas condensing and non-condensing boilers. Bonaros, V. et al. [14] presented the graphs of energy efficiency of condensing boilers depending on the heat power for different temperature conditions of the return line at the return temperature of 30/45/60 0C. When the return temperature equals 60 0C, the efficiency value is practically the same in the whole range of 20-100% and is NCV 94% (GCV 85%). But when the return temperature is 30 0C, the maximum efficiency at 30% of heat load is NCV 105% (GCV 94.5%) and drops to NCV 102% (GCV 92%) at the heat load of 100%.

Similar results for boilers were also obtained by other researchers [15-16].

High temperature in the return line is characteristic for countries where heating radiators are used as heating appliances (Great Britain: the share of radiator heating is about 90%). For non-condensing wall-mounted gas boilers the efficiency is lower than for the condensing ones. The smooth power modulation change is possible only from 40%-100% of heat power, at the same time, the efficiency changes from 86% up to 92% (NCV) [14]. At lower values of heat load the boiler works in the cyclic mode. The efficiency at 30% of load in traditional boilers drops to 75% (NCV) and lower. All indicated boiler efficiency investigations were carried out for stable operation modes of boilers with testing duration over 30 minutes. From the emission indexes of combustion products CO2 values are indicated for maximum and 30% heat loads, and for non-condensing boilers – for nominal loads. The investigations demonstrated that during the operation of boilers the emission parameters of CO and NOx gases depend on the load and change up to 3-4 times [17]. It is necessary to point out that when assessing the lifecycle of boiler equipment, the values of energy efficiency for nominal heat loads are applied. In real situation boilers never work at nominal loads for the whole operation period. The notion of "season efficiency" is used to assess the efficiency in the heating period. In [18-20] the efficiency of cyclic operation of non-condensing boilers, which are not currently used for new premises, was assessed, but 60 million pieces of them are operated all over the world and this cannot be ignored. The season efficiency of modern low-temperature non-condensing boilers is 79%, for condensing boilers it equals 89% (GCV). In autonomous heating systems the operation of condensing boilers in cyclic load modes and assessment of emission of the combustion products in the given operation modes are not studied well.

3. Materials and methods.

The actual technical characteristics of energy efficiency, emission of combustion products during the operation of wall-mounted non-condensing and condensing boilers for autonomous heat supply systems of the apartments with the area of 400-600 square feets and houses with the area up to 3000 square feets were investigated. The tests were conducted on the research stands during the operation of boilers in the mode of heat power smooth modulation and in the mode of cyclic operation of the boiler. The autonomous heat supply system with low-temperature wall-mounted non-condensing gas boiler Ariston HS 24FF at heat load of 2700-8500 BTU with nominal heat load of 82000 BTU and condensing wall-mounted gas boiler Baxi Duo-tec Compact 24 GA at heat load of 10000-50000 BTU with nominal heat load of 82000 BTU was investigated. The temperatures of heat transfer medium (water) at the boiler inlet and outlet, heat transfer medium consumption, gas consumption, temperature of flue gases, CO and CO2 emission were measured. NG G20 gas was used as the fuel.

4. Results.

The graphs of the change in the energy efficiency, CO and CO2 emission depending on the produced heat power are given in Figure 1 for non-condensing low-temperature gas boiler Ariston HS 24FF.

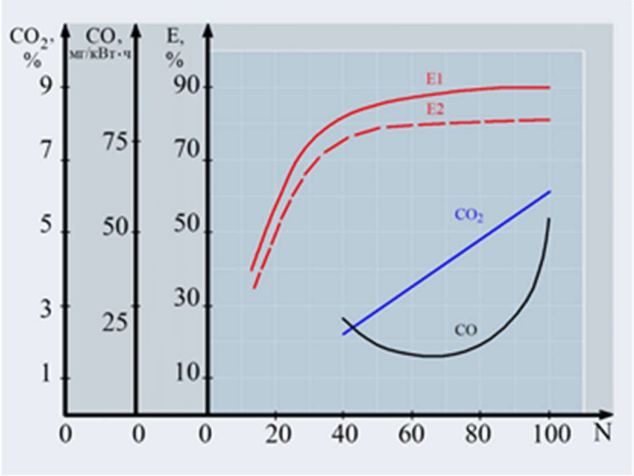

Fig. 1. Graphs of the change in the energy efficiency E1(NCV), E2(GCV), CO and CO2 emission depending on the heat load for non-condensing low-temperature wall-mounted gas boiler.

The heat power smooth modulation was carried from 40 up to 100% of the nominal power. When the heat load was below 40% from the nominal one, the boiler shifted to the cyclic operation mode. The number of the boiler operation cycles could reach up to 15 per hour. The steep drop in the boiler operation energy efficiency occured in the range of 20-40% of the nominal heat power. The values of CO and CO2 emission are shown only during the burner device operation. The range of the energy efficiency change at the heat load of 40-100% from the nominal power changed linearly from 86.5 up to 91.8% (NCV). The range of CO emission change was from 0,005 up to 0,016 mg/BTU CO2 – from 2.1% up to 6.2%.

The graphs of CO and CO2 emission change for non-condensing and condensing boilers at the operation start depending on time at the nominal heat load are demonstrated in Figure 2. CO2

emission values changed insignificantly during the whole operation start period of condensing and non-condensing boilers. During the first 40 seconds of operation CO emission both in condensing and non-condensing boilers exceeded in up to two times CO emission values for stable modes. In 80-100 seconds after the operation start the significant drop in CO emission levels was observed in condensing boilers in comparison with the stable operation mode.

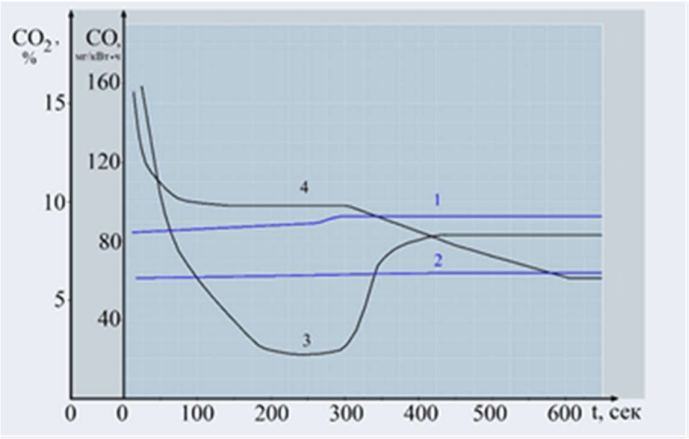

Fig. 2. Graphs of CO and CO2 emission values for condensing and non-condensing boilers in time during the operation start. 1, 3 – CO2 and CO emission for condensing boiler. 2, 4 – CO2 and CO emission for non-condensing boiler.

5. Discussion.

5.1. Initial data.

Wall-mounted gas boilers are not the final consumption product. They are an integral part of the autonomous heat supply system, comprising, apart from the boiler, the heating circuit filled with heat transfer medium and heating devices. Heating radiators and water-to-air heat exchangers are used as the heating devices.

The assessment of the lifecycle, energy efficiency, value of the emission of gas combustion products depends on the combination of all devices of the heat supply system in operation.

The main factors influencing the abovementioned parameters are the following:

- geographical factor defining the ranges of possible changes in the environment air atmosphere;
- architectural and constructional factor defining the sizes of the heated premises, shapes of the buildings and glass panels, heat conductivity of the enclosure structures;
- social factor defining temperature and hygienic mode inside the premises.

The peculiarity of autonomous low-power heat supply systems is the fact that, apart from heating, the boiler also provides water preparation in the household. When using wall-mounted gas boilers for the heat supply for households, the hot water preparation is determinative by power. The instantaneous power of 50000-82000 BTU is required for this function. The value of energy necessary to heat premises depends on the premises size, heat conductivity of the enclosure structures, external temperature and internal temperature inside the premises. In a number of countries of Eastern Europe and Asia autonomous heat supply systems have been applied for apartments in multistory buildings for the recent 20 years. The area of apartments

is sometimes 400-600 square feets. Aluminum bimetallic water radiators are used as heating devices. The ranges of changes in the heat loads for such apartments in the heating and hot water preparation modes are given in Figure 3. The data were calculated for the climatic conditions of the southern part of the Baltic sea in Europe, however, these data can be also used for Asia with the total number of boilers over 60 million pieces.

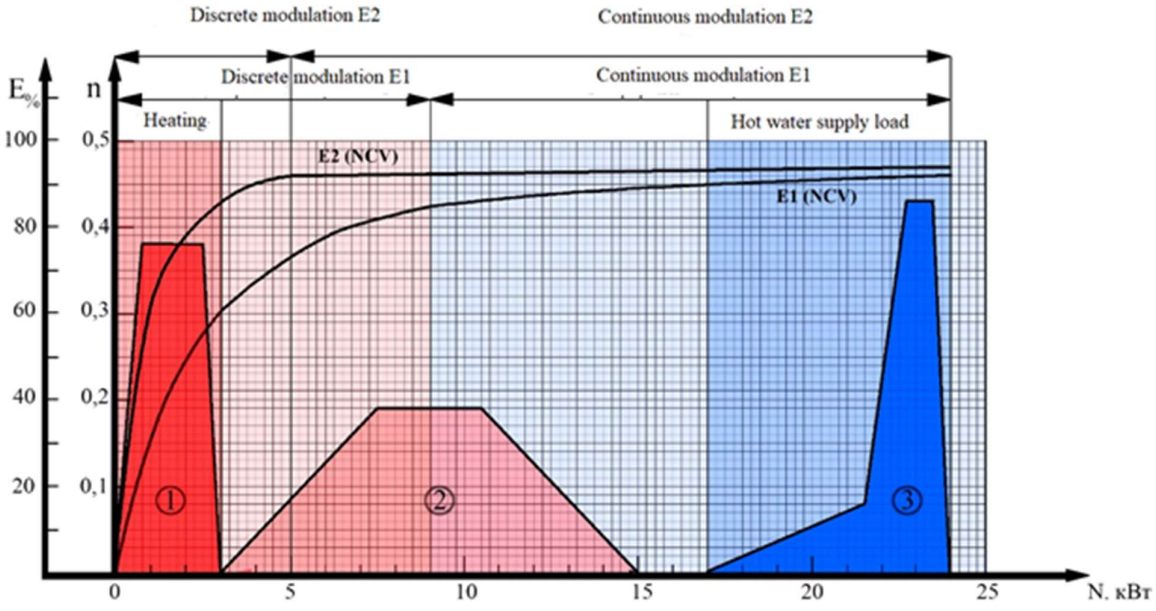

Fig. 3. Ranges of changes in the heat loads of autonomous heat supply systems. 1 – apartment of 500 square feets, 2 – house of 1500 square feets, 3 – hot water preparation for the family of 4 people.

The calculations show that the range of changes in the heat loads during the heating operation mode of the apartment with the area of 500 square feets wss from 1700 up to 6800 BTU. The average value in the heating period of the year was 3700 BTU The average necessary power for hot water preparation was 68000 BTU. One boiler was used for heating and hot water preparation. The range of changes in the heat loads was 20 times in average (zone 1 and zone 3 in Figure 3). Another situation was for the individual house with the area of 1500 square feets. The heat load distribution for the house with the area of 1500 square feets for the same geographical location, as for the case with the apartment location, is also demonstrated in Figure 3. The heat load for heating during the heating period of the year was in the range of 10000-50000 BTU. The load coefficient was 8-1.6. The energy efficiency for the non-condensing boiler is shown by E1 (NCV), condensing boiler – E2 (NCV), heating devices are the bimetallic heating radiators. The ranges of smooth and cyclic modulation for non-condensing boiler E1 and condensing boiler E2 are also shown in Figure 3.

5.2. Autonomous low-power heat supply systems. Operation options.

Non-condensing boilers have the range of the smooth change in the heat load of 2.5, condensing boilers – up to 5 [14], [21]. Non-condensing and condensation boilers in the considered variants of heat supply systems for the apartments with the area of 500 square feets will work in the

cyclic mode. The energy efficiency of boilers in this mode is much lower than that declared by manufacturers for stable operation modes. The indexes of energy efficiency and emission levels of the combustion products for the considered cases never correspond to the maximum nominal heat loads declared by boiler manufacturers. The use of the nameplate data for energy efficiency and gas emission in the lifecycle assessment, in the evaluation of the payback period of the boiler replacement for the considered autonomous heat supply systems will lead to erroneous results.

When using the wall-mounted non-condensing boiler for autonomous heat supply of the house with the area of 1500 square feets, for half of the heating season the boiler will work in the power smooth modulation mode, for the second half – in the cyclic mode. The use of the data by energy efficiency and product emission for nameplate data of the nominal heat loads is also unauthorized.

When installing a condensing boiler for heating the house with the area of 1500 square feets, it can be stated that for the main part of the heating season the boiler will work in the range of power smooth modulation, and the value of the season heat load and indexes of energy efficiency for it can be defined by the nameplate data, but by gas emission – not for nominal values. The emission parameters differ from the nominal ones by 30-100%. If a non-condensing boiler is installed in the household, it will be nearly always working in the cyclic operation mode, which does not correspond to the energy efficiency and emission data declared by the manufacturers. The indexes of CO2 emission can be obtained based on stoichiometric calculation but taking into account the actual season heat load. The calculation of emission of CO and NOx combustion products by the values of nameplate data of these gases for nominal loads results in errors in several times.

5.3. Cyclic modes of the boiler operation.

In the nameplate data of the boiler manufacturers the energy efficiency parameters are indicated for the stable operation modes with the constant heat load. In reality, at each boiler operation cycle the initial boiler burner blowing with the fan, fuel feeding to the burning device, gaseous fuel mixing with air oxygen, ignition of the gas-air mixture and gradual heating of the boiler heat exchanger take place. It requires time. The establishing of the constant consumption of flue gases in the chimneys needs time as well, therefore, the concentration of combustion product emission changes at each boiler operation cycle. The number of boiler operation cycles per hour depends on many factors:

- boiler type;
- boiler nominal power;
- ratio between the minimum power of the boiler modulation range and nominal power;
- heat losses of the heated premises for the temperature differences of the atmospheric air and air in the premises;
- type of heating devices (radiators, floor heating, convectors), their size, weight;
- boiler operation mode.
- heat transfer medium volume in the heating circuit, and other factors.

In practice of applying wall-mounted gas boilers for autonomous heat supply systems of apartments there are cases of installing 2-3 heating radiators in apartments – studios with the area of 350-400 square feets. In such cases, the number of boiler operation cycles can be 10-

15 per hour. The boiler stable operation mode is impossible in such conditions [22]. The burner operation time in the boiler cyclic mode depends on the heat transfer medium volume in the circulation circuit, circulation pump productivity, heat response rate of the heating devices, boiler nominal power and boiler operation algorithm. The manufacturers of the boiler equipment set up the pause of 1-3 minutes between the neighboring cycles in the operation algorithms. However, the heat transfer medium volume in the heat supply systems of apartments can be only 7-10 liters. In such cases, the operation time of the burner equipment is about one minute. Consequently, each boiler operation cycle will be connected with exceeding the standard value of CO emission in two times in comparison with the nominal nameplate data.

5.4. Service life of the wall-mounted gas boilers.

In the assessment of the lifecycle and payback period of the equipment replacement for autonomous heat supply systems of small-area houses it is important to know the service life of the boilers. The use of the statistic data for floor-mounted boilers for heating the houses, which were used for decades, is erroneous. There are several reasons of significant decrease in the service life. Wall-mounted gas boilers are mounted on the wall. Their weight is very important. The main elements of the fuel combustion chamber are produced from materials-substitutes or from thinner steel sheets. The wall-mounted boilers are operated in the cyclic mode at low heat loads. The number of cycles influences the reliability of the elements.

For the recent several decades wall-mounted gas boilers have been used for autonomous heat supply systems of apartments in multistory buildings in a number of countries. The cyclic operation mode for these variants of boiler application is more intensive in comparison with heating of individual houses. These and other reasons result in shortening the service life of the boiler equipment of this type. The service life also depends on the manufacturer and boiler price. The declared period of standard operation of wall-mounted gas boilers of upper price segment (Viessmann, Vaillant) is 10-15 years, mid-price segment (Proterm, Bosch) - 10-12 years, lower price segment (Ariston, Baxi, Navien) - 8-10 years, however, the indicated time periods correspond to the boiler operation in the established mode in the range of heat power smooth modulation. The mode of constant cyclic load, which occurs when operating boilers for small-area apartments, decreases the service life by 30-40%. When evaluating the average service life of boilers, it is reasonable to judge from the share of the boilers of certain brand on the market of countries. Generally, the boilers of lower and mid-price segment prevail in the world by the share of applications. Consequently, the average service life of wall-mounted boilers for apartments is 7 years, for the operation of wall-mounted boilers for individual houses with the area of 1200-3000 square feets - 10 years.

6. Conclusion.

The boiler cyclic operation mode has low energy efficiency and increased level of greenhouse gas emission. Thus, the question about the correct designing of autonomous heating systems of hot water preparation for small-area apartments and households comes up. With the large difference in the boiler power required for heating and hot water supply it is erroneous to use the standard values of the boiler characteristics indicated in the documents to evaluate ecological impacts of the boiler operation on the planet atmosphere.

Due to the revealed peculiarities of gas boiler application for autonomous heat supply systems, it is reasonable to introduce the notion "Ecological sustainability of heat supply system" characterizing the value of combustion product emission during the heating system operation in the range of complete change in possible heat loads of the object location. The calculations should be carried out for minimum, average and maximum heat loads for the heating period. The obtained results should be compared with the gas emission standards established in the country of the object location.

7. Conclusions.

1. Indexes of energy efficiency and emission levels of fuel combustion products of wall-mounted gas boilers for autonomous heat supply systems depend on many factors. During the lifecycle assessment and other investigations the nameplate data indicated in the documentation of boiler manufacturers for nominal power values can result in erroneous results.
2. When using wall-mounted gas boilers for autonomous heat supply systems of small-area apartments in heating mode, the cyclic operation mode occurs. The value of energy efficiency indexes of the heating system in this mode decreases to 50% (GCV) with non-condensing gas boilers and to 75% (GCV) with condensing boilers. The indexes of CO emission levels of combustion products can exceed 2 times CO emission values of stable modes.
3. Service life of wall-mounted gas boilers depends on the area of the heated premises and boiler brands, which differ for each country. If the country is not specified, then to heat apartments with the area up to 700 square feets the boiler average service life is 7 years, for individual houses with the area of 1200-3000 square feets – 10 years.
4. When designing objects and selecting boilers for autonomous heat supply systems, it is reasonable to check the emission levels of the combustion product emission for minimum, average and maximum heat loads of the heating system. If the established ecological standards are complied with in the whole range of the heat load change, the heat supply system gets the approval of "Ecological sustainability".

REFERENCES

1. European Commission, 2012a. Heat and Cooling Demand and Market Perspective. Joint Research Centre, Institute for Energy and Transport, Luxembourg. URL: https://www.diva-portal.org/smash/get/diva2:994989/FULLTEXT01.pdf
2. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). URL: https://eur-lex.europa.eu/eli/dir/2010/31/oj
3. ISO, 2006a. Environmental Management and Life Cycle Assessment Principles and Framework, ISO 14040:2006(E). International Organization for Standardization, 2006.
4. ISO, 2006b. Environmental Management and Life Cycle Assessment, in: Requirements and Guidelines, ISO 14044:2006(E). International Organization for Standardization, 2006.

5. Viral P. Shah, David Col Debella, Robert J. Life cycle assessment of residential heating and cooling. Energy and Buildings. 2008. Vol.40. P.503-513. DOI: https://doi.org/10.1016/j.enbuild.2007.04.004
6. Gajewski, A., Siergiejuk, J., Szulborski, K. Carbon dioxide emission while heating in selected European countries. Energy Build. 2013. Vol. 65, P.197-204. DOI: https://doi.org/10.1016/j.enbuild.2013.05.042
7. Koroneos, C.J., Nanaki, E.A. Life cycle environmental impact assessment of a solar water heater. Journal of Clean Production. 2012. Vol. 37, P. 154-161. DOI: https://doi.org/10.1016/j.jclepro.2012.07.001
8. Laschi, A., Marchi, E., Gonzalez-García, S. Environmental performance of wood pellets' production through life cycle analysis. Energy. 2016. Vol. 103, P. 469-480. DOI: https://doi.org/10.1016/j.energy.2016.02.165
9. Chiesa, M., Monteleone, B., Venuta, M.L., Maffeis, G., Greco, S., Cherubini, A., Schmidl, C., Finco, A., Gerosa, G., Ballarin Denti, A. Integrated study through LCA, ELCC analysis and air quality modelling related to the adoption of high efficiency small scale pellet boilers. Biomass and Bioenergy. 2016. Vol. 90, P. 262-272. DOI: https://doi.org/10.1016/j.biombioe.2016.04.019
10. Mahmoud, M., Ramadan, M., Naher, S., Pullen, K., Olabi, A. The impacts of different heating systems on the environment: A review. Science of The Total Environment. 2021. Vol. 766. DOI: https://doi.org/10.1016/j.scitotenv.2020.142625
11. Vignali, G., Environmental assessment of domestic boilers: A comparison of condensing and traditional technology using life cycle assessment methodology. Journal of Cleaner Production. 2017. Vol. 142. P. 2493-2508. DOI: https://doi.org/10.1016/j.jclepro.2016.11.025
12. Ibrahim O., Fardoun F., Younes R., Louahlia-Gualous H. Review of water-heating in systems: general selection approach based on energy and environmental aspects. Building and Environment. 2014. Vol. 72. P. 259-286. DOI:10.1016/j.buildenv.2013.09.006
13. Andric I., Pina A., Ferrao P., Lacariere B., Le Corre O. On the performance of district heating systems in urban environment: an emergy approach. Journal of Cleaner Production. 20167. Vol. 142 (P1). P. 109-120. DOI:10.1016/j.jclepro.2016.05.124
14. Bonaros, V., Gelegenis, J., Haris, D., Giannakidis, G., Zeryas, K. Analysis of the energy and cost savings caused by using condensing boilers for heating dwellings in Greece. Conference: 5th International Conference on Applied Energy ICAE2013 At: Pretoria, South Africa. 2013. DOI:10.13140/RG.2.1.2731.4406
15. Comakli, K. Economic and environmental comparison of natural gas fired conventional and condensing combi boilers. Journal of the Energy Institute. 2008. Vol. 81. P. 242-246. DOI:10.1179/014426008X371031
16. Lazzarin, R. Condensing boilers in buildings and plants refurbishment. Energy and Buildings. 2012. Vol.47. P.61-67.
17. Havanov P.A., Markevich Yu.G. Study of the efficiency of thermal blocks with a "Closed" firebox in apartment heating systems. Vestnik MGSU, 2012. No. 12. pp.199-203.

18. Malmstorm, T., Mundt, B., Bring, A. A simple boiler model. Paper CH-85-02 No 3, ASHRAE Trans 1985;91:87-108
19. Rosa, L., Tosato, R. Experimental evaluation of seasonal efficiency of condensing boilers. Energy and Buildings. 1990. Vol.14. P.237-241. DOI: 10.1016/0378-7788(90)90050-s
20. Park Ch, Liu S. Performance of a commercial hot water boiler. Report NISTIR 6226. U.S. Dept of Commerce, National Institute of Standards and Technology; 1998.
21. Toropov A.L. Analysis of Operation of Gas Valves of Low-power Convection Boilers. AVOK, 2020. №3. P. 58-61 URL:https://www.abok.ru/for_spec/articles.php?nid=7505.
22. Toropov A.L. Issues of operating efficiency of non-condensing wall gas boilers with apartment heat supply. Plumbing, Heating, Air Conditioning. 2021; № 6 (234): P.42-45. URL: https://www.c-o-k.ru/articles/voprosy-effektivnosti-raboty-konvekcionnyh-nastennyh-gazovyh-kotlov-pri-pokvartirnom-teplosnabzhenii.
23. Kotisuryam, M. O. O. L. E., and G. O. D. I. G. A. N. U. R. Sharanappa. "Investigating HVAC thermal comfort and energy efficiency in commercial buildings." Int J Mech Prod Eng Res Dev 9 (2019): 319-328.
24. Ahmed, AYESHA SULTANA, D. RATNA Kumari, and T. Neeraja. Purchase Behavior of Women Consumers, towards Energy Efficient Household Products. Diss. Univeristy Rajendranagar, 2017.
25. Yemelyanova, V. S., et al. "Processing fly ash from the thermal power stations for gas emissions purification from sulfur dioxide." International Journal of Mechanical and Production Engineering Research and Development 9.4 (2019): 1015-1026.
26. Chaurasiya, Ritesh Kumar, and Priyash Agarwal. "Thermodynamic Analysis for Performance Improvement of Power Plant by Flue Gas Heat Recovery System." International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) 8 (2018): 569-578.
27. Joshi, Krishna. "Application of Energy Concepts for Green Buildings." International Journal of Civil, Structural, Environmental and Infrastructure Engineering Research and Development (IJCSEIERD) ISSN (P) (2016): 2249-6866.
28. Jain, R. A. C. H. N. A., and I. N. D. U. Kashyap. "An efficient energy aware link stable routing protocol in MANETS." International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) 8.3 (2018): 623-634.