DIGITAL MODIFICATION OF CHIMNEY GATE VALVE CHARACTERISTICS AS A WAY TO REDUCE THE FUEL CONSUMPTION AND CO_2 EMISSION

Mariusz WNĘK

Silesian University of Technology, Faculty of Materials Engineering and Metallurgy, Department of Industrial Informatics, Katowice, Poland, EU, mariusz.wnek@polsl.pl

https://doi.org/10.37904/metal.2019.994

Abstract

The chimney gate valve is widely used in the metallurgical industry as a control element in fume extraction systems of the furnace chamber. However, its flow characteristics are not appropriate for controlling this flow. Linear characteristics would be the most appropriate.

The aim of this study is to present the problems of control technology in the metallurgical industry - conducted improperly due to many difficulties or lack of knowledge of controlled installation. The chimney gate valve (as an element of control), installed in the heating pusher furnace, is presented in the paper. The proposal to address the identified problems is also presented. The solution is to use a digital control linear setting element which significantly reduces the negative environmental and economic consequences.

As a result of the chimney gate valve digital control and the measurement of the exhaust gas pressure in the furnace chamber, a significant reduction in gas fuel consumption and reduction of CO_2 emissions have been achieved. The reduction of fuel did not change the technological temperature of the metallurgical process.

Keywords: Chimney gate valve, heating furnace, CO_2 reduction, environmental protection, energy savings

1. INTRODUCTION

In industrial heating gas furnaces, basic adjustment parameters are as follows: the furnace temperature in one or more zones, the ratio of combustion substrate streams (gas and air) and exhaust pressure in the furnace chamber. The control parameters are streams of substrates and combustion products. For their control, the most appropriate are adjustment elements with linear operating flow characteristics where the stream of gaseous medium is proportional to the percentage of opening [1].

The exhaust stream, generated in the burners, is a sum of combustion substrate streams. When the furnace is properly adjusted, the exhaust stream that is transferred to the flue gas duct should equal the exhaust stream that is generated in the burner installation. The exhaust stream in the duct is difficult (and, in practice, impossible) to measure so it cannot be an adjustment parameter. A measurable (so adjustment) parameter is the exhaust pressure in the furnace; its value is usually $p_s \in [-30 \div +30]$ Pa and depends on the exhaust stream transferred to the chimney; therefore, it is a control parameter [2]. To adjust the exhaust stream, gate valves (in addition to butterfly valves) are commonly used but they are characterised by highly nonlinear operating flow characteristics (**Figure 1**) which can also be presented as the relationship of its sensitivity and the percentage of opening (**Figure 2**). The highest sensitivity of gate valves is seen when the opening percentage is small; in

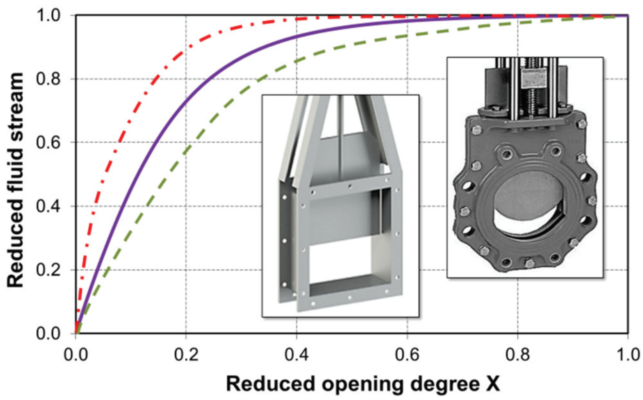

Figure 1 Exemplary flow characteristics for gate valves

practice, it very often reaches its maximum in furnace installation, which results in negative manometric pressure in the furnace. Then, additional amounts of environmental air enter the furnace through technological windows and leaks. This air requires combustion of additional gas to maintain the assumed technological temperature in the furnace and leads to energy loss. Therefore, a very important issue for the furnace operation is maintaining of proper distribution of exhaust pressure in the combustion chamber, which is a significant regulatory problem [2].

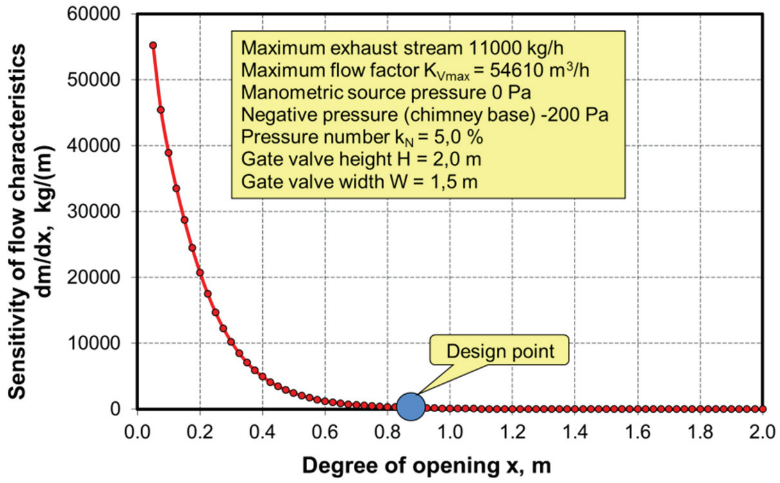

Figure 2 Flow characteristics dm/dx versus the opening percentage x

2. COMPUTED ASSISTANCE FOR DESIGNING OF ADJUSTMENT FLOW CHARACTERISTICS OF THE GATE VALVE

In terms of control, the most appropriate is linear characteristics; conventional adjustment elements, i.e. gate valves in fume extraction systems of industrial heating furnaces, do not demonstrate such characteristics. However, due to certain modifications of design or the method of automatic control, the required effects can be obtained. During own investigations, the LINEAR-2 programme was developed that supports programming of linear operating flow characteristics for the gate valves (**Figure 3**).

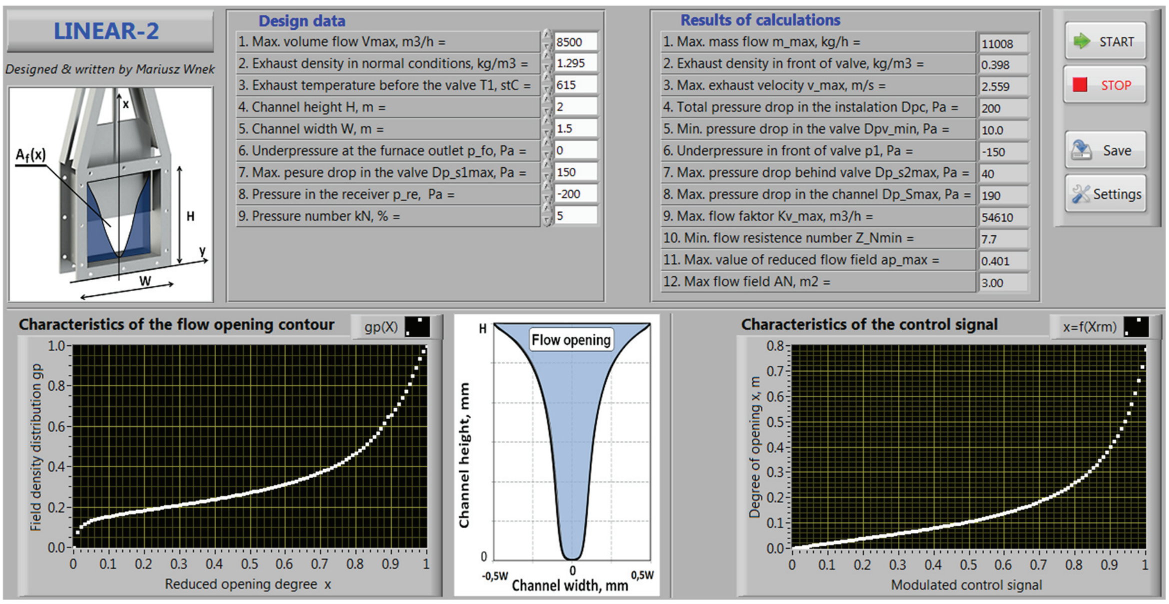

Figure 3 The LINEAR-2 programme panel

The programme was developed in the LabVIEW environment. When the necessary information is entered ("Design data"), a solution for advanced automated systems can be achieved as a function of the modulated control signal. The function must be programmed in the industrial system of the gate valve control which changes the relevant process parameter.

3. LINEARIZATION OF OPERATING FLOW CHARACTERISTICS FOR THE GATE VALVE REFERRING TO ITS DESIGN

One of the ways of obtaining linear adjustment flow characteristics of a conventional gate valve (**Figure 4a**) is proper profiling of the flow opening in the orifice (**Figure 4b**) that is placed in the duct before the aperture. The opening has a specific shape [2,3] for flow characteristics that are presented in **Figure 1**. Practical use of the procedure of flow opening profile determination resulted in very favourable effects but this form of linearization requires modification of the valve design, which (for industrial systems) means stopping the device, disassembling the gate valve and modifying its design.

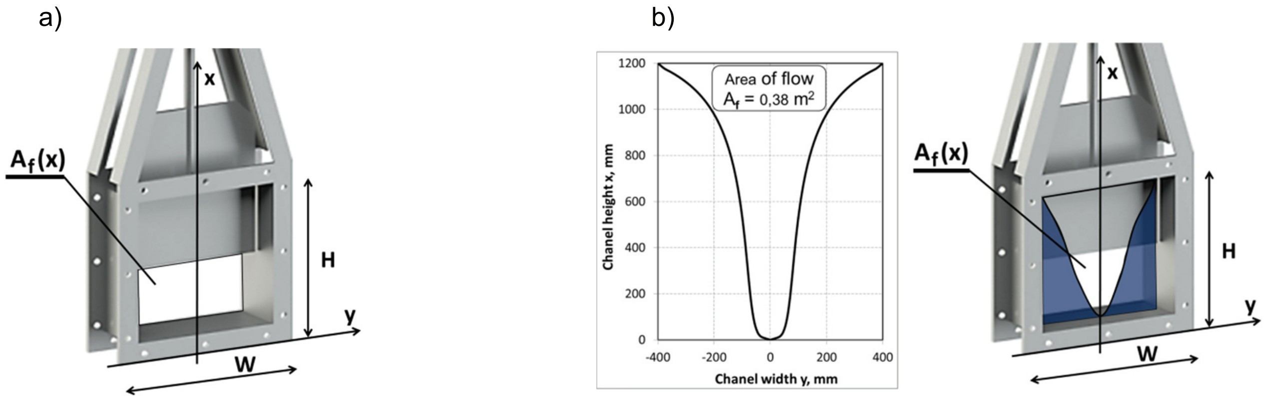

Figure 4 Conventional chimney gate valve (a) and a valve with profiled flow opening (b); were: *H* - height, *W* - width, A_f - an area of fluid flow

4. DIGITAL LINEARIZATION OF OPERATING FLOW CHARACTERISTICS OF THE GATE VALVE

One of the ways of obtaining linear adjustment flow characteristics of a conventional gate valve (**Figure 4a**) is proper profiling of the flow opening in the orifice (**Figure 4b**) that is placed in the duct before the aperture. The opening has a specific shape [2,3] for flow characteristics that are presented in **Figure 1**. Practical use of the procedure of flow opening profile determination resulted in very favourable effects but this form of linearization requires modification of the valve design, which (for industrial systems) means stopping the device, disassembling the gate valve and modifying its design.

Considering design linearization (obtained through flow opening shaping), a method of digital linearization was developed - an algorithm of programmed control of the valve drive. This solution can be applied for a conventional gate valve (**Figure 4a**) without any design modifications or its disassembling from the industrial installation. To date, no such modification of adjustment element flow characteristics has been reported in literature!

The method requires designing of a proper digital or analogue and digital transducer which, together with an actuator, converts the input signal *y* (digital or analogue) into a properly modulated signal for the opening percentage *x* of the adjustment element. The developed (during own investigations) algorithm determines a function, according to which the transducer and actuator convert the input signal *y* into the output signal so that the fluid stream is proportional to the signal *y*, i.e. the linear operating flow characteristic is obtained.

For the calculation algorithm, it is necessary to know the basic flow characteristics of adjustment element as well as the flow resistances for the pipeline or duct, pressures in the source and the receiver. Bulk, turbulent exhaust stream that flows through the gate valve can be determined based on the formulation resulting from the stream energy balance and parameters that define the flow coefficient, as follows:

$$\dot{m} = C_1 K_V(x) \varepsilon \sqrt{\Delta p_N \rho_1} \tag{1}$$

where:

C_1 - number coefficient, C_1 = 0,101 (s/m)

$K_V(x)$ - flow factor (m^3/h)

m - mass flow rate (kg/h)

Δ_{pN} - pressure drop in the valve (Pa)

ε - expansion coefficient (-)

ρ_1 - exhaust density for the exhaust parameters before the valve (kg/m^3)

The flow factor K_V is an international parameter (commonly used outside the U.S.) that describes basic flow characteristics of control valves and most manufacturers present it in their specifications. The flow factor K_V is defined as the flow of water with temperature ranging 5 - 30 ºC through a valve in cubic meters per hour (m^3/h) with a pressure drop (across the valve) of 1 bar. There is also the flow coefficient C_V - it is based on the imperial units system and is commonly used in the U.S. [4,5]. In technical literature, a description of basic flow characteristics of adjustment elements also contains a number of local flow resistance Z_N that refers to the fluid flow rate in the pipeline or inlet channel. A relation between Z_N and K_V can be determined, using formulation (1) and a parameter defined in the standards that describes a number of local flow resistance, which ultimately can be presented as follows:

$$Z_N(x) = C_2 \left[\frac{D_N^2}{K_V(x)} \right]^2 \tag{2}$$

where:

C_2 - number coefficient, C_2 = 15.7·10^8 ((m/h)^2)

D_N - nominal diameter of the valve (m)

For the analysis, an empirical relationship (called generalised, basic flow characteristics) is highly useful (or even necessary) - between a number of local flow resistance and reduced flow surface area, that has been determined based on the own investigations and literature data [6]. Considering flow resistances in the flue gas duct, a formulation that links the control signal y and the valve opening percentage x was also obtained:

$$A_N \sqrt{\frac{C_2}{Z_N(x)}} \sqrt{\left(\frac{\Delta p_C}{y^2} - \Delta p_{S\,max} \right) \frac{1}{\Delta p_C\, k_N}} - K_{V\,max} = 0 \tag{3}$$

where:

K_{Vmax} - maximum, computable flow coefficient for the expected maximum exhaust stream (m^3/h)

Δp_{Smax} - maximum pressure drop in the duct (Pa)

Δp_{Nmin} - minimum pressure drop in the valve for the maximum stream (Pa)

$\Delta p_C = \Delta p_{Smax} + \Delta p_{Nmin}$ - overall pressure drop in the installation (Pa)

The k_N in the formulation (3) is a so-called pressure number, defined as follows:

$$k_N = \frac{\Delta p_{N\,min}}{\Delta p_C} \tag{4}$$

5. ANALYSIS OF RESULTS

In formulation (3), the control signal *y* is received as a normalised value between 0 and 1. In the algorithm of the method of linearized control of the gate valve, a control function is searched that links the predefined percentage of valve opening with the control signal from the managing system (programmable function adjustor, controller, computed industrial system). The function results from the assumed shape of adjustment characteristics as well as the flow characteristics of the net and adjustment device. A result of the digital linearization procedure for a conventional chimney gate valve, used in the LINEAR-2 programme, is presented in **Figure 5**. It shows a relationship between the modulated control signal and the percentage of valve opening in terms of fluid stream proportionality, meaning linearity of operating flow characteristics of the system [7].

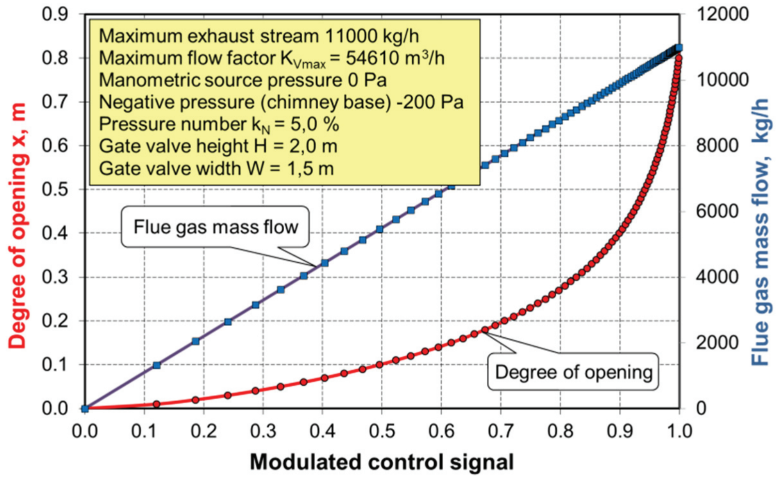

Figure 5 Flow characteristics of the gate valve following linearization

6. PRACTICAL APPLICATION OF DIGITAL LINEARIZATION IN INDUSTRY

At present, the reason of not maintaining proper exhaust pressure distribution in the chamber of metallurgical heating furnace is lack of automatic adjustment and difficulties in determination of its optimum value as well as improper (considering control) characteristics of the adjustment element. Manual adjustment of exhaust pressure at a satisfactory level is not possible. The use of digital linearization of flow characteristics for chimney gate valves in metallurgical heating furnaces remarkably improves the control quality and, therefore, facilitates maintaining of proper exhaust pressure in the heating furnace [7], which ensures significant energy saving that has been confirmed in relevant investigations using an experimental heating furnace with the nominal power of about 8 MW (**Figure 6**).

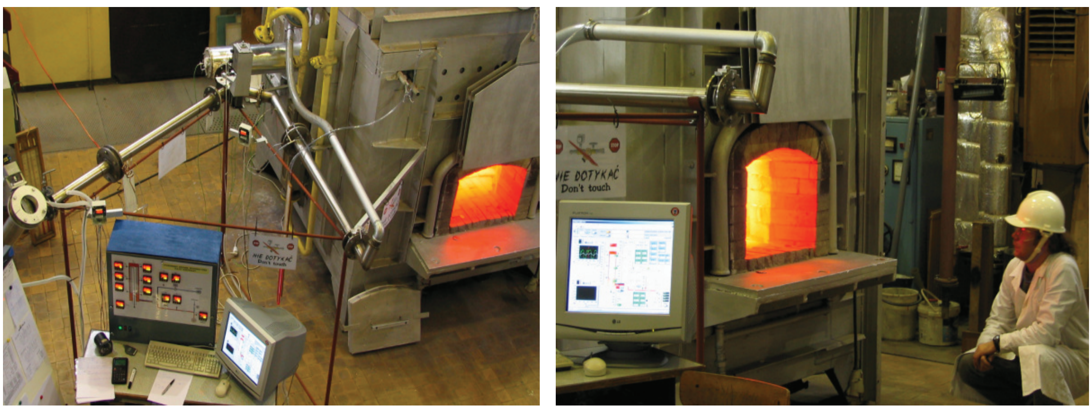

Figure 6 Experimental furnace - research

As a result of control according to the presented method, optimum pressure values in the combustion chamber for various numbers of excess air λ in burners were achieved (**Figures 7a** and **b**). Optimum pressure (-0.5 Pa, measured at the furnace hearth for λ=1.05) ensured the reduction of gas fuel consumption by 271 m^3/h: from 885 m^3/h down to 614 m^3/h, which is about 31 % compared to the initial pressure of about -15 Pa. The paper describes a situation when a metallurgical heating furnace operates for 11 months per year and 24 hours daily. The twelfth month is meant for the furnace service. Assuming that the petroleum gas costs approximately 0.43 €/m^3 [8], savings of more than 923000 €/year can be achieved. Recommended limitation of gas fuel consumption also means a significant reduction of CO_2 emission, which is a very important environmental issue. CO_2 emission reduction creates a potential for the sale of CER units to the so-called carbon market [9] and this makes an additional enterprise revenue. In the presented example, the setting of the metallurgical heating furnace at the optimum pressure level in its chamber ensures limitation of environmental burden: over 4100 Mg of not emitted CO_2 per year.

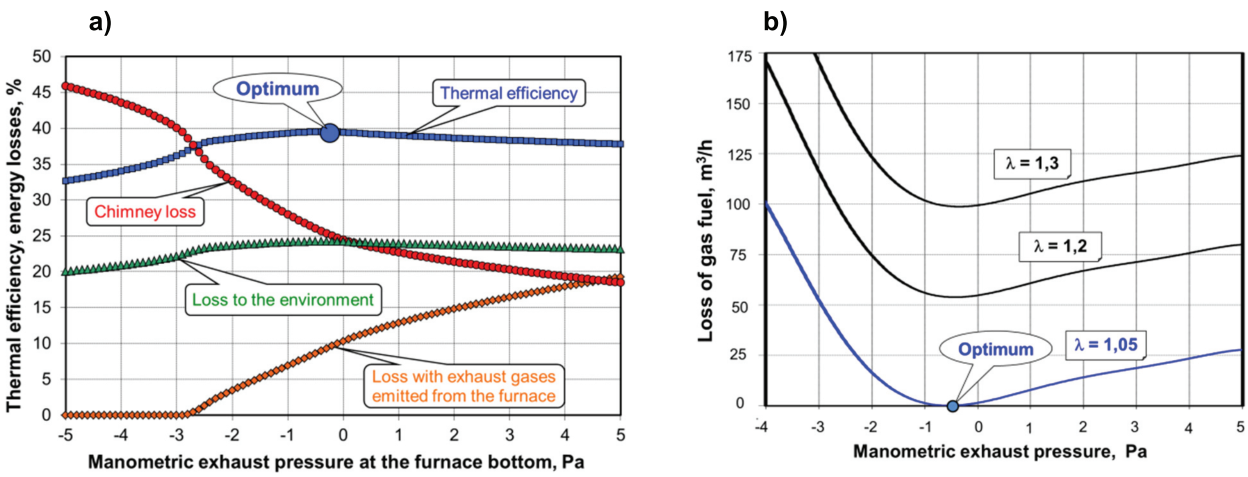

Figure 7 Characteristics: a) operating; b) energetic

7. CONCLUSION

At present, the reason for not maintaining proper exhaust pressure distribution in the chamber of metallurgical heating furnace is lack of automatic adjustment and difficulties in determination of its optimum.

The method of digital linearization of chimney gate valve flow characteristics requires programming of a transducer that converts the input signal y into a properly modulated signal for the opening percentage of the adjustment element. The developed algorithm determines a function for this transducer so that the fluid stream is proportional to the signal *y* - then, the linear operating flow characteristics can be ensured. For the calculation algorithm, it is necessary to know the basic flow characteristics of adjustment element as well as the flow resistances for the pipeline or duct, pressures in the source and the receiver.

The use of digital linearization of chimney gate valve flow characteristics and implementation of automatic adjustment of exhaust pressure does not require design modifications of the adjustment element and are not costly from the investment point of view. The improvement of control quality is beneficial due to significant financial savings (923000 €/year) resulting from the limitation of gas fuel consumption and favourable environmental effects related to reduced CO_2 emission of 4100 Mg/year.

There are ongoing studies on the use of digital linearization method for other types of adjustment elements: butterfly valves and ball valves.

REFERENCES

[1] MOHAMMADREZA, Kamali, SEYED, A. Jazayeri, FARID, Najafi, KENJI, Kawashima, TOSHIHARU, Kagawa. Integrated nozzle - flapper valve with piezoelectric actuator and isothermal chamber: a feedback linearization multi control device. *Journal of Mechanical Science and Technology*. 2016. vol. 30, no. 5, pp. 2293-2301.

[2] TOMECZEK, Jerzy, PUSZER, Andrzej, WNĘK, Mariusz. Możliwości obniżenia zużycia paliwa w przelotowych piecach grzewczych. *Hutnik*, 2004 no. 4, pp. 178-181.

[3] TOMECZEK, Jerzy, PUSZER, Andrzej, WNĘK, Mariusz. Sposób kształtowania regulacyjnych charakterystyk przepływowych elementów nastawczych strumienia płynu. *Pomiary Automatyka Kontrola*. 2007. vol. 53, no. 11, pp. 38-43.

[4] The Engineering ToolBox. [viewed 2019-04-28]. Available from: https://www.engineeringtoolbox.com/flow-coefficient-factor-d_238.html.

[5] Physics Department - Detector Technology - Gas Section. [viewed 2019-04-28]. Available from: http://detector-gas-systems.web.cern.ch/detector-gas-systems/downloads/kv_calc_doc.pdf.

[6] SENKARA, Tadeusz. *Obliczenia cieplne pieców grzewczych w hutnictwie*. 2nd ed. Katowice: Wydawnictwo Śląsk, 1981. p. 502.

[7] WNĘK, Mariusz. Cyfrowa linearyzacja przepływowej charakterystyki regulacyjnej zasuwy kominowej. *Hutnik*, 2016 no. 1, pp. 18-22.

[8] Europe’s Energy Portal. [viewed 2019-04-28]. Available from: http://www.energy.eu/.

[9] Commodity exchange Bratislava. Carbon place. [viewed 2019-04-28]. Available from: http://www.carbonplace.eu/info-commodities-CER.