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THE INFLUENCE OF THERMO-MODERNIZATION ON THE LOW-STACK EMISSION REDUCTION – A CASE STUDY OF A SINGLE-FAMILY HOUSE

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Abstract

In the article, technical and ecological analyses of thermo-modernization of a single-family house located in Kraków and the adaptation of the building to the current regulations were made. The parameters of the energy performance of the building before and after thermo-modernization were presented. For calculating the *U-factor* of building partitions and the heat demand for the building, the Sankom Audytor HL (OZC) software was employed. The Sankom Audytor ECO 1.0 software was utilized to calculate ecological assessment. In the case of existing buildings subject to thermo-modernization, it is practically challenging to provide a building with a level considered to be energy efficient without introducing additional system solutions in the building's internal installations as well as using highly efficient renewable energy sources. Due to the constantly growing requirements of the Technical Conditions in the area of limiting the consumption of heat carriers and reducing the U coefficient, thermo-modernization is one of the most important stages of decreasing the building's demand for primary energy.

Keywords: thermo-modernization, low-stack emission, ecological effect

INTRODUCTION

The impact of a single-family building on air quality is subject to the type, quantity and quality of fuels used for heating purposes and the method of their combustion. The amount of fuels burned may be reduced by improving the energy efficiency of a building and the degree of use of dispersed and available renewable energy sources (Oleniacz *et al.* 2016). Currently, high costs of heating buildings result from disproportionate energy consumption. Until now, no special attention has been paid to the amount of energy consumed, and its main cause was the excessive heat loss. Most of the buildings in Poland are thermally insufficiently insulated. In the past building regulations placed little demands in this area, and even these minimum requirements were often not met. Therefore, the 'shell' of numerous buildings, i.e. external walls, ceilings of the top story (under the attic) or flat roofs let much more heat through than it is currently required. Significant heat losses are also caused by windows that are generally of low quality and rather not air-tight (Robakiewicz 2002). Reducing the energy demand in single-family housing is possible by increasing the energy efficiency of a building and the degree of use of prosumer energy based on dispersed and locally available renewable energy sources. As the most appropriate solution for buildings with low thermal insulation Oleniacz *et al.* (2014) see in the implementation of comprehensive thermo-modernization. This will result in better comfort of living due to the fact that the heat transfer coefficient (*U*) will be improved, the aesthetics of the building (façade, external window and door joinery) will be enhanced, which will also affect the higher sense of satisfaction of the building occupants (Foryś 2006, Jędrzejuk and Wieczorkiewicz 2013).

According to the Directive of the European Parliament and of the Council 2012/27/UE of October 25, 2012 energy efficiency should be understood as the ratio of the obtained size of the utility effect of a given facility, technical device or installation on typical conditions of their use or operation, to the amount of energy consumption by this object, technical device or installation. The entities responsible for the implementation of tasks in the field of energy efficiency and reduction of low-stack emission, from the point of view of the legislation in force in Poland, are primarily public sector entities responsible for initiating, financial support and control of activities in this area (Kaczmarczyk 2017).

The Act of November 21, 2008 on supporting thermo-modernization (Journal of Laws No. 223 item 145) and refurbishment defines thermo-modernization projects as "improvement, which reduces the demand for energy supplied for heating and DHW heating and heating of residential buildings, collective housing buildings and buildings owned by local government units which are utilized to carry out public tasks. Kasperkiewicz (2018) and Ostańska (2016) report that the thermo-modernization of a building is „a set of activities aimed at reducing the energy consumption of buildings erected earlier”. The European directive on the energy performance of the building, its original version and the amended one show that it is technically possible to reduce energy consumption for heating, air conditioning and heating water in residential buildings and in other buildings also for lighting without reducing the comfort of use. Thermo-modernization of residential buildings is an interdisciplinary problem whose effective solution requires the use of knowledge from various fields such as Architecture, Building Construction, Thermal Physics of the Building, Heating, Materials Engineering, Economics, and in some cases also Heritage Preservation. The scope of thermo-modernization is determined by an energy audit conducted. The energy audit should be understood as “a study defining the scope and economic and technical parameters of a thermo-modernization project” (Dzikuć 2017).

The most frequently carried out activities as part of thermo-modernization include: insulation of external walls, roofs, flat roofs, roofs over unheated basements, floors laid on the ground, replacement of window and door joinery, replacement or modernization of heating systems, modernization or replacement of the hot water supply system, improvement of the ventilation system, implementation of devices using energy from renewable sources (Dzikuć 2017).

Thermo-modernization brings many benefits, including in particular: social benefits which reduce energy poverty: energy-efficient houses and flats provide thermal comfort for families with low income and health benefits: improvement of air quality, comfort and standards of living in thermo-modernized flats result in a decrease in the morbidity of users, which in turn results in reduction of treatment costs and sick leave periods. The environmental benefits of reducing carbon dioxide emissions cannot be ignored. Energy-efficient buildings do not require as much energy as before modernization, which significantly reduces CO_2 emissions to the atmosphere. The reduction of air pollution is caused by reducing the demand for energy produced from fossil fuels (Koc *et al.* 2014).

According to Kryk and Kaczmarczyk (2016), any thermo-modernization investment that saves natural resources, increases energy efficiency and reduces pollution is from a social point of view desirable and even expected.

There are also barriers hindering the development of thermo-modernization. These include too little public support for actions to increase energy saving, the relatively low public wealth and limited financial commitment capacity as well as the poor effect of energy-saving actions taken by households. Low social awareness of the benefits resulting from introducing energy efficiency in households, the lack of educational programs at all levels of education, including the academic level, the lack of qualification development systems in the technical methods and ways of increasing energy efficiency aimed at such professional groups as: engineers, architects, government decision makers and local administration are considered to be socio-economic barriers to effective thermo-modernization (Koc *et al.* 2014).

Emission of fossil fuel combustion products into the atmosphere has been recognized as serious air pollutant. The negative effects of fossil fuel combustion can be completely eliminated using solely the energy from renewable sources or at least partially reduced by increasing the efficiency of energy use (Kasperkiewicz 2018) „Air quality assessments performed by the Provincial Inspectorate for Environmental Protection in Kraków indicate a very poor condition of air quality in Kraków due to exceedance of the permissible levels of PM10 particulate matter, PM2.5 particulate matter and nitrogen dioxide and the target level of benzo(a)pyrene (BaP)" (Resolution No. XVIII/243/16).

Table 1. Emission of pollutants to air from point sources in Kraków in the years 2010-2016

Type of pollutant	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
	Mg·year^{-1}						
sulphur dioxide	8821.9	8450.2	8575.6	7592.0	10900.9	8852.0	3002.8
carbon dioxide	4404363.4	4857325.9	5024383.3	4750963.5	4753222.1	4812139.0	4412646.6
brown coal dust							
carbon-graphite dust, soot	43.1	43.2	41.0	38.8	36.0	38.2	46.3
particulate matter from fuel combustion	806.8	769.6	949.7	838.1	702.7	437.0	274.0
other particulate matter	928.5	3376.0	839.0	739.9	493.4	378.1	336.1
carbon monoxide	16431.5	23198.6	12153.6	6998.5	8897.9	10823.0	8808.0
nitrogen oxides (NO2)	6533.7	6463.9	6354.4	5919.5	7282.6	5353.9	4293.8
ring, aromatic hydrocarbons and their derivatives	46.0	52.5	57.5	51.4	45.5	39.5	40.8

Source: Author's own elaboration based on data obtained from the Provincial Inspectorate for Environmental Protection in Kraków in the public information mode (correspondence dated July 21, 2017)

METHOD AND OBJECT OF ANALYSIS

The aim of the study was to conduct a technical analysis of the implementation of thermo-modernization of a single-family house located in Kraków and the adaptation of the building to the currently applicable regulations. In the developed analysis and thermo-modernization process, the applicable technical conditions set out in the Regulation of the Minister of Infrastructure of April 12, 2002 on technical conditions which should be met by buildings and their location were taken into account (Journal of laws of 2017, item 2285). The Sankom Audytor HL (OZC) software was employed to calculate the *U-factor* (heat transfer coefficient) of building partitions and the heat demand for the building. To determine the ecological assessment, the Sankom Audytor EKO 1.0 software was used.

A single-family house located in Kraków was selected for the analysis. It was a two-story building without a basement, located in residential area, with a building area of approx. 94 m^2 and a usable floor area of 180 m^2. The building was designed and erected employing traditional technology with a brick structure in the 1960s. The load-bearing walls of the building were made of solid, double brick using mortar and covered with lime-cement plaster. Klein's roof was supported by steel tees. The roof truss had a wooden gable structure (impregnated wood). The roof was covered with corrugated sheet.

RESULTS AND DISCUSSION

The basic source of supplying the building with heat was a gas condensing boiler installed in the building just before thermo-modernization. Before planning the thermo-modernization works, a detailed inspection of the building was conducted. Window and door joinery in the tested facility did not meet the current requirements for thermal protection of the building due to the high value of the heat transfer coefficient (*U*) and the evident deformation and permeability. During the inspection of the building and on the basis of the available technical documentation and calculations of the energy performance of the building, it was found that the floor on the ground (concrete screed, building rubble) covered with stoneware tiles was in poor technical condition. In addition, there was neither insulating layer nor water insulation. During the assessment of the technical condition of the building, it was found that it did not meet the requirements of proper thermal insulation, caused by permeable window frames and external partitions. The obtained results of the energy assessment showed that the building did not meet the thermal protection standards. Due to the low primary thermal insulation of the analyzed building, a thermo-modernization consisting of the following items was proposed (Table 2):

- windows replacement,
- external doors replacement,
- insulation of external walls,
- roof insulation.

The building was subjected to thermo-modernization in 2016, while since 2017 monitoring of its effects has been carried out. Characteristics parameters after thermo-modernization were determined based on the carried out analyzes and are presented in Table 2. The analyzes obtained meet the requirements set by the Technical Conditions of 2017 in accordance with the Regulation of the Minister of Infrastructure. Insulation materials available on the market were used. The materials were selected taking into account their thermal conductivity index, the optimized price and the type of partition on which they were going to be applied.

Table 2. Characteristics of the condition of the building before and after thermo-modernization

Elements of the building	Before thermo-modernization	After thermo-modernization
External walls	double solid brick on lime-cement plaster, no insulation, $U=1.22\ W\cdot(m^{-2}\cdot K^{-1})$	double solid brick on lime-cement plaster lime-cement plaster, no insulation, insulation with graphite polystyrene $\lambda=0.031\ W\cdot(m\cdot K)^{-1}$, d=0.12 cm, $U=0.21\ W\cdot m^{-2}\cdot K^{-1}$
Floor on the ground	stoneware tiles, concrete screed, construction rubble, $U=0.57\ W\cdot(m^{-2}\cdot K^{-1})$	stoneware tiles, concrete screed, construction rubble, hard polystyrene $\lambda=0.040W\cdot(m\cdot K)^{-1}$, d=0.06m, $U=0.29\ W\cdot m^{-2}\cdot K^{-1}$
Roof	Simple Klein's slab of 18 cm supported with steel tees, lime-cement plaster, insulation layer of loose blast-furnace slag of 20cm, formwork, corrugated sheet $U=0.87\ W\cdot(m^{-2}\cdot K^{-1})$	Simple Klein's slab of 18 cm supported with steel tees, lime-cement plaster, insulation with graphite polystyrene $\lambda= 0.031\ W\cdot(m\cdot K)^{-1}$, d=0.16m, formwork, corrugated sheet, $U=0.179\ W\cdot m^{-2}\cdot K^{-1}$
Windows	wooden framed, $U=3.0\ W\cdot(m^{-2}\cdot K^{-1})$	hermetic, double-glazing, filled with argon with a low-emission coating $U=1.0\ W\cdot m^{-2}\cdot K^{-1}$
Doors	solid wood $U=3.0\ W\cdot(m^{-2}\cdot K^{-1})$	steel, thermally insulated, $U=1.3\ W\cdot m^{-2}\cdot K^{-1}$
Inter-story slabs	Klein's slab, joists, floor board	Klein's slab, joists, floor board

In order to improve the thermal insulation of partitions, walls were insulated (with graphite polystyrene of the parameters $\lambda=0,031\ W\cdot(m\cdot K)^{-1}$, d=0,12 cm, $U=0,21\ W\cdot m^{-2}\cdot K^{-1}$. The insulation from the outside resulted in the elimination of a thermal bridge, created an even insulation on the entire surface of the partition, reduced the negative wall temperature zone and increased the thermal stability of the wall, as well as helped to remove wall permeability creating a new aesthetic façade of the building (Table 2). The window and door joinery was replaced and the graphite polystyrene 16cm thick with the coefficient of $\lambda=0.031\ W\cdot(m\cdot K)^{-1}$ was used to insulate the building. Corrugated metal sheets were utilized ($U=0.179\ W\cdot m^{-2}\cdot K^{-1}$) for roofing. The cost of thermo-modernization works amounted to PLN 6677.1 (Table 3) The analysis of costs was based on the prices published in the first quarter of 2018 on Sekocenbud.pl website.

Table 3. Summary of investment costs for the thermo-modernization of the object in question

No.	**Insulated element**	**Area [m²]**	**Unit price (Cj) related to the surface of the element [PLN·m⁻²]**	**Cost [PLN]**
1.	Floors	79.9	89	7111.1
2.	Exterior doors	2.1	1333	2800.0
3.	Roof	103.4	47	4859.8
4.	Walls	232.1	122	28316.2
5.	Exterior windows	18	940	16920.0
		Total		60007.1

Cj. contains complex values of material, labor and equipment.

According to Danielak (2014), thermo-modernization actions are only economically justified when the building in question was planned to be renovated, maintained or replaced. For example, the external wall of the building is insulated at the time when the façade of the building is planned to be renovated. The analysis of the profitability of investment in modernization is rather challenging due to the fact that saving energy and operating costs is not one of its positive effects. Environmental protection, due to energy-saving technology, greater comfort of use, modernization of technology, restoration of the building are just some of the additional benefits.

The amount of pollutant emission before and after modernization was determined to assess the environmental effects in the building. Ecological effects (Table 4), which can be obtained as a result of the thermo-modernization of the building, were determined as the difference in the emission of pollutants introduced into the air during gas heating before and after thermo-modernization. The analyzed equivalent (substitute) emission is a general quantity of pollutant emission originating from a specific source of pollution. This quantity results from the sum of the actual emissions of particular types of pollutants coming from this source, multiplied by their toxicity coefficients, in accordance with the formula:

$$E = \sum E_t \cdot K_t \tag{1}$$

where:
E – equivalent emission of emission sources
E_t – actual emission of pollutants with the *t* index
K_t – toxicity coefficient of a pollutant with the *t* index; the coefficient expresses

the ratio of the permissible mean annual concentration of pollutant e_x to the permissible annual mean value of a given pollutant e_t, which can be determined by the formula:

$$K_t = e_x / e_t \tag{2}$$

Pollutant toxicity coefficients were determined in compliance with the Regulation of the Minister of the Environment of January 26, 2010 on the reference values for certain substances in the air Journal of Laws of 2010 No.16 item 87).

Table 4. Summary of basic components of pollutant emissions

Emission / Symbol / Unit			**Toxicity coefficient [-]**	**Emission limit value [$\mu g \cdot m^{-3}$]**	**Before thermo-modernization**	**After thermo-modernization**	**Emission reduction [%]**
equivalent	Er	$kg \cdot year^{-1}$	-	-	218.5	153.04	29.9
total SO_2	ESO_2	$kg \cdot year^{-1}$	1.00	30	3.1	1.4	54.8
total NO2	ENO_2	$kg \cdot year^{-1}$	0.75	40	18.9	12.8	32.3
Total particulate matter	E_{PM}	$kg \cdot year^{-1}$	0.75	40	0.1	0.07	30.1

The conducted analysis made it possible to conclude (Table 4) that the basic source of heat, which was a gas boiler in the building in question, was an ecological source. Although the emission of pollutants has its source mainly in the combustion of gaseous, liquid and solid fuels in order to obtain thermal energy, its size is also significantly affected by the design of the devices and the method of regulating the heating system. Due to the specificity of the combustion process, its main products include: carbon dioxide, water in the form of steam and nitrogen oxides (NO_x). Additionally, due to the fuel composition or in the course of the combustion process and its stoichiometry, sulfur oxides (SOx), carbon monoxide (CO) and soot or other particulate matter may also appear. Natural gas used in the analyzed building for heating purposes is one of the cleanest conventional fuels, which is characterized by a relatively small proportion of pollutants in the case of a proper combustion process.

The thermo-modernization carried out in the analyzed single-family building, consisting in insulation of external walls, replacement of door and window joinery, did not currently meet the applicable requirements of the Technical Conditions for newly erected buildings. However, referring to the Regulation of the Minister of Transport, Construction and Maritime Economy of July 5, 2013 | (§ 328) in the case of a building subject to reconstruction, the fulfillment of the condition of not exceeding the condition of the EP (primary energy) limit value is not obligatory (Journal of Laws of 2013 item 926). Only partitions, which are rebuilt, are subject to the requirements for compliance with the *U-factors*. The necessity to apply modern material solutions (thermal insulation materials) as well as installation systems (renewable energy sources, recuperation, and heat pumps) will be the consequence of the increasing legislative requirements regarding the EP limit value (Table 5).

Table 5. List of demand for particular types of energy before and after thermo-modernization of the building

Energy demand	**Type of energy**	**Unit**	**Before thermo-modernization**	**After thermo-modernization**	**Reduction of energy demand [%]**
Individual demand for usable energy	EU	kWh·m^{-2} year^{-1}	499.4	152.1	69.54
Individual demand for final energy along with auxiliary equipment	EK		575.9	186.6	67.60
Individual demand for non-renewable primary energy together with auxiliary equipment	EP		637.4	208.3	67.32
The unit limit demand for non-renewable primary energy for a building in compliance with Technical conditions 2017	EPWT 2017			95	
The unit limit demand for non-renewable primary energy for a building in compliance with Technical conditions 2021	EPWT 2021			70	

In order to meet the EP requirements for the analyzed building, further thermo-modernization is recommended, involving deep interference in the other components of the EP, i.e. modernization of the heating installation, preparation of hot tap water and recuperation of the ventilation air stream. The scope of these works was not the subject of this study.

CONCLUSIONS

- The results of the ecological analysis presented in the article demonstrate the validity of the thermo-modernization of the building. Once external partitions and window and door joinery meet the requirements in accordance with the applicable technical conditions, it is possible to reduce the emission of pollutants: NO_x and particulate matter into air of up to 30%.
- As a result of the improvement of the parameters of *U* coefficient of the partitions, the parameters of useful energy (EU), primary energy (EP) and final energy (EK) decreased by 67%.
- A comprehensive completion of the entire investment is necessary to verify the effects of thermo-modernization owing to the fact that the unfinished investment, e.g. unregulated boiler room operation or the lack of thermal insulation of the ducts, can significantly affect the amount of fuel consumed.
- Due to the constantly growing requirements of the Technical Conditions in the area of limiting the consumption of heat carriers and reducing the *U* coefficient, thermo-modernization is one of the most important stages of decreasing the building's demand for primary energy.
- In the case of existing buildings subject to thermo-modernization, it is practically challenging to provide a building with a level considered to be energy efficient without introducing additional system solutions in the building's internal installations as well as using highly efficient renewable energy sources.
- The payback period for expenditures incurred for thermo-modernization depends to a large extent on the price of the energy carrier used for heating a building.

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