

The reduction of emission production of small heat-sources for solid-based fuels by applying control mechanisms

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Abstract

INTRODUCTION: Production of emissions from small heat sources burning solid fuels in households in Slovakia is relatively high. At the present time, the operation of such devices are neither controlled nor regulated properly and effectively.

OBJECTIVES: This work presents a research analysis of current monitoring and maintenance procedures and certified norms for all solid-fuel small-scale heating systems utilized in households.

METHODS: The research compared data from over 13 countries in the European Union, evaluating information regarding certified emission limits, efficiency levels, normalized monitoring procedures for both fuel standards and heating system performance. A proposition is therefore presented for a new monitoring and inspection guide for solid-fuel heating systems in Slovak Republic households, where regulations, such as Ecodesign or the EN 305-5, were integrated.

RESULTS: Using a mathematical-statistical model, the implementation of the proposed regulations brings an emission saving of almost 140 tons per 10,000 inhabitants for both central and local heating systems.

CONCLUSION: The study demonstrated substantial opportunity in decreasing operation cost, prolongation of product lifetime, and last but not least, the reduction of health risks of local citizens

Received on 20 July 2021; accepted on 16 August 2021; published on 18 August 2021

Keywords: emissions, heating systems, control mechanism, regulation, Slovak Republic

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doi:10.4108/eai.18-8-2021.170675

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1. Introduction

To attain thermal comfort in households, it is necessary to ensure a sufficient amount of thermal energy, that is commonly created by burning fuel: Solid (wood, coke, coal), liquid (oil) or gaseous (natural gas) fuel. During the chemical reaction, emissions are formed and released into the air. Based on the knowledge of the greenhouse effect, adverse effects are present affecting public health and brings forth operational risks. The European energy organizations have introduced standards and standardized procedures for the control of household heating appliances in aims of reducing emissions while extending operation lifetime.

Currently, there is a high number of outdated and unmaintained equipment in operation. This creates a high concentration of harmful substances in the environment and directly within a household as well.

According to a study carried out on a sample of Slovak households in 2018, the average age of solid fuel boilers in Slovakia is 12 years, and for fireplace stoves up to about 21 years old [17].

1.1. Emissions

All chemical reactions in which energy conversion takes place produces pollutants or emission substances that are harmful to health and air purity. The main pollutants are considered to be particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO), carbon monoxide (CO), carbon dioxide (CO_2) and heavy metals [15]. The types of emissions that are released into the air are divided according to the Slovak Air Act no. 137/2010 para. 11 § 20 : 9 groups in total based on the chemical origin of the given substance. Particulate matter (PM) is the sum of all particulate matter and

Formula	Source	GWP	Health impact
PM ₁₀	Blowing dust from roads, industrial plants and solid combustion	-	They easily penetrate into the lung tissues, breathing difficulties
PM _{2.5}	All types of combustion processes	-	Breathing difficulties
CO ₂	All types of combustion processes	1x	Blocking the supply of oxygen to the tissues
CH ₄	All types of combustion processes	25x	Suffocation
NO _x	Combustion processes at high temperatures, exhaust gases	33x	Mild to severe bronchitis and pneumonia
N ₂ O	Combustion of fossil fuels	298x	Headache, fatigue

Table 1. Overview of sources of basic emission substances, their environmental and health harmfulness

Class	Efficiency (%)	CO (mg/m ³)	OGC (mg/m ³)	PM (mg/m ³)
Class 1	47 + 6*log P _n	25,000	2,000	200
Class 2	57 + 6*log P _n	8,000	300	180
Class 3	67 + 6*log P _n	5,000	150	150
Class 4	80 + 2*log P _n	1,200	50	75
Class 5	87 + log P _n	700	30	50

Table 2. Evaluation of biomass boilers up to 50 kW according to the standard STN EN 305-5.

liquid particles in the air, namely dust, pollen, soot, smoke and liquid droplets. This is further divided into particle sizes up to 10 μm (designated as "PM10") and up to 2.5 μm (designated as "PM2.5") [13] [8]. Heavy metals are defined as metals with a density greater than 4.5 g / cm³ (Pb, As, Cr, Cu, Hg, Cd, Ni, Se, Zn, Sn, Mn) [10].

The harmfulness of individual substances for global warming can be described by the GWP - "Global Warning Potential" coefficient [8]. The GWP value expresses the equivalent amount of CO₂ released needed to achieve the same warming effect as when burning one kilogram of a given substance [1]. Emissions are measured with respect to a certain concentration of oxygen in the air, which allows the correct comparison of the values of emission substances under different conditions (most often to 12% O₂).

2. Emission control methodology

2.1. Emission standards

The European standard STN EN 305-5 is focused on solid fuel boilers with a rated power output of up to 500 kW. This standard is in use in the Slovak republic. The standard defines five emission groups, according to which the efficiency and emission purity of any heating device is determined. "P_n" denotes the normalized output in units of MBtu / h. Emission classes 1 to 2 will be banned from operation, effective from 1.1.2022 [12].

Parameter	Value
Seasonal efficiency [%]	≥ 75
Particulate matter (PM)	≤ 60 mg/m ³
Organic gas compounds (OGC)	≤ 30 mg/m ³
Carbon monoxide (CO)	≤ 700 mg/m ³
Nitrogen oxides (NO _x)	≤ 200 mg/m ³ (biomass) ≤ 350 mg/m ³ (fossil fuels)

Table 3. Evaluation of boilers according to the Ecodesign system for manually operated boilers.

Another essential standard system within the EU is named "Ecodesign". The Ecodesign directive is a system of requirements aimed for low-emission boilers (up to nominal power of 120 kW) according to the new European Union Regulation 2015/1189 [16].

2.2. Emission control methods

Production of gaseous emissions (CO, NO_x and OGC) is measured by a flue gas analyzer which is able to record the concentration of specific substances in units ppm (parts per million). These values have to be converted to mg/m³ according to the equation 1:

$$Y = X * \frac{M}{22,41} * \frac{p}{101325} \quad (1)$$

where Y represents a calculated emission production in mg/m³, X is the measured emission in ppm units, M represents the molecular weight of the components in g/mol, the value 22.41 represents the standard molar volume in dm³/mol and p represents the pressure in Pa. The normalized concentration of oxygen in the flue gas from a boiler O_{2n} is considered to be 10 %. Therefore, the measured concentration values are recalculated according to the formula 2 to meet homogeneity requirements.

$$Y_{(10\%O_2)} = Y * \frac{21 - O_{2n}}{21 - O_{2avg}} \quad (2)$$

where Y(10%O₂) is the normalized emission concentration in mg/m³, Y represents the emission concentration, which is calculated by a previous equation (Eq. 1) in mg/m³, O_{2n} represents the normalized concentration of oxygen in the flue gas in % and O_{2avg} represents the mean value of the oxygen concentration in the flue gas in %. These measurement devices have to be regularly calibrated by authorized personnel.

The production of particulate matter may be measured via the optic method or gravimetric method. The latter consists of multiple sampling by the use of a complex sampling apparatus under isokinetic

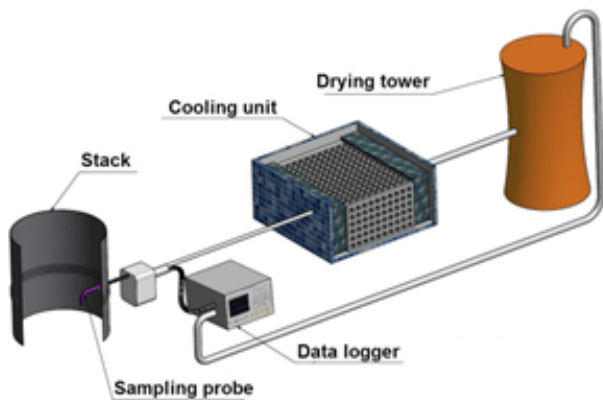


Figure 1. The measurement scheme for a flue gas analysis by gravimetric method.

conditions, following the gravimetric analysis itself. Isokinetic sampling is a sampling technique in which the velocity of gas in the nozzle of the sampling probe is the same as the velocity of gas in the flue-gas ducting [11]. The samples are collected on so-called flat filters.

For the measurement of particulate matter production, the analyzer Tecora (Fig. 1) can be used alongside the three-stage separation impactor ISOSTACK. Such devices allow for automatic isokinetic measurements of low, medium and high concentrations of particulate matters complying to norms EN 13284-1 and STN ISO 9096. The use of the aforementioned impactor enables to determine the particle size distribution: Concentration above 10 μm , concentration between 2.5 μm to 10 μm , and below 2.5 μm (PM_{2.5}). The regulation of isokinetic condition for flue gas sampling is done via modifying the flue gas velocity. The flue gas velocity is measured by the Pitot tube. These measurement devices have to be regularly calibrated by authorized personnel.

3. Comparison of control methodology in EU countries

3.1. Procedures in Slovak republic

In Slovakia, Act no. 17/2007 Coll. presents procedures and intervals for regular inspection of boilers, heating systems and air conditioning systems (Table 4) [6]. These inspections must be carried out before the boiler room is put into operation, after each overhaul and reconstruction of the boiler. It must be also inspected when the type of fuel is changed, after the first year in operation, and a seasonal inspection is conducted at the beginning of each season.

Rated boiler output	Fuel	Regular inspection interval (year)	
		Family houses, apartment houses	Other buildings
20 – 30 kW	Fossil solid and liquid fuels other than natural gas	10	7
	Natural gas	15	12
	Biomass, biogas	12	15
30 – 100 kW	Fossil solid and liquid fuels other than natural gas	4	4
	Natural gas	6	6
	Biomass, biogas	10	10
From 100 kW	Fossil solid and liquid fuels other than natural gas	2	2
	Natural gas	3	3
	Biomass, biogas	6	6

Table 4. Frequency of regular inspections of boilers in Slovakia. [6]

3.2. Control procedures in Czech republic – "Semaphore/Stoplight" Methodology

In the Czech Republic, according to Act no. 172/2018 on air protection § 17 paragraph 1 entitled "Obligations of the stationary source operator", states that the boiler operator is obliged by law to burn solely fuels that meet the requirements for fuel quality set by the manufacturer and corresponding legislation party. The method called "Semaphore", in translation "Stoplight", is intended to indicate the combustion of waste or contaminated fuel (CF) in stationary boilers with a rated output of up to 300 kW via ash analysis. The method measures 7 standard indicators: Pb, Cu, Zn, Cl, Sb, Sn, Ti [5].

The result of the analysis of each indicator is evaluated with three possible scenarios (depicted using a stoplight):

- Significantly exceeded value (A) - RED: The exceedance index of the given indicator is greater than 200%
- Suspicious value (B) - ORANGE: The exceedance index of a given indicator is greater than 100% and less than or equal to 200%.
- Permissible value (C) - GREEN: The exceedance index of the given indicator must be less than or equal to 100%

3.3. Control procedures in Nordic countries (Finland, Sweden and Denmark)

In Denmark, they regulate emissions utilizing the standard STN EN 305-5 [12]. Sweden uses its own established regulation directives such as the BFS 2006:12 for boilers up to 1025 MBtu/h, in which the concentrations of OGC and OC are regulated for boilers and pellet stoves. Furthermore, the Nordic Council has introduced an exceptional award "The Nordic Swan"

Device	Efficiency (%)	CO (mg/m ³)	NOx (mg/m ³)	OGC (mg/m ³)	PM (mg/m ³)
Stove	≥ 85 %	200/450	170/-	10/20	30/-
Boiler		100/225	170/-	5/5	25/-

Table 5. Exceptional German award "The Blue Angle" (at 12% O₂, normal load / part load).

for meeting very strict CO, NO₂, OGC and dust emission limits for all manufacturers and suppliers of manual and automatic boilers within the Scandinavian countries [12] [2]. Boilers are categorized (1) based on type of heating - primary and secondary,(2) according to the loading method - manual and automatic, and (3) according to the rated output - up to 170 MBtu/h, from 170 to 510 MBtu/h and from 510 MBtu/h.

3.4. Fuel control

Decree no. 228/2014 Coll., introduced by the Slovak Ministry of Environment, sets requirements for the quality of fuels and their operational records. The decree sets limits on the content of sulfur, water and ash. For each type of fuel, it defines the procedures for the formation of bulk samples (STN SIO 5069-1 for brown coal), and the creation of samples for general analysis (STN 44 1314). Additionally, it drives the official form which records the amount of solid fuel sold [4] [14].

3.5. Exceptional awards from Germany

German energy agencies award prizes to boiler suppliers once in a while after meeting strict emission limits. For example, the "The Blue Angle" award is an exceptional award from the German Federal Environmental Agency intended for pellet stoves and boilers. Specific limits are shown in table 5 [12].

4. Proposal of control methodology

4.1. Proposal of a new methodology for the control of small heating devices in Slovakia

The integration of new Ecodesign requirements over the coming years will eliminate the operation of Class 1 and 2 boilers in Slovakia in early 2022. Basic operational control will consist of efficiency, particulate matter concentration, OGC, CO, CO₂ and NO_x measurements. The ash is sampled and a chemical analysis is made to determine combustion of unsuitable fuel. Additionally, it recommends measurements of smoke particles and its opacity [18].

The aim of this work is to design a theoretical model of heating in the future. This aim will be achieved by using previous knowledge about various methodologies of managing small heat devices abroad, in the

Fuel type	Own heating		Central heating	
	Proportion (%)	number of households	Proportion (%)	number of households
Wood	35	438	35	438
Black coal	5	62	5	62
Brown coal	10	125	10	125
Natural gas	50	625	50	625

Table 6. Distribution of fuel types between inhabitants of the mathematical model

introduction of new equipment and decommissioning of older, already incompatible, equipment. It is also visioned to introduce stricter measures to control flue gases and emissions, which are a by-product of heating. The control of airborne substances and the reduction of the use of incorrect / unsuitable fuel will be the focus conditions for improving the ecological, environmental and technical aspects of heating in the near future.

4.2. Mathematical model of heating in Slovakia

In order to anticipate and evaluate the positive effects of the implementation of the proposed boiler control methodology in Slovakia, a mathematical heating model was created for a "town" with 10,000 inhabitants, which evaluates the savings in emissions and energy per year. It is assumed that 50% of the population lives in family houses (self-heating) and 50% in apartment buildings (central heating). Based on the professional experience of the authors, the distribution of fuels is assumed as presented in table 6.

The values of emissions per kWh of burnt wood were evaluated by a Slovak study [9]. The specific energies of fuel were chosen at 15 MJ/kg for wood and coal and 22.7 MJ/kg for gas [3]. According to a Slovak project carried out in 2018, a sample of 1549 households assessed the average wood consumption per year (8.7 tonnes/household), where energy consumption is based on 366 MJ/day/household. The apartment buildings in the model have 64 apartments, where the energy consumption is 309MWh per year, specifically 72.42 MJ / day / household [7].

It has been estimated that up to 56% of households use obsolete and unmaintained boilers, stoves and fireplaces, which produce a high percentage of emissions [17]. The mathematical model also assumes a new division of boilers in operation - class 3 would be used by 20% of the population, class 4 by 40% and class 5 by 40% of the population.

4.3. The results of analysis

Self heating in family houses recorded energy savings of 60.4% and 62.5% less emissions per year. Apartment

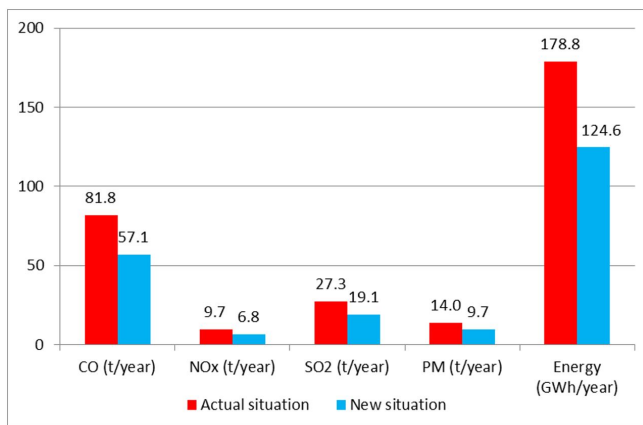


Figure 2. Evaluation of the results of a mathematical model for the population of 10,000.

buildings (central heating) recorded 43.8% energy savings and 49.9% less emissions per year. The largest decrease in the emission substance was TZL (by 55.3% and 52.0%) for both cases.

5. Conclusion

At present, the situation in Slovakia is insufficient in terms of citizens' knowledge of the correct way of heating, cleaning boilers / other heating equipment and their correct maintenance. There are cases when residents do not have the necessary knowledge on how to properly burn a particular fuel, and this often results in a state where a very unsuitable fuel is burned, for which a particular boiler is not designed and damages the particular boiler and the air. Mandatory inspections of heating systems are ignored and, as a result, old boilers and stoves, which should have been taken out of service a long time ago, are often used for many years there on.

The results, which result from the mathematical model, suggest an average improvement of 30% in air quality, which has a positive effect on both the exterior and interior of households, as the excretion of harmful substances during heating is significantly reduced. An important conclusion is more than 30% energy savings, which represents significant fuel savings. It can be assumed that the implementation of these incentives and the reduction in unsuitable fuels would result in a significant improvement in air quality and thus in the overall well-being of humans.

Acknowledgments

This work has been supported by the project KEGA 033ŽU-4/2018 "Heat sources and pollution of the environment", VEGA 1/0479/19 "Impact of combustion conditions on the production of particulate matter in small heat sources" and APVV-17-0311 "Research and

development of zero waste technology for the decomposition and selection of undesirable components from process gas generated by the gasifier".

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