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BUILDING HEATING SOURCE CHOICE USING EXERGOECONOMIC APPROACH

Introduction

Energy saving is the one of the most promising direction of state policy development, that can provide the solution of a number of economical and ecological problems as well as sustainable development conditions. Residential and municipal sector consumes a large part of energy around the world in general and specifically in Ukraine (about 33%) [1]. Major part of fuel and energy resources consumption is accounted for natural gas – 57.61% and thermal energy – 19.12% [1]. Since Ukraine is the importer of natural gas, the improvement of the energy efficiency is the promising direction of residential and municipal sector development. The principle of decentralization on the basis of distributed generation [2] is ultimate for the development of residential and municipal sector heat supply system [3]. In this context the heat source selection is important as well as consideration of building along with heat source. As regards building as the energy system [4, 5], which includes heat source, exergy analysis has got widespread use in this direction [6-8]. Combination of exergy and ecology enabled the development of the new discipline exergoecology and the exergy flows cost estimate gave rise to exergoeconomics. Special "hybrid procedure" of exergetic processes flow optimization – "thermoeconomics" was developed in the USA by M. Trybus and R. Evans [9]. Exergoeconomics (thermoeconomics) is the unique combination of exergy and cost analyses, where the principle of exergy cost is applied [10]. Basic terms within exergy and exergoeconomy analysis are: fuel exergy, product exergy, destruction of exergy and exergy loss. Definitions, terms and common denominations used within exergy and exergoeconomy analysis are identified in [11]. Exergoeconomics is frequently used for buildings and heat sources in particular for geothermal heat supply system [12], for heating systems [13]. The specific energy cost method SPECO gained widespread application analysis of exergy flows in buildings [14]. The author [15] has placed greater focus on three stages of SPECO method namely: 1) exergy flows assessment, 2) definition of the terms "fuel" and "product", 3) cost balance estimation and additional equations.

Exergoeconomic analysis evolution is identical to exergy one and has developed in emergence of modern exergoeconomic analysis (ALEXERGO) [15]. This method was used for assessment of the system with LNG regasification plant and electric generator unit [17] and characteristics estimation of essential heating system components in the building [16] and in other works.

So, thermoeconomic analysis makes it possible to determine the cost of exergy losses in the building. Comparison of investment and operational costs, maintenance costs on the one hand and exergy dissipation costs on the other hand for essential components is urgent for development of design and engineering solutions that are likely to improve cost efficiency of the whole system. In view of thermoeconomic analysis development for the building integrally, the application of this approach to complex heat source and building envelope selection is a necessity.

Objects and methods

The main objective of this work is the applying the exergoeconomic approach for complex selection of heat source and building envelope. The principle of energy and exergy flows complex analysis is widely used around the world, so it is suggested to realize a comprehensive approach to the heat source selection, considering the building envelope. Figure 1 displays the scheme of exergy cost flows for various heat sources (electric and natural gas boiler, electric floor heating and heat pump).

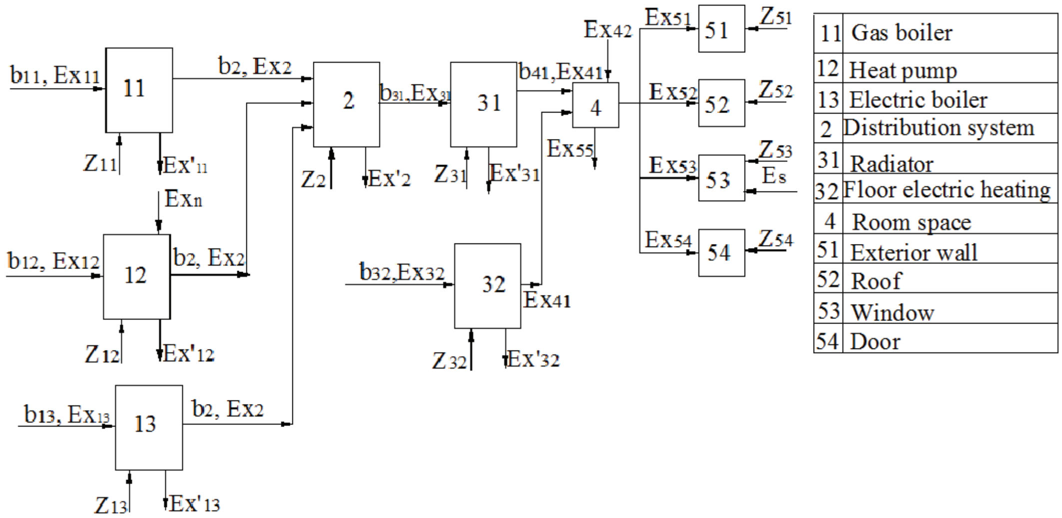

FIGURE 1. *Exergoeconomic model of building with different heat sources: Ex – input exergy, Ex' – exergy loss, b – specific exergy cost, Z – capital maintenance costs*

The feature of thermoeconomic analysis is that cost value is given to each of the exergy flows. So, taking into account the cost of exergy for input and output substance flows *E'* and *E''*, mechanical energy *W* and heat exchange *Q* respectively following interrelations will be used [18]:

$$C' = b' \cdot E' \quad (1)$$

$$C'' = b'' \cdot E'' \quad (2)$$

where: *C'*, *C''* – cost of input and output exergy flows respectively; *b'*, *b''* – average cost of exergy unit in standard units per GJ.

The calculation of the input and output exergy flows is carried out in accordance with the approach described in [19]. Exergy of heat flow is calculated by taking into account the temperature factor [19] and exergy consumption, taking into account relevant factors [20].

Cost balance within thermoeconomic analysis for system components:

$$\sum C_i'' = \sum C_i' + Z_i \quad (3)$$

Thermoeconomic evaluation of the energy system is associated with identification of the following characteristics for each component [18]: 1) exergetic efficiency of heat sourse ε_k, 2) exergy destruction, E_D, and exergy losses, E_L, 3) capital cost Z_k, operational and maintenance costs Z_e, and total cost, *Z*, 4) exergy dissipation cost, Z_D, 5) relative costs difference, r_k, 6) exergoeconomic factor, $f_k = \dfrac{Z_k}{Z_k + c_{P,k}(E_{D,k} + E_{L,k})}$.

For heat source selection along with building envelope it is proposed to analyze following characteristics: 1) exergy efficiency for heat source, 2) specific cost of exergy consumed by the system, 3) investments, 4) cost of the exergy unit lost through the building envelope.

Exergetic efficiency of heat source can be calculated as follows [21]:

$$\eta_{ex} = 1 - \frac{Ex_{1i}^{D}}{Ex_{1i}} \quad (4)$$

where: Ex_{1i}^{D} – exergy destruction in the heat source; Ex_{1i} – fuel exergy, consumed by the heat source.

Balance equation for system exergy cost can be written in the following form [22]:

$$b_5 \sum_i Ex_{5i} = \sum_j b_{1j} Ex_{1j} + \sum Z \quad (5)$$

where: b_{1j} – cost of fuel exergy flow for the "heat source – building envelope" system, \$/kWh; b_5 – cost of product exergy flow, \$/kWh.

According to equation (4) the cost of product exergy flow for the system is:

$$b_5 = \frac{\sum_j b_{pj} Ex_{pj} + \sum Z}{\sum_i Ex_{5i}} \quad (6)$$

where: b_p – cost of the fuel exergy unit, which enters the system; Ex_p – inlet fuel exergy; Ex_5 – exergy, lost by the building through building envelope and for ventilation; j – heat source.

Capital cost for building envelope improvement is defined using the following equation [23]:

$$Z_5 = \sum_i (A_i + B_i \cdot F_i) \cdot \lambda \cdot R_i + \sum_j (A_j + B_j \cdot F_j) \cdot R_j \quad (7)$$

where: A_i, A_j – coefficients, which define the cost of thermal insulation installation and the building envelope type, which are subject to replacement respectively, \$/m, \$·W/m²·K; B_i – coefficient, which includes isolation material cost, normalized to its thermal resistance, \$/m³; B_j – coefficient, which includes cost of the building evelope which are subject to replacement normalized to its thermal resistance, \$·W/m⁴·K; λ – insulation material thermal conductivity, W/m·K.

Capital cost for heating system for building envelope thermal resistance changes:

$$Z_1 = i_0 \cdot P \quad (8)$$

where: P – necessary heat source capacity, kW; i_0 – cost value per unit of heat source capacity, \$/kW.

Cost of the product exergy flow is the major thermoeconomical optimum indicator of the heat pumps operation [22]. The majority of researchers define thermoeconomic characteristics for one hour equipment operation [14-17]. In this case a time interval equal to heating period is analyzed, considering the specifics of providing thermal comfort in the "heat source – building envelope" system. The cost of the product exergy flow for the system is chosen as a thermoeconomical optimum indicator of the building:

$$b_5 = \frac{b_p E_p + \sum_j Z_j \cdot k_j}{\sum_i E_{5i}} \quad (9)$$

where: k_j – equipment cost payments parts [24]; j – the system element, for which capital expenses are considered; E_{5i} – exergy losses through the building envelope and ventilation.

The cost of consumed exergy normalized per production unit is widely used in thermoeconomic analysis [14, 15, 18]. Considering the fact that exergy in the buildings is consumed through building envelope and ventilation to provide adequate thermal comfort conditions, it is possible to estimate average cost of exergy unit, that is consumed by the building not during the heating season, but during specific time period that is equal to the time of heating system operation. This approach allows considering change of the cost of consumed energy resources over time and the thermoeconomical optimum indicator of the building can be calculated in the following way:

$$b_5' = \frac{\sum_{t=1}^{n} \frac{b_p E_p (1+l_i)^t}{(1+E)^t} + \sum_n Z_{k.i} \cdot k_i + \sum_n \frac{Z_{e.i}}{(1+E)^n}}{\sum_n E_5} \quad (10)$$

where: n – depth of calculation, years; $Z_{i,j}$ – capital expenses on each section of thermoeconomic model, \$; E – discounting rate is taken to be 0.22; l– rate of increase for energy prices. For gas it is 0.3, for electricity – 0.2.

Research model

In order to analyze the cost of exergy flows, which are lost by the building with various heat sources, research object is taken as energy supply system in the room 4×4 m as the part of building, built in 80s in Kyiv. The room model is equipped with heating system and devices so capital expenses for them will not be considered. So exergy and thermoeconomic characteristics will be defined during improvement of building envelope thermal resistance and heat source change. Let us consider four variants of building envelope: 1) meets standards of 80s, 2) standards of 90s, 3) standards of 2008, 4) standards of 2016. For comparison and analysis following heat sources have been chosen: natural gas boiler, condensation natural gas boiler, electric boiler, cable electric heating and heat pump. Among various types of heat pumps (HP) the "air – water" HP type with average energy efficiency COP = 3 has been chosen. All cost indicators are presented in US dollars because of unstable exchange rate for the 10.29.2016. Design conditions are presented in Tables 1-3.

TABLE 1. *Heat source parameters*

Heat source	i_0, $/kW		*t*, year*		*k*
Natural gas boiler	35		10		0.063
Condensation natural gas boiler	40		10		0.063
Electric boiler	30		10		0.063
Heat pump	600		10		0.063
Electric floor heating	80		10		0.063
Thermal insulation	A_i	B_i	λ	t	k
	3	30	0.05	30	0.006
Window	A_j	B_j	t	k	
	8	80	30	0.006	

* *t* – useful lifetime of system elements

TABLE 2. *Energy supply cost (2016)*

Energy supply type	Energy unit cost	Exergy unit cost
Gas	0.0298 $/kWh	0.0271 $/ kWh
Electricity	0.0273$/ kWh	0.0273$/ kWh

* prices are presented with regard to energy consumption per month.

TABLE 3. *Building parameters*

Building envelope	Area, m²	*R*, m²·K/W			
		80-s	90-s	2008	2016
External wall	6.25	0.8	2.5	2.8	3.3
Window	3.75	0.17	0.5	0.6	0.75

Results and Discussion

The exergoeconomic method is used for the building in general and specifically for heat source. The exergoeconomic results are presented in Table 4. The highest exergetic efficiency is typical for heat pump; the lowest one for cable heating and the indicators of specific exergy consumption by the building during heating period are the lowest for system with heat pump and the highest for system with natural gas boiler. This kind of difference is due to the quality factor of input flow of heat, which is determined by the temperature. The temperature of input heat flow for different heat sources was taken according to [19]. At the same time the heat pump cost is the highest and the cost of electric boiler is the lowest.

TABLE 4. *Exergoeconomic indicators of the system*

Exergoeconomic results of the system	Exergy efficiency of heat sourse, ε_k	Specific exergy, consumed by system during heating period kWh/m²				Capital cost Z_{1j}, $				Thermoeconomical optimum indicator b'_5, $/kW·h			
		Ex.1 *	Ex.2	Ex.3	Ex.4	Ex.1	Ex.2	Ex.3	Ex.4	Ex.1	Ex.2	Ex.3	Ex.4
Natural gas boiler	0.193	239.47	138.11	128.39	117.57	48.125	31.78	30.215	28.455	0.758	0.669	0.657	0.641
Condensation natural gas boiler	0.201	182.65	105.34	97.93	89.67	55	36,32	34.532	32.52	0.615	0.544	0.534	0.523
Electric boiler	0.24	195.73	112.88	104.94	96.09	41.25	27.24	25.899	24.39	0.384	0.342	0.334	0.33
Heat pump	0.603	64.13	34.47	30.10	26.14	825	544.8	517.98	487.8	0.349	0.331	0.325	0.321
Electric floor heating	0.179	161.33	93.04	86.5	79.2	110	72.64	69.064	65.04	0.337	0.303	0.299	0.294

Ex.1 – thermal resistance of building envelope meets standards of 80s; Ex.2 – standards of 90s; Ex.3 – standards of 2008; Ex.4 – modern standards.

To resolve differences between exergy and economic characteristics the thermoeconomic optimum criterion is defined. Figures 2a and 2b display calculation data of b_5 to b_5' respectively. In accordance with attained results it is obvious, that system with cable heating has the lowest general cost of exergy unit, consumed by the building and system, while autonomous natural gas boiler and electric boiler have the highest one.

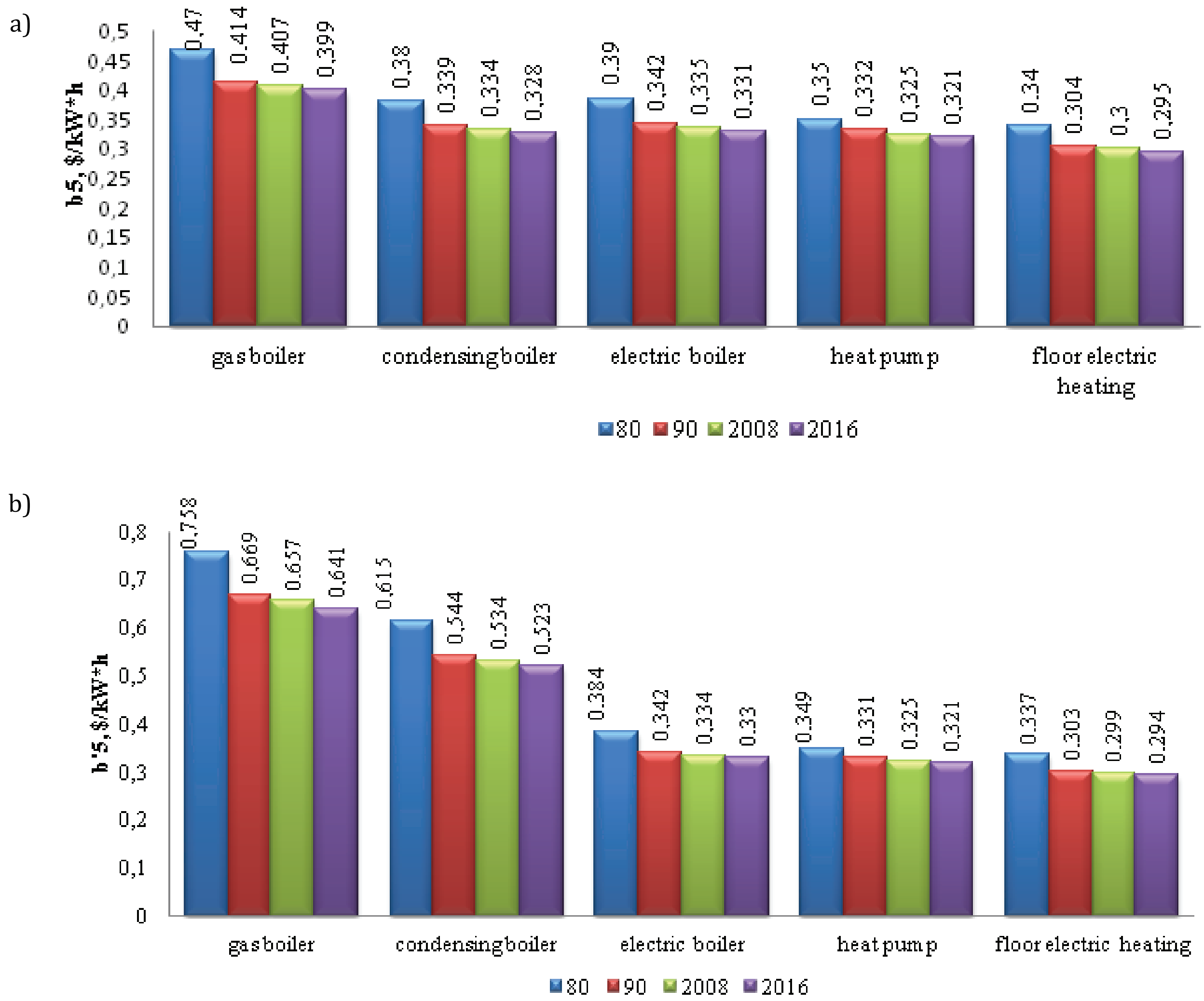

FIGURE 2. Exergoeconomic results of the system "heat source – building envelope": a) thermoeconomical optimum indicator for heating period, b) thermoeconomical optimum indicator for n = 10 years

Thermoeconomical optimum indicator that takes into account the rate of energy prices increase during 10 years (Fig. 1b) for system, which consumes gas is higher in comparison with systems, which consume electric energy, that is caused by higher increment of gas price. Indicator, calculated for ten years period, in absolute value is larger than the idicator determined for the heating period for systems that use gas fuel.

Proposed exergoeconomic indicators allow defining the cost of exergy unit, lost through the building envelope: first – during heating period; second – during 10 years time period. The specific feature of the last one is that the heat source selection can be made along with the building envelope consideration; and it takes into account the rate of energy prices increase over time.

Conclusions

In this study, exergoeconomic analysis to a system "heat source – building envelope" was applied. There are following conclusions according to research results:

1. The highest exergetic efficiency is typical for heat pump; the lowest one for cable heating and the indicators of specific exergy consumption by the building during heating period are the lowest for system with heat pump and the highest for system with natural gas boiler. This kind of difference is due to the quality factor of input heat flow, which is determined by the temperature. At the same time the heat pump cost is the highest and the cost of electric boiler is the lowest. To resolve differences between exergy and economic characteristics the thermoeconomical optimum indicator is defined.

2. Two exergoeconomic indicators for complex selection of heat source and building envelope are proposed.
3. First criterion defines cost of exergy consumption for providing comfort conditions inside the building for heating period. The highest value is typical for system with natural gas boiler and the lowest one – for cable electric heating. The improvement of building envelope thermal protection causes the criterion decrease, that is related to consideration of different lifetime of heat sources and building envelope by means of coefficients *k*.
4. Second criterion evaluates the cost of exergy consumption for providing comfortable conditions inside the building for 10 years and allows to take into account the rate of energy prices increase over time by means of coefficient. The highest value is typical for system with natural gas boiler and the lowest one – for cable electric heating.

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