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Analysis of Efficiency of Heat Generator System Depending on Type and Load

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Subject review

The efficiency of heat generators (boilers) of different types commonly used in today's heating systems is analyzed in this paper. The dependency of the efficiency on load is shown and an analysis of the total efficiency of the heating system is derived. The referential system consists of four heat generators guided by the stage sequencing control. Three different types of heat generators, i.e. standard, low temperature and condensing heat generators have been taken into consideration. The heat generator thermal load, number of heating days (hours) and total thermal load are the most important influential factors that have to be taken into consideration. A numerical example is presented for a case of 2,4 MW maximum heating load. Comparison of results has been made accompanied by a commentary and final conclusions.

Analiza učinkovitosti kotlovskih sustava u ovisnosti o konstrukciji i opterećenju

Pregledni članak

Rad sadrži pregled karakteristika iskoristivosti generatora topline (kotlova), različitih konstrukcijskih izvedbi, kakvi se danas koriste u sustavima za grijanje. Prikazane su njihove ovisnosti o opterećenju, te je u sklopu toga izvedena analiza ukupne učinkovitosti sustava s više, odnosno do najviše četiri kotlovske jedinice spojenih kaskadno. Analiza je provedena za tri različite konstrukcijske izvedbe, odnosno za tzv. standardne kotlove, nisko-temperaturne kotlove i kondenzacijske kotlove. Analiza je provedena uzimajući u obzir stupanj opterećenja sustava, broj pogonskih sati, te ukupno toplinsko opterećenje sustava, kao najutjecajnijeg čimbenika. Numerički je primjer prikazan za slučaj maksimalnog ukupnog opterećenja od 2,4 MW. Uz usporedbu rezultata, dat je komentar, te zaključci analize.

1. Introduction

There are several different ways, besides maintenance on a regular basis, to achieve better and more efficient work of heat generators. An essential element in designing such heating systems is proper sizing depending on thermal load through the whole season of heating. Oversized systems have higher investment cost, more expensive maintenance and lower flexibility during operating period. Other crucial element in designing such systems is selection of number of heat generators (boilers) that should produce required thermal energy. The correct selection is dependent on the purpose of system and also on the dependency of the efficiency of heat generators on partial load. Standard heat generators (older design) have efficiency rising with the increase of load. Today, the most part of units installed involves standard heat generators. Low temperature and condensing heat generators have an opposite feature. Their efficiency decreases with growth of load. Such a difference affects on design of heating systems and correct selection of heat generators, what is the subject of the consideration in this paper. Despite of the developed nowadays technology of heat generators, further research is still needed. A short preview of different approaches to improve efficiency and to decrease emission of CO, CO_2, NO_x, and SO_2.

Franco, A. and Giannini, N. [1] gave general method for the optimum design of heat generator. They defined the optimization of efficiency through three stages of different complexity: operating parameters, geometrical details and technological elements. Manczyk, H. [2] suggested procedure of selecting optimal heat generator

Symbols/Oznake

b_V - number of working hours per year, h/year
- broj radnih sati za jednu godinu

H_d - net calorific value, kJ/kg
- donja ogrijevna moć

H_g - gross calorific value, kJ/kg
- gornja ogrijevna moć

Q_a - annual consumption of heat, kWh/year
- potrošnja energije na godišnjoj razini

$\dot{Q}_N$ - standard required heat (DIN 4701), kW
- standardna toplinska energija (DIN 4701)

φ_k - heat generator load
- opterećenje generatora topline

η - efficiency of heating generator
- stupanj djelovanja generatora topline

Indices / Ineksi

N - standard efficiency of heating generator
- standardni stupanj djelovanja generatora topline

φ, i - efficiency of heat generator on different partial load (e. g. 13, 30, 39, 48 or 63 %)
- stupanj djelovanja generatora topline pri djelomičnom opterećenju (npr. 13, 30, 39, 48 ili 63 %)

size according to seasonal change of efficiency. He gave alternative strategy that opposes the one that suggests installation of high efficiency boilers. His main idea is to ensure the system which is optimally sized and that the system operates at an output that is appropriate for the demands of the facility throughout the heating season. Prelec, Z. described several different procedures to improve efficiency of heating systems. He gave rewiev of influences that various types of burners have on the optimization of burning processes [3]. The same author in [4] proposed the method for optimization of a steam generating system in varying operating conditions based on Lagrange's multiplier. In [5] the author elaborated how to increase furnace efficiency by optimum use of flue gas heat and in [6] a rewiev is presented of main factors for rational energy use in steam generator plants. Donjerković, P. et al. [7] presented the method and procedure to determine the heat generator efficiency. Lots of works concerning air pollution reduction and improvement of efficiency have been done in legislative departments of United Kingdom and European Community. In [8] and [9] a group of authors presented directives on efficiencies that the industry should follow. Brkic and Tanaskovic [10] presented the selection of a type of heating system according to the disposition of buildings in the area, their number, size and insulation quality. Based on these characteristics, authors made calculations of investments and exploitation costs for 96 presented cases. Corgnatti et al. [11] carried out a survey in order to collect, elaborate and analyze data concerning the actual energy consumption for space heating of a sample of about 140 buildings (120 high schools) in the Province of Torino (Italy). The energy consumption data, both annual and monthly, were normalized and statistically analyzed in order to compare different buildings and different heating seasons. Their conclusion was that such a methodology is suitable for long period assessment on large building stocks, and that is being very useful for assessing the annual and overall cost of energy service contracts. Different technical papers has been done by two great manufacturers of heating equipment. The Viessmann group and Buderus Heiztechnik published series of technical papers that deal with their product characteristics, installation, maintenance, and efficient (optimum) use ([13-15] and [22]).

2. Characteristics of heat generators

2.1. Standard efficiency of heat generator

Standard DIN 4708-8 defines testing method to provide the standard efficiency based on standard tests and analyses with predefined partial loads. Standard efficiency is defined from five efficiencies measured on different partial loads (13, 30, 39, 48 and 63 % of total load). This defines unique value for a simple comparison of heat generators of different types.

$$\eta_N = 5 / \sum_{i=1}^{5} (1/\eta_{\varphi,i}) . \tag{1}$$

In previous expression η_N is the standard efficiency of heat generator and $\eta_{\varphi,i}$ is the efficiency on different partial load. The standard efficiency considers ratio among gained and used energy in predefined working conditions. For the comparison of more heating units, the expression (1) gives prompt results. Figure 1 shows average values of efficiencies of heat generators of different design. The best values are accomplished to the boilers of new generation operating with low temperature heating media.

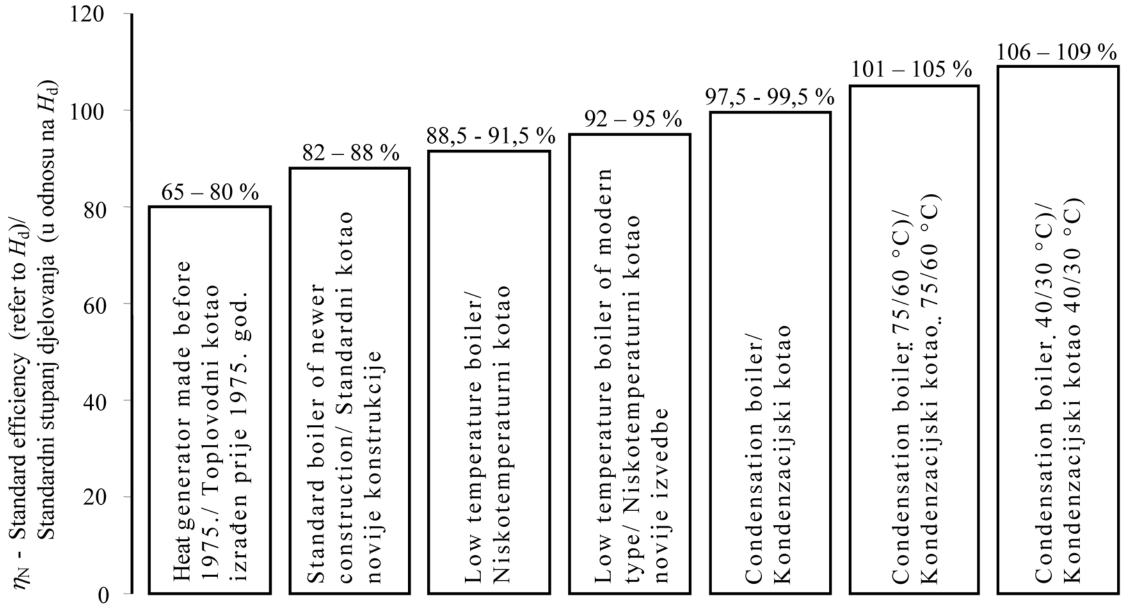

Figure 1. Efficiencies of different type heat generators [13]

Slika 1. Stupanj iskoristivosti kotlova različitih konstrukcijskih izvedbi [13]

2.2. Efficiency of heat generators

To calculate efficiency of heat generator, the net calorific value (lower) is being taken into consideration as referent value. The net calorific value of fuel (H_d) represents amount of heat that can be gained from unit of volume or mass of fuel while flue gas is not cooled bellow of condensation temperature of steam. The gross calorific value (H_g) includes, comparing to H_d, the energy of steam evaporation contained in flue gas. If we take in consideration that the net calorific value of fuel is referent size (H_d = 100 %), than it is not unusual that condensation heat generators have efficiency higher than 100 %. Natural gas has the evaporating heat of approximately 11 %. This part of energy remains unused with standard and low temperature heat generators. Figure 2 shows a comparison between low temperature and condensing heat generators.

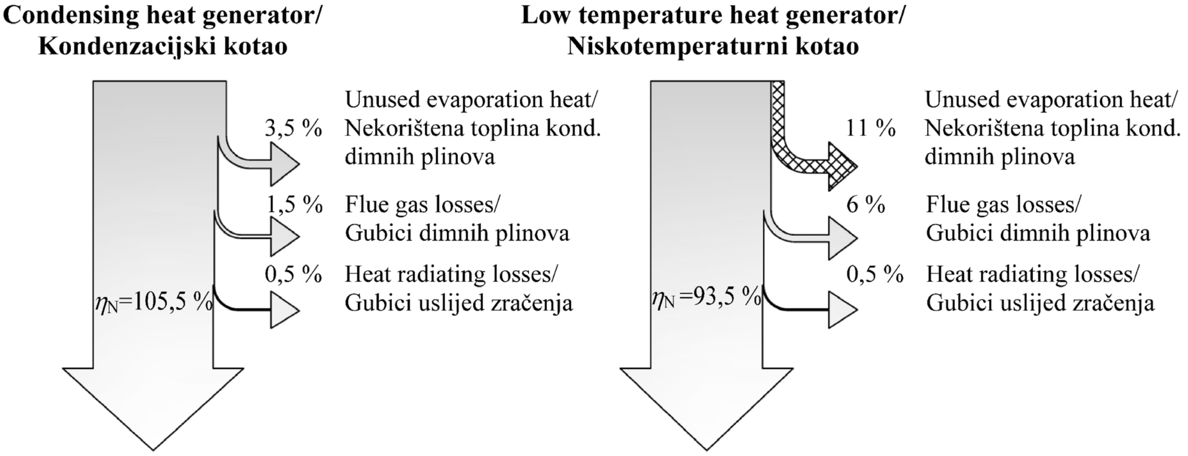

Figure 2. Energy balance comparison of a typical low temperature and condensing heat generator [22]

Slika 2. Usporedba bilance energije kod kondenzacijskog i niskotemperaturnog kotla[22]

Figure 3 shows the qualitative dependency of efficiency on load of different heat generator types. Trends of change of efficiency for standard, low temperature and condensing heat generators are noticeable from the figure. The curve *V* presents characteristic of heat generator produced 30 years ago. Temperature of heating fluid is higher than 75 °C. Highest (best) efficiency is accomplished at maximum load. The curve *IV* shows characteristic of similar heat generator produced 20 years ago. The trend of change of efficiency dependent on partial load for low temperature heat generator of newer generation is presented with the curve *III*. For condensing heat generators, efficiency curves depend on temperature of heating media. The curve *II* is for temperature 75/60 °C and *I* for temperature 40/30 °C.

Heat generators can be divided in three main groups according to the design and operation characteristics: *standard, low temperature and condensing boilers*. Standard boilers have average temperature of heating media higher than 75 °C to avoid potential dew problems. A high loss due to the sensitive heat of flue gasses is the characteristic of these boiler types. The efficiency is about 80 % based to the net calorific value. Low temperature boilers have ability to work continuously with inlet temperature of the heating fluid from 35 to 40 °C. The prerequisite for these boiler types is the adequate heating surface built to avoid the flue gas condensation. This is their main disadvantage because such condition can hardly be attained and maintained. Condensing boilers make possible the use of most heat contained in flue gas. This principle enables the raise of efficiency up to 111 % basing on the net calorific value (when natural gas is used as fuel). Figure 4 shows gains of energy that would otherwise be lost by flue gases.

2.3. General rules for energy efficiency management in heating systems

One of the main contribution to the environment protection is the energy conservation and efficient use. To meet this issue, lots of guidelines and directives have been made. Example for this is Council Directive 92/42/EEC [9] on heat generators with capacity up to 400 kW. Figure 5 shows requirements for all new units that are going to be produced in European Union. Maximum boiler load of 100 % is not usual in practice. It occurs only few times in a year during coldest days. Therefore it is not representative for the energy estimation and validation. The minimum efficiency, in accordance with Council Directives [9], at 30 % partial load includes characteristic behaviors of units during the operation and standby losses, too.

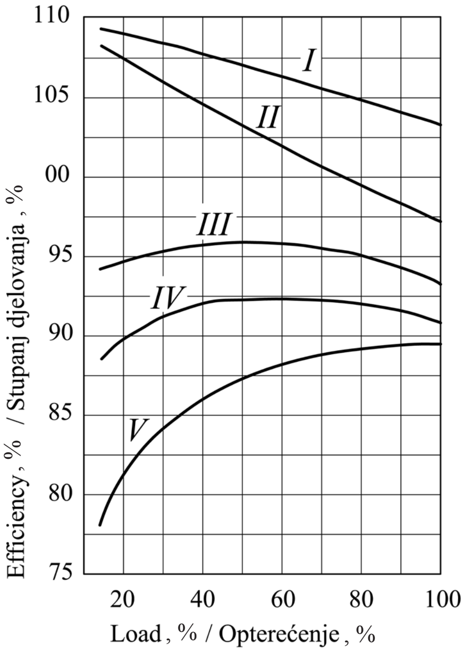

Figure 3. Efficiency depending on heat generator load [14]
Slika 3. Stupanj djelovanja kotla u ovisnosti o opterećenju [14]

3. Consumption of heat in heating systems

Standard DIN 4701 prescribes the calculation method for annual consumption of heat for buildings. This calculation is based on maximum heat losses of house during one hour (Q_N). Total annual need for heat determinates consumption of energy i.e. of fuel. The fuel consumption depends on many factors such as: type and quality of heat loss protection (type of wall building materials, outside insulation and class of windows), the heat value of fuel (gas, oil, wood, biomass,…), efficiency of heat generator, pipeline losses, quality of control system, discontinuance during operation period, heat accumulation of building and specific user needs (higher room temperature, summer heating,…).

The annual consumption of heat, according to standard DIN 2067, can be determined approximately by the following expression:

$$Q_a = b_v \cdot \dot{Q}_N , \tag{2}$$

where b_V is number of working hours of heating system per year and $\dot{Q}_N$ standard required heat according to DIN 4701.

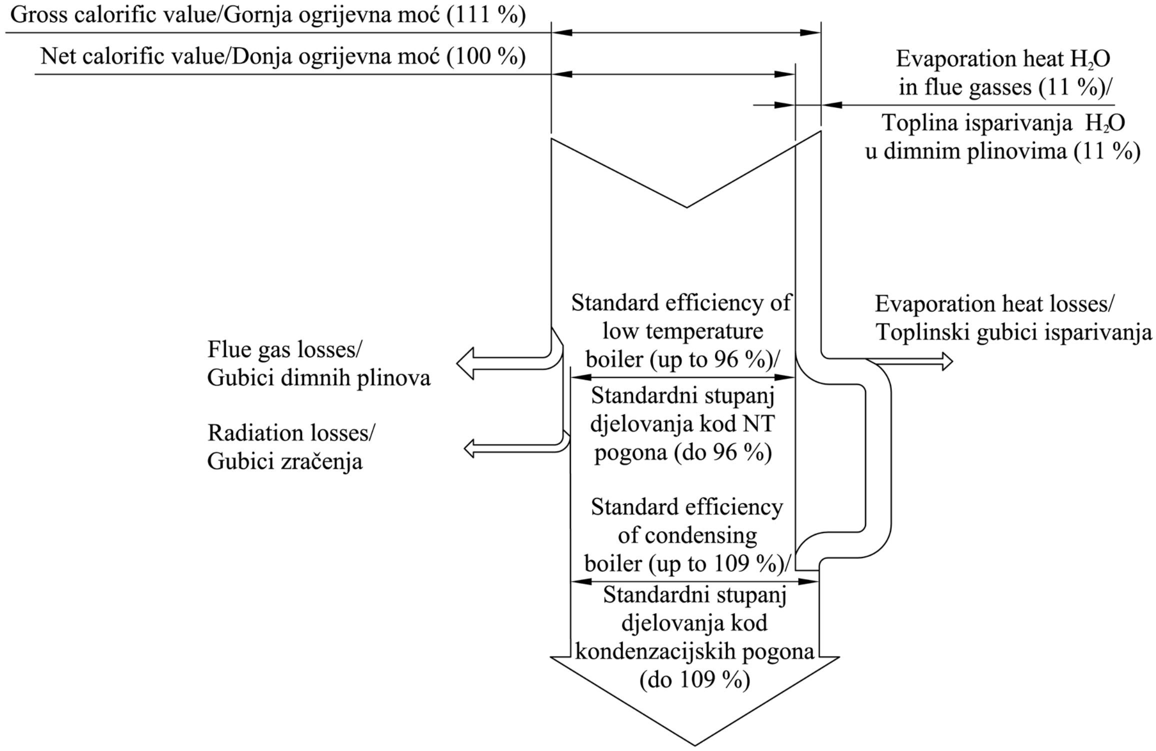

Figure 4. Energy balance diagram for condensing heat generator [13]

Slika 4. Dijagram toplinskog toka kondenzacijskog kotla [13]

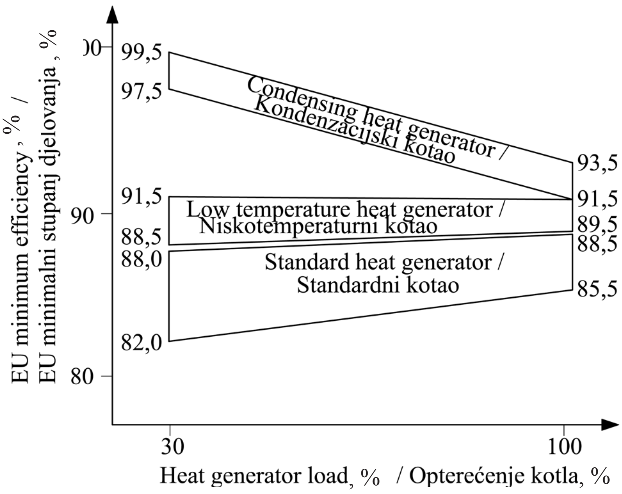

Figure 5. EU requirements for efficiency at rated output [9]

Slika 5. EU zahtjevi za stupanj djelovanja pri određenom opterećenju [9]

Technical directive on energy saving and heat losses reduction in buildings [9] provides in appendix "E" tabular overview of meteorological values, geographical position and altitudes for referent places. In the numerical example, presented in this paper, referent values for town of Rijeka have been considered.

For the purpose of this analysis and comparison of fuel consumption for different combination of heating systems, a system with total load of 2,4 MW has been chosen. The system starts to operate if average outside temperature falls under 12 °C during two days consecutively. By this directive, depending on weather conditions, the heating period starts around 1st of October and ends around 15th of April. The heating load distribution is shown on Figure 6. The operation of eight hours per day is assumed.

The total number of degree-days and degree-hours, defined by preceding calculation, corresponds to those prescribed by standard DIN 4701. It is easy to notice that the greatest number of working hours belongs to the heat load range between 20 and 60 %. Obtained results correspond well to examples from practice.

4. Analysis of heating system efficiency

Figure 7 shows a simplified scheme of heating system with four heat generators in the parallel connection. The advantage of this connection is the modularity of the system. The market already offers systems of automatic control for more than ten units. The scheme presents two secondary heating circles and a simplified system of automatic control.

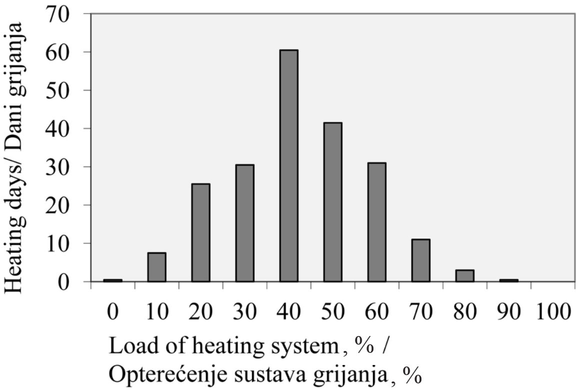

Figure 6. Load distribution during one year's season of heating

Slika 6. Distribucija stupnja opterećenja tijekom godišnje sezone grijanja

For the purpose of this paper, the heating system of 2,4 MW has been considered. An analysis has been made for standard, low temperature and condensing heat generators. First calculation has been made for a referent system with installed only one heat generator covering all needs for energy (total system power of 2,4 MW). Comparison has been made with systems composed of two units (2 x 1,2 MW), three units (3 x 0,8 MW) and finally four units (4 x 0,6 MW). As input parameters for this analysis, same efficiency have been taken for all sizes of heat generators, corresponding to catalogues of Buderus [22] and Viessmann [15].

4.1. Case analysis of standard heat generator

Figure 8 shows the dependency of efficiency on partial load for standard heat generators. Values change from 78 % up to approximately 90 %.

Results presented in Table 1 show savings with the use of various numbers of units in periods of one, five and ten years. The use of lower capacity units is economically justified due to increase of total efficiency. The stage sequencing control is supposed to run units with the optimum load distribution. The investment cost is neglected in this analysis. The additional advantage is smaller number of working hours per each heat generator because the control system can change the leading heat generator in predefined periods.

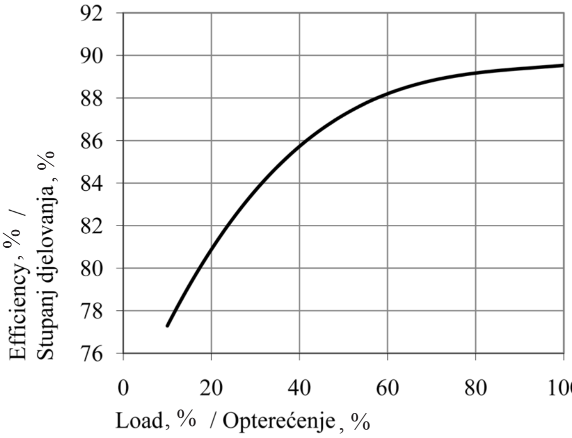

Figure 8. Efficiency curve of standard heat generator [22]

Slika 8. Krivulja stupnja iskoristivosti standardnog kotla [22]

4.2. Case analysis of low temperature heat generator

Modern low temperature heat generators achieve better efficiency due to several reasons. Surface heat losses are lowered to less than 1/10 of older standard type heat generators by the use of weather-compensated digital boiler circuit control and of high effective heat

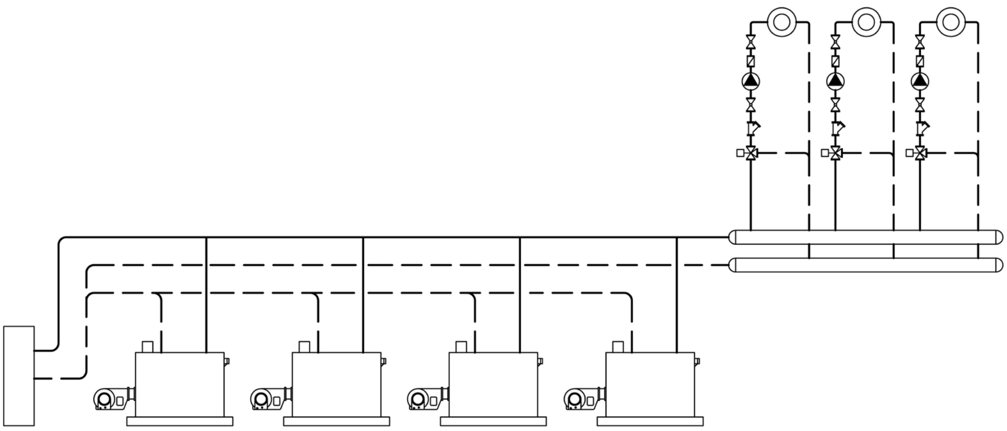

Figure 7. Basic scheme of heating system with four heat generator units

Slika 7. Osnovna shema sustava grijanja s četiri kotla insulation. This type of digital control is guided by modern regulation circuit so hot water temperature can be adjusted accordingly to claimed temperature. Figure 9 shows the dependency of efficiency on partial load for low temperature boilers of different capacities. The graph displays minor decrease of efficiency on higher partial loads. The value varies from maximum of 95 % to approximately 92 % for the highest load.

was that the condensation heat generators, regardless to their advantages, should be compared directly with heat generators of different construction types and the test results for both types should share the same equations as opposed to this article where condensing heat generator is distinguished from low temperature heat generator.

In condensing heat generators the steam condensation is desirable and the design of heat generators and flue gas system are made in a way to avoid possible troubles caused by condensate. In cases of smaller partial load the heat generator efficiency gets higher values according to Figure 10.

The efficiency of condensing heat generator depends on hot water temperature. Figure 10 shows typical behavior of efficiency depending on load for that type of heat generators. In case of floor heating, when high heating water temperature is not needed, the heat generator can work with the most efficient mode. Effects with heating water temperature in the range of 90 /70 °C are obtainable in operation with small par load of boilers.

Table 1. Annual savings by use of up to 4 heat generators

Tablica 1. Ušteda pri radu sustava s najviše 4 kotla

Number of heat generators/ Broj ugrađenih kotlova	Consumption of fuel/ Potrošnja goriva, m^3	Fuel costs/ Trošak goriva, kn	Saving (1 year)/ Ušteda (1 godina), kn	Saving (5 years)/ Ušteda (5 godina), kn	Saving (10 years)/ Ušteda (10 godina), kn	%
1 unit	214614	446 398,00	0	0	0	0
2 units	209411	435 575,00	10823	54113	108226	2,42
3 units	209174	435 083,00	11315	56575	113150	2,53
4 units	207304	431 193,00	15205	76025	152050	3,41

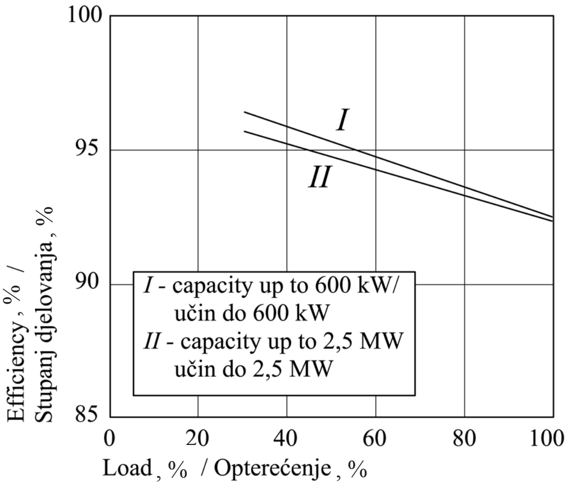

Figure 9. Efficiency curves of low temperature heat generators [22]

Slika 9. Stupanj djelovanja niskotemperaturnog kotla [22]

4.3. Case analysis of condensing heat generator

One of the main topics for discussion, during SEDBUK project (The Seasonal Efficiency of Domestic Boilers in the UK - method of assessing energy efficiency developed under The Government's Energy Efficiency Best Practice Programme with the cooperation of boiler manufacturers [20]) was whether to introduce a new category for condensation heat generators and distinguish them from low temperature heat generators. The conclusion

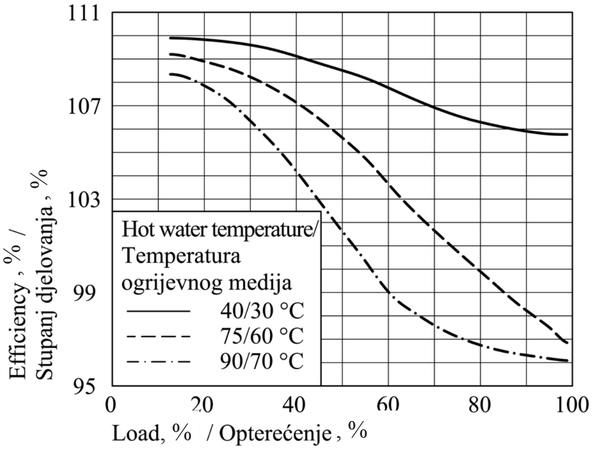

Figure 10. Efficiency of condensing heat generator [13]

Slika 10. Stupanj iskoristivosti kondenzacijskog kotla [13]

5. Conclusions

This paper presents economical validation of more standard heating units in parallel operation and guided by stage sequencing control. Such conditions justify the introduction of a separate small capacity heat generator as summer heating units (boiler with capacity sufficient for summer operation). Units with smaller capacity achieve nominal loads more often and the higher efficiency comes together with the higher partial load. An additional advantage in this case is also due to smaller number of working hours per each boiler.

Comparing to the standard heat generator, low temperature and condensation heat generators achieve higher efficiency at lower load. The efficiency of approximately 96 % can be reached at partial load of 30 %. Raising of load, the efficiency slowly decreases to 92 %. In this analysis, only one low temperature boiler has been selected for all heat loads. Similar results of fuel consumption are obtained by systems with one, two, three and four low temperature heat generators.

Benefits of exceptional construction of condensing and modern low temperature heat generators comparing to standard heat generators are accomplished in several ways. The main improvements becomes due to better performances achieved by decreasing of flue gas heat losses and by optimized digital control. As a benefit of fuel consumption decreasing, environment effects have also to be added especially due to proportionally lower emission of CO_2 and NO_x into atmosphere.

The conclusion from results of this analysis is that there are no economical reasons for modularity of systems consisting of low temperature heat generators. The main reason for such implementation would be the enhancement of whole system (to decrease possibility of breakdown of the system due to single boiler unit). Such implementations bring higher investment and maintenance costs. The use of separate summer unit is also questionable because of higher efficiency of low temperature and condensing heat generators at lower load. Advantages of modular built systems with several heating generators arise in systems for special purposes, when the operation availability and safety have to be assured (important institutions, hospitals, nursing homes and others).

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