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IMPACT OF TECHNICAL SYSTEMS EFFICIENCY AND CALCULATION METHOD ON EVALUATION OF BUILDING ENERGY PERFORMANCE AND CARBON EMISSION

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ABSTRACT: This work determines the influence of building technical systems efficiency and uses a calculation method for the evaluation of whole building energy efficiency and carbon emission. Two types of commercial buildings are considered: an office building and multifunctional building and these are examined by two methods to determine the efficiency of the building systems. The analysis was performed for two different thickness of pipes and ducts thermal insulation in a heat distribution system: according to minimum energy saving requirements and with doubled thickness. It was found that selection of the applied calculation method has significant impact on energy efficiency of building services evaluation and as a consequence – on the energy efficiency evaluation of the whole building and its emissivity.

KEY WORDS: building systems efficiency, carbon emission, energy efficiency

 JEL: C6, Q4, Q5

Introduction

It is estimated that the construction market is responsible for the consumption of approx. 40% of the energy generated within the EU, and the pollution emission is on the level of 37% (Broniewicz, 2017; EU, 2010; Lewis et al., 2013), making the construction market one of the most significant, achievable areas for a substantial reduction of energy consumption coming from conventional sources and the emissions resulting from it. On 19 May 2010 a recast of the Energy Performance of Buildings Directive (EU, 2010) was adopted and on 19 June 2018 the directive (EU, 2018) was published. The first directive revision strengthened the energy requirements for new and existing buildings and their systems. The second one introduces targeted amendments to the directive aimed at accelerating the cost-effective renovation of existing buildings, with a vision of a decarbonised building stock by 2050 and the mobilisation of investments.

A technical building system is a combination of equipment, accessories, means of interconnection, operations, and controls that use energy to perform a specific function. Examples include HVAC (Heating, Ventilation, and Air Conditioning), water heating, lighting, thermal envelope, and miscellaneous electrical load systems. Energy efficiency of the system is defined as the ratio of the functions or services provided by a building system to the amount of energy that system consumes. The thermal load imposed on (or thermal energy contributed to) other building systems are also taking into consideration. The systems efficiency is one of the strategies used to implement whole building design, but highly efficient components do not necessarily result in an efficient building. Substantial savings on the building technical systems are dependent on the efficiency of the building in general. The potential for savings in HVAC systems might be reduced by higher requirements for the building envelope (Lausten, 2008). Optimized building efficiency therefore requires consideration of the interactions among components (services) and with the building, and equipment and heat distribution systems insulation should be chosen so that the losses would be as low as possible (Romanova, 2016).

Energy used for space heating, ventilation and space cooling (air conditioning) systems represent over 50% of building energy demand in cold climates (Bøhm, 2013; Klimczak, 2018), such as the climate of Poland. HVAC systems are by far the largest users of energy in commercial buildings, therefore in order to optimize energy use, we must consider specifying efficient HVAC systems to include efficient distribution, controls, accumulation and efficiency of heat sources (exchangers). Building Codes will often address the efficiency of the system in general and of the components of the system. In the majority of the EU countries the technical building requirements on energy saving include direct references to specific standards (Pedro et al., 2010). Under Polish building law (PL, 2002), basic energy requirements address the HVAC distribution efficiency and are defined in two ways: as a basic requirement determined by the minimum thickness of thermal insulation for pipes and ducts (PL, 2002), and from the whole building efficiency in case of the index of the building energy performance (PL, 2015). Similar requirements are formulated in other EU countries, such as in Finland (FIN, 2002; FIN 2011, Romanova, 2016).

This paper deals with the analysis of the influence of the building technical systems efficiency and used calculation method on evaluation of whole building CO_2 emissions and energy efficiency. The analysis was performed taking into account two simplified methods: a flat-rate method and more advanced one, related to the outer diameter of the pipes and ducts and the thickness of the pipes and ducts thermal insulation. Both methods are given by (PL, 2015), and are similar to those used in other countries, for example, in Finland (Romanova, 2016).

In the flat-rate method used in Poland, it is assumed that the heat losses from heating pipelines can be partially recoverable, so they range from 0 to 25% of useful heating demands (PL, 2015). In comparison, according to Finnish National Building Code, they are taken as zero (FIN, 2011; Romanova, 2016). The second method takes into account a number of parameters affecting the efficiency of the heat distribution system, such as: supply and return temperature of the medium, nominal diameter of the pipeline, thickness and thermal conductivity of the insulation material, total length of the pipeline, shut-off fittings and ambient characteristics.

An overview of literature

Due to buildings high energy consumption introduction of energy efficient strategies is essential to achieve the targets defined by the EPBD-recast (EU, 2010) regarding energy efficiency and reduction of carbon emission. Some of works are focused on the improvement of thermal insulation of building partitions in existing and new buildings, bypassing the impact of the efficiency of technical systems on total energy consumption, for example (Boeri et al., 2013; Silva et al., 2013) or (Tanasa et al., 2013).

The energy losses caused by distribution system can be reduced in the two basic ways: limiting heat loss by thermal insulating the pipelines and operation correction of system ensuring the required temperature of the medium (Klimczak et al., 2016). Most of authors focused their investigations on improving energy efficiency of district heating networks (Čarnogurská et al., 2016a; Pellegrini et al., 2018; Yang et al., 2018) or on hot water circulation systems, for example (Klimczak et al., 2016).

The mathematical model of heat losses from insulated pipes has been described by McNabb and Weir (McNabb et al., 1980). According to (Čarnogurská et al., 2016a, 2016b; Morvay, 2008) pipeline heat losses per one meter of insulated pipe can be presented by the formula:

$$\frac{Q}{L} = \pi \cdot D_3 \cdot U \cdot \left(T_{in} - T_{out}\right). \tag{1}$$

The relation describing the coefficient U can be written in the form (Klimczak et al., 2016):

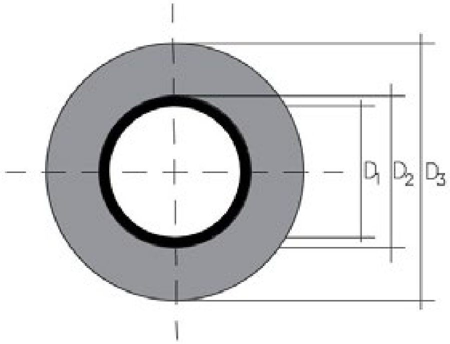
$$U = \frac{1}{\frac{D_3}{D_1 \cdot h_{in}} + \frac{D_3 \cdot \ln\left(\frac{D_2}{D_1}\right)}{2 \cdot k_{pipe}} + \frac{D_3 \cdot \ln\left(\frac{D_3}{D_2}\right)}{2 \cdot k_{insulation}} + \frac{1}{h_{out}}}, \tag{2}$$

where:
$D_1 - D_3$ – pipe and thermal insulation diameters according to figure 1 [m],
L – pipe length [m],
$(T_{in} - T_{out})$ – difference between the temperature of fluid within the pipe and the ambient temperature [K],
h_{in} – resistance to heat transfer from liquid to the pipe wall [W/m^2/K],
h_{out} – resistance to heat transfer from thermal insulation to the environment [W/m^2/K],
k_{pipe} – thermal conductivity of pipe material [W/m/K],
$k_{insulation}$ – thermal conductivity of thermal insulation [W/m/K]

The resistance to heat transfer from the pipe wall is significantly smaller than the resistance to heat transfer from the insulation to the environment therefore, theoretically, the flow speed of the medium inside the pipeline does not have a significant impact on the coefficient U. However, it has an influence on the difference of temperatures on a given section of the pipeline (Čarnogurská et al., 2016a; Klimczak et al., 2018).

Himpe and co-workers in their work (Himpe et al., 2014) demonstrated that it is possible to make good estimations of the annual and monthly distribution heat losses in the system, by using a limited amount of input data from EPBD calculations and design data from the network, thus avoiding the need for detailed dynamic simulations or in situ measurements.

Figure 1. Cross section of insulated pipe



Source: author's own work.

In none of the presented works is analysed the impact of thermal insulation thickness on distribution heat losses and total energy demand in the building.

Research methods

The analysis was performed as a case study on two commercial buildings – an office building and a multifunctional property. General descriptions of the buildings (1 and 2) are presented in table 1.

Table 1. Description of the subject buildings

Description	Building 1	Building 2
Type of building	Office building	Multifunctional building including service function, office function, built-in garage and storage areas
Floor area	2,472.34 m^2	2,112.96 m^2
Surface area to volume ratio	0.51 m^2/m^3	0.58 m^2/m^3
Design air tightness	0.8 h^{-1}	0.8 h^{-1}
Average heat transfer coefficient of building envelope	0.16 $W/m^2/K$	0.19 $W/m^2/K$
Multiplicity of air exchange	1.5 h^{-1}	2.8 h^{-1}
Design heat load	14.5 W/m^2	4.9 W/m^2
Index of annual energy demand for space heating and ventilation	12.1 $kWh/a/m^2$	29.9 $kWh/a/m^2$

Source: author's own work.

The annual energy demand for space heating and ventilation, calculated according to PN-EN ISO 13790 standard (PN, 2009), were taken into consideration. Central heating and ventilation systems of both buildings include distribution systems in the building such as pipes, ducts, tanks, pumps, fans, and exchangers. The efficiency of the overall building technical system depends on the efficiency of all its components. According to Polish calculation method of energy performance of a building the average annual efficiency of the X-system (H – heating, C – cooling, V – ventilation system) is determined from the formula (3):

$$\eta_{X,tot} = \eta_{X,g} \cdot \eta_{X,e} \cdot \eta_{X,d} \cdot \eta_{X,s}, \tag{3}$$

where:
η – average annual efficiency of a building system [–],
subscripts:
g – energy conversion of energy source [–],
e – regulatory control [–],
d – energy distribution [–],
s – energy storage (eg., in tanks) [–].

According to the simplified method (PL, 2015) specific system efficiency for space heating (including ventilation) is defined in one of two ways: as a flat-rate value independent of system's characteristics or as a value influenced by system parameters and an annual amount of heat demand of building which are represented by two variables namely the annual energy distribution efficiency ($\eta_{H,d}$) and the annual energy storage efficiency ($\eta_{H,s}$). The annual energy distribution efficiency and annual energy storage efficiency can be determined by following relations (4-8):

- the annual average distribution efficiency given in kWh/a:

$$\eta_{H,d} = \frac{Q_{H,nd} + \Delta Q_{H,e}}{Q_{H,nd} + \Delta Q_{H,e} + \Delta Q_{H,d}}, \tag{4}$$

where the seasonal heat losses due to imperfect system regulatory control ($\Delta Q_{H,e}$) given in kWh/a are:

$$\Delta Q_{H,e} = Q_{H,nd}\left(\frac{1}{\eta_{H,e}} - 1\right), \tag{5}$$

and the seasonal heat losses from distribution system ($\Delta Q_{H,d}$) given in kWh/a are:

$$\Delta Q_{H,d} = \sum_i \left(l_{zi} \cdot q_{li} \cdot t_{sG} \right) \cdot 10^{-3} \ . \tag{6}$$

- the annual average energy storage efficiency given in kWh/a is:

$$\eta_{H,s} = \frac{Q_{H,nd} + \Delta Q_{H,e} + \Delta Q_{H,d}}{Q_{H,nd} + \Delta Q_{H,e} + \Delta Q_{H,d} + \Delta Q_{H,s}} , \tag{7}$$

where the seasonal buffer tank heat losses ($\Delta Q_{H,s}$) given in kWh/a are:

$$\Delta Q_{H,s} = \sum_i \left(V_s \cdot q_s \cdot t_{sG} \right) \cdot 10^{-3} , \tag{8}$$

where:
l_{zi} – equivalent length of the *i*-th section of the heat distribution system [m],
q_{li} – unit heat loss from the *i*-th section of the distribution system determined according to (PL, 2015) [W/m],
q_s – unit heat loss from the buffer tank according to (PL, 2015) [W/dm^3],
t_{sG} – length of the heating season [h].

The values of unit heat losses of the distribution system are related to (PL, 2015) and comparable with values used in other countries (Romanova, 2016): the minimum thickness of the thermal insulation of the pipes and ducts, given in table 2 (PL, 2002), the outer diameter of the pipes and ducts, and the surrounding environment (conditioned or unconditioned). The analysis was performed considering:
- the flat-rate value of the distribution efficiency for the flat-rate method (method A, marked as MA): 0.96,
- two different thickness of the thermal insulation of the pipes and ducts: according to the minimum energy saving requirements for single thickness (method B-1, marked as MB-1) and for doubled minimum of the thermal insulation thickness in the advanced calculation method according to (PL, 2015) (marked as MB-2),
- non-renewable primary energy input coefficient of a heating network: 0.96,
- carbon emission factor for the heating network: 94.61 kg CO_2/GJ (KOBIZE, 2017a),
- carbon emission factor for an electrical grid: 806 kg CO_2/MWh (KOBIZE, 2017b).

The following heating system features were taken into consideration:

- the minimum thickness of the thermal insulation of the pipes ware defined in accordance with Polish building law requirements (PL, 2002) (table 2),
- regarding real project conditions, parameters of the heating system: supply/ return temperature 70/55°C,
- conditioned surrounding environment for the whole heating system,
- average annual heat source efficiency: 0.98 (substation powered from the heating network),
- average annual system regulatory control efficiency: 0.89,
- average annual energy storage efficiency: 1,
- calculated length of the heating season affecting the energy use and auxiliary energy of season-length-dependent technical building systems for heating, according to (PL, 2015; PN, 2009), for Building 1: 4,525 h and for Building 2: 6,235 h,
- total length of the heating system pipelines and ducts for Building 1: 1,842 m and for Building 2: 1,820 m, designated from the buildings designed,
- the assessed rate of heating system auxiliary energy: 1.24 kWh/a/m^2 for Building 1 and: 1.17 kWh/a/m^2 for Building 2.

In relation to the characteristics of the heat distribution system in both buildings and the simplified method (PL, 2015) under consideration, the heat losses per one meter of insulated pipeline, set out in table 3, were adopted for calculations.

Table 2. Examples of the minimum thickness of the thermal insulation of the pipes and ducts and their requirements for building energy distribution systems according to Polish building law

Type of pipe and ducts	The minimum thickness of thermal insulation made for thermal insulation with thermal conductivity equals 0.035 W/m/K	Minimum thermal resistance of thermal insulation made for thermal insulation with thermal conductivity equals 0.035 W/m/K
Internal diameter up to 22 mm	20 mm	0.57 m^{2}K/W
Internal diameter from 22 to 35 mm	30 mm	1.0 m^{2}K/W
Internal diameter from 35 to 100 mm	equals to the inside diameter of the pipe (from 35 to 100 mm)	1.0 – 2.86 m^{2}K/W
Internal diameter over 100 mm	100 mm	2.86 m^{2}K/W

Source: (PL, 2002).

Table 3. Heat losses per one meter of insulated pipeline for 70/55°C parameters of the heating system and conditioned surrounding environment for the whole heating system

Thickness of thermal insulation	DN 10-15	DN 20-32	DN 40-65
Single thickness according to energy saving requirements (table 2)	3,6 W/m	4,4 W/m	4,3 W/m
Double thickness according to energy saving requirements (table 2)	2,7 W/m	2,8 W/m	2,8 W/m

Source: PL, 2015.

Results and discussion

The annual energy demands for space heating for Buildings 1 and 2 was calculated according to local climate conditions and monthly method delivered by the standard used for calculation of energy performance of buildings (PN, 2009). Design heat load for both of buildings was assessed according to the standard PN-EN 12831 (PN, 2006). Then delivered energy was estimated according to flat-rate and simplified methods. The results of the investigations are collected in table 4.

For each examined building, the simplified flat-rate method (MA) for determining the efficiency of distribution gives an overestimation of annual efficiency of heat distribution in comparison to the method B (MB) addressed to characteristic system parameters and amount of annual energy demand for space heating. Compared to calculation methods and the minimum energy saving requirements for the thermal insulation of heating system pipes (table 2), the diversity of the distribution heat losses obtained by the method B for single thickness of thermal insulation, is significant and tightens from 171% for Building 1 to 213% for Building 2, in comparison with the constant value of distribution heat losses given in the flat-rate method (MA). Doubling the required minimum thickness of the thermal insulation for the pipelines (MB-2) slightly reduces this difference – over the range of 150% to 178%. Observed overestimation of the annual distribution efficiency and further – total efficiency of heating system calculated by flat-rate method (MA), results in a decreasing of the amount of annual energy demand for space heating by 41% for Building 2 to 52% for Building 1 in the case of applying a single thickness of pipeline insulation (MB-1), and by 33% to 42% according to the results obtained with double thickness of thermal insulation of pipelines (MB-2), respectively.

Table 4. Score board of results for methods of heating distribution efficiency

Description	Building 1			Building 2		
Index of annual energy demand for space heating and ventilation, EU_H, kWh/a/m^2	12.1			29.9		
Rate of heating system auxiliary energy, $E_{H,aux}$, kWh/a/m^2	1.24			1.17		
Average annual heat source efficiency, $\eta_{H,g}$, –	0.98			0.98		
Average annual system regulatory control efficiency, $\eta_{H,e}$, –	0.89			0.89		
Average annual energy storage efficiency, $\eta_{H,s}$, –	1			1		
Average annual distribution efficiency evaluation method	MA	MB-1	MB-2	MA	MB-1	MB-2
Average annual heating distribution efficiency, $\eta_{H,d}$, –	0.96	0.45	0.54	0.96	0.56	0.64
Index of annual energy delivered to building for space heating demand, EK_H, kWh/a/m^2	15.6	32.3	27.0	36.8	62.2	54.6
Carbon emission factor, Mg CO_2/ a/m^2	0.006	0.012	0.010	0.013	0.021	0.019

Source: author's own work.

The amount of delivered energy to the heating systems include auxiliary energy not directly related to the energy demand of the space heating. The carbon footprint of heating system is also distorted by carbon emission of auxiliary energy. The overestimation of the annual total efficiency of heating system calculated by flat-rate method (MA), results in a decreasing of the amount of annual carbon emission by 39% for Building 2 to 47% for Building 1 in the case of applying a single thickness of pipeline insulation (MB-1), and by 31% to 38% according to the results obtained with double thickness of thermal insulation of pipelines (MB-2), respectively.

In case of energy efficiency of the whole building including and its technical systems, the low calculated efficiency of the distribution system (obtained from method B), in relation to the high quality of the building envelope (table 1), is clearly highlighted. One of the main reasons for this situation is the relatively low energy savings requirements set in Polish building law for the distribution system elements (PL, 2002). Current requirements for this cause were established in 2008 as an amendment to the main regulation (PL, 2002) and have not been changed so far. In comparison, the thermal insulation requirements for building envelope have been tightened twice – in 2014 and 2017.

Conclusions

The study has focused on the relationship of the delivered energy amount for space heating, carbon emission and the method used to evaluate the heating system distribution efficiency. The findings of this research have crucial meaning for the choice of method used for estimating the annual efficiency of heating distribution in a building model and in this connection for the building energy performance and its environmental impact. The results reveal that using a simplified flat-rate method unrelated to specific of the heating system (MA), for the energy distribution efficiency estimation causes underestimation of the energy demand supplied to the building and the amount of carbon emission in comparison with results obtained by the other simplified evaluation method but addressed to characteristic system parameters and amount of annual energy demand for space heating (MB). Additionally, due to the current requirements in the field of thermal insulation of pipelines and ducts for energy distribution systems (table 2), in buildings, in order to improve the energy performance of the entire building, it is recommended to use the thermal insulation of pipes and ducts with a higher thermal resistance than the applicable minimum values (table 4).

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