Bulletin Chemical Communications, Volume 53, Special Issue B (pp. 34-41) 2021 *DOI: 10.34049/bcc.53.B.0054*

Novel flue gases waste heat recovery methodology avoiding wet gas cleaning technologies in thermal power plants

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Flue gases waste heat recovery of coal-fired power plants is associated with lowering their temperature to values significantly above the dew point, because acid deposition leads to corrosion of the affected heating surfaces. When wet gas cleaning technologies are used, additional heat is lost to heat the purified gases with hot air before they enter the stack. The proposed innovative method provides for a more complete use of thermal energy of exhaust gases and eliminates the need for additional reheating of the wet gases before entering the stack. This can be achieved by directing a portion of the gas stream to a bag filter in which there is slight reduction of the flue gas temperature and then mixing this portion with the main stream passing via the economizer or air preheater in a pre-existing mixing chamber to achieve the desired humidity and temperature of flue gases. A technical and economic assessment of the expediency of utilizing the waste heat from the flue gases by means of an economizer or an air preheater of several different coal-fired steam generators which are using purification technology with battery emulsifiers has been made - the boiler BKZ-160-100F in Almaty CHP-3 has an indisputable advantage.

Keywords: Waste heat recovery, flue gases, feasibility study, battery emulsifier second generation, bag filters

INTRODUCTION

Waste heat recovery leads to a reduction of the total losses of the steam generator and increases its thermodynamic efficiency [1]. Sometimes however, the possibilities for lowering the temperature of the exhaust gases are accomplished by the respective gas purification methods [2]. In some countries of Asia, incl. Russia and Kazakhstan, wet gas purification methods have become very popular [3]. The reason for this is the lack of policy for the recovery of collected ash after electrical precipitators and further sale as a building material [4]. The study reveals that the ash together with suitable hydraulic binders forms building materials with maximum operational temperature up to 1150 °C. The properties of the produced by the coals ash is studied in [5]. The main output from the analysis shows that mechanical strength of the cyclone ash is reduced in comparison with the ash collected with the electrostatic precipitator. The similar study [6] also confirm that the ash from electrostatic precipitator has the necessary strength to produce the construction materials in steel and chemical industry.

In terms of the ensuring the environmental safety of the coal fired TPP different flue gas purifications systems have been examined. In [7] the simulation process of the wet cleaning system is proposed. Focus of the study is by controlling the operational parameters to reduce the environmental impact and improve the energy efficiency. Certain numbers of TPP have been equipped with the electric filter systems for dry-wet purification of the stack gases [8]. The study shows that in about 60% is the efficiency of the system.

In the European Union, where gases are mainly cleaned by electrical precipitators, 80% of the waste ash is sold and this increases the economic feasibility of using this type of gas purification [9]. Different systems related with processing of coal deposits are also available. Within the range of the proposed system the mutual impact on the usage of wet and dry-cleaning technologies, organization of fuel combustion, and using the different types of filters to clean flue gases from impurities could significantly improve the efficiency of the plant. The main idea also from the study is to be utilized the spent TPP lubricants in the power plant cycle.

The use of ashes in construction began in the 30s of the last century in the manufacture of bricks and cinder blocks. Strategically important objects

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built with the use of ashes include the Tallinn TV Tower and the Sankt Petersburg Nuclear Power Plant. Among the latest sites also constructed using ashes are the cargo port in Helsinki (Finland) and the port of Trondheim (Norway) [10]. Ashes are also applied in a variety of areas: in road construction (in the construction of subgrade, for the construction of fortified foundations and embankments); soil stabilisation measures: strengthening weak soils, as an additive to binders in order to save them when strengthening soils; in asphalt-cement concrete (as a filler and mineral powder in asphalt concrete; for hydrotechnical embankments, etc.).

In recent years, second-generation battery emulsifiers have been widely used in many thermal power plants in Kazakhstan, using mainly Ekibastuz coal [11, 12]. The principle of operation of the second generation battery emulsifiers is a highly efficient heat and mass transfer between the ascending flow of flue gas swirled in the blades and the liquid supplied by the counterflow with the formation of a vortex emulsion layer, in which effective gas cleaning takes place (the so-called phase inversion mode) [13, 16, 17].

Based on the performed literature overview, it is quite clear that scientific studies in this area are limited where a combination of innovative waste heat recovery method, comprising a combination of an additional air preheater and a bag filter, or alternatively an additional economizer and a bag filter should be examined [14, 15].

The present paper proposed innovative waste heat recovery method, comprising a combination of an additional air preheater and a bag filter, or alternatively an additional economizer and a bag filter. Several novelties based on the study done are available:

- opportunity to use the useful temperature drop of the flue gases, whereby part of the hot gases are purified with higher efficiency in a bag filter and then mixed with the wet gases after the existing emulsifier, without the need for hot air from the boiler air preheater;
- a technical and financial analysis showing the feasibility of the implementation of waste heat recovery units (WHRU);
- presentation of several variants of WHRU characterized by an attractive low Payback period (2.77 - 6.78 years);
- high environmental impact presented for example with the reduction of the Ekibaztuz coal, depending on the selected boilers.

Determination of the allowable temperature of the exhaust gases after economizer or air preheater

The technical and economic analysis is made for waste heat recovery from different type of boilers using Ekibastuz coal. There are two alternatives: installing an additional economizer or using an air preheater in front of the existing battery emulsifier. However, which of the two possible options to choose should determine the allowable level of cooling of the exhaust gases in order to avoid low-temperature corrosion on the non-heated surfaces of the heat exchangers [13, 18, 19].

The elemental composition and calorific value of coal are presented in Tab.1. It should also be noted that the price of coal varies from region to region, which affects the payback period for waste heat recovery facilities.

Table 1. The elemental composition and calorific value of Ekibastuz coal [3, 12]

Rank	units	value
Carbon, C^r	%	46.03
Hydrogen, H^r	%	2.85
Nitrogen, N^r	%	0.86
Oxygen, O^r	%	6.56
Sulphur, S^r	%	0.70
Water, W^r	%	5.0
Ash, A^r	%	38.0
HHV	kJ/kg	16 493

With sufficient accuracy for practice, the theoretical dew point temperature can be determined by equation (1) [1]:

$$t_{dp}^{t} = \Delta t_{dp}^{t} + t_{dp}^{H_2O},\ {}^0C \quad (1)$$

where:

$t_{dp}^{t},\ {}^0C$ – the theoretical temperature difference between the acid dew point of the gases and the condensation temperature of the water vapor;

$t_{dp}^{H_2O},\ {}^0C$ – dew point temperature of pure water vapor [1, 21];

$$\Delta t_{dp}^{t} = \frac{200 \cdot \sqrt[3]{S_{rel}^{r}}}{1.25^{a \cdot A_{rel}^{r}}},\ {}^0C \quad (2)$$

where

a - share of what was taken away with the ashes, -;

S^r_{rel} and A^r_{rel} - reduced sulfur and ash contents relative to 1000 kJ/kg of fuel oil heat, %.kg/MJ [1, 23].

Following these formulas (1 and 2) for the selected base fuel according to Table 1 the theoretical dew point is obtained: $t^t_{dp} = 84.0,\ ^0C$.

Complete exclusion of low-temperature corrosion for air preheaters or economizers is provided if the temperature of the wall of the coldest section is higher than the dew point temperature by not less than 5÷10°C (minimum temperatures refer to minimum loads) [13].

In the present analysis it is accepted that the temperature to which the gases in the utilization facility will be cooled down to is 120÷125°C. At this temperature, the gases will enter the emulsifier.

It should be noted that in emulsifiers, almost complete trapping of sulfuric anhydride occurs. This means that the dew point of sulfuric acid vapors contained in the flue gases t^t_{dp} after entering the emulsifiers approaches the dew point of water vapor itself. Therefore it is not required to determine said temperature before the emulsifier stage [24].

THE ESSENCE OF THE INNOVATIVE METHOD FOR WASTE HEAT UTILIZATION

Baseline (current situation)

Most of the TPPs under analysis are characterized by high exhaust gas temperatures (150÷180 °C), leading to large heat losses with the exhaust gases and respectively low efficiency of the steam generator. A characteristic feature of steam generators is that the purification of gases is carried out by battery emulsifiers of the second generation and they are used in almost all thermal power plants, except for those in which first generation emulsifiers or even scrubbers are still in operation [2]. To prevent corrosion of the gas path, the purified gases at the outlet are heated by adding hot air to them after the boiler air preheater. After heating, the purified gases are sent through the outlet flue to the suction of the flue and then into the stack. The existing gas purification system not only does not allow the utilization of waste heat from the gases, but leads to a further reduction in the efficiency of the steam generator by about 3-4%. In Fig.1 shows a schematic diagram of the gas path after the steam generator with a battery emulsifier.

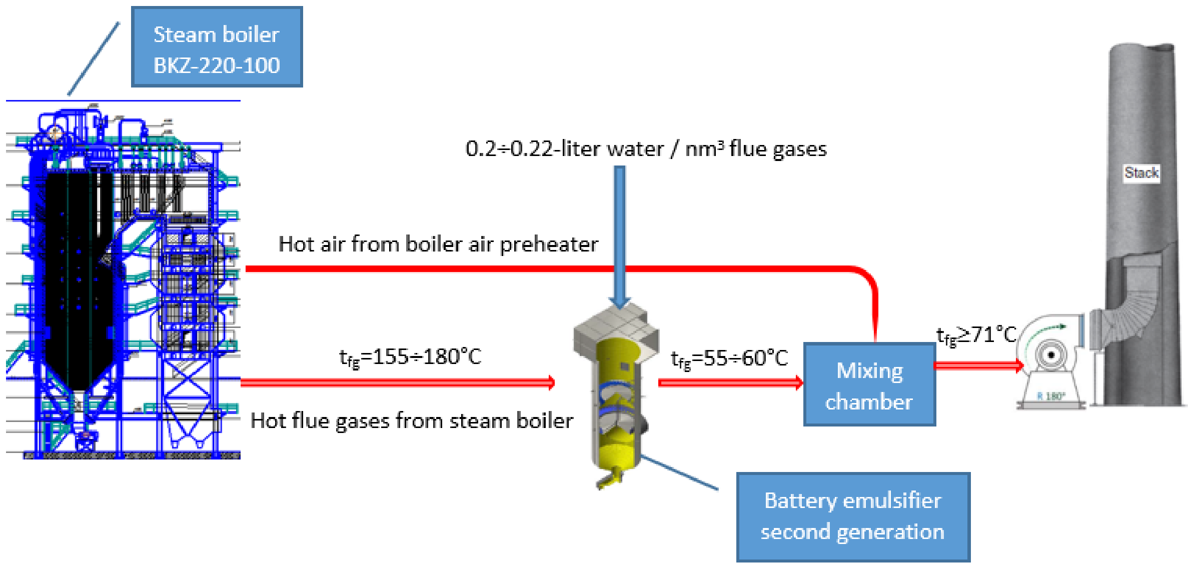

Fig.1. Schematic diagram of the gas path after the steam generator with a battery emulsifier

Description of the proposed method for heat waste recovery

The proposed method to improve energy efficiency provides for a more complete use of thermal energy of flue gases and the elimination of the need for additional heating in front of the stack. This can be achieved by directing a portion of the gas stream into a bag filter, which does not significantly reduce their temperature, and then mixing this portion with the main stream in the existing mixing chamber to achieve the desired overall temperature. The aerodynamic resistance of the bag filter, which will be connected in parallel with the emulsifier, (140÷170 mm h.c.) does not differ from the resistance of the battery emulsifier, which will allow using the existing exhauster without changes.

Moreover, such a scheme also allows deeper heat recovery from the main flue gas stream using an additional air preheater or economizer. Accordingly, two options for the implementation of this event are proposed:

1. Installation of a bag filter and an air preheater;
2. Installation of a bag filter and economizer.

Thus, several positive effects are simultaneously achieved:

• energy consumption for heating flue gases with hot air is eliminated;
• part of the heat energy of flue gases is utilized;
• deeper cleaning of gases from ash is carried out;
• emulsifiers are unloaded, the volume of flush water directed to the ash dump is reduced, which reduces the load on the emulsifier and flush water pumps and theoretically makes it possible to reduce their power consumption (for example, by installing a frequency control when it is economically justified by the current prices and tariffs);
• If there is market demand and economically viable transportation opportunities, baghouse ash can be sold for use in construction, agriculture or other industries.

After installing the bag filter, as a result of eliminating the need for heating the exhaust gases with air and saving significant heat output, the annual coal consumption will decrease. At the same time, the level of cleaning of the total the volume of gases from ash will be increased by about approximately 15%.

We will consider the two possible variants of the method implementation:

Option 1: Bag filter and air preheater installation:

This version of measures to improve energy efficiency provides for the installation of an air preheater simultaneously with the installation of a bag filter. However, only part of the gases (about 85% of the volume) must pass through the air preheater and emulsifier, and the rest will enter the bag filter in parallel flow. The thermal power of the air preheater is calculated at an average load of all analysed boilers. In the air preheater, the exhaust gases will be cooled from 150÷180 to 120÷125 °C depending on the flue gas temperature, and the air entering the air preheater will be heated from ambient temperature to a certain value. The sulfuric acid dew point, calculated according to the standard method, is 83.4°C, while the calculated temperature on the surface of the wall of the air preheater pipe will be 110 °C, which guarantees the absence of corrosion during the operation of the air preheater even in winter modes. In Fig.2 a diagram of the gas path after installation of a bag filter and an air preheater is shown.

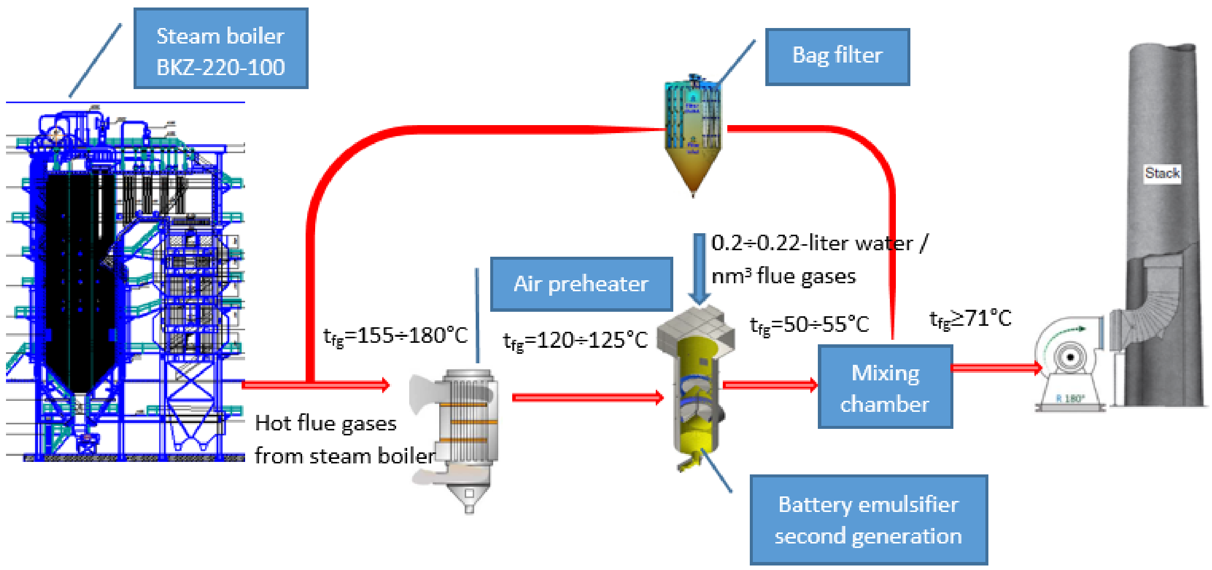

Fig.2. Diagram of the gas path after installation of a bag filter and an air preheater

After cooling the exhaust gases passing through the air preheater, they are purified in the existing emulsifier, in which the temperature of the gases will decrease even more, and the relative humidity will increase to 100%. The rest of the hot gases (about 15% of the volume, depending of the initial flue gas temperature), which pass through the bag filters, after deeper cleaning from 35÷50 g / m^3 to 25÷35 mg / m^3 will be mixed with the rest of the gas volume in front of the chimney. Despite the fact that the temperature of the main gas stream after cleaning in the emulsifier decreases to 50÷60 °C, due to the rather high temperature of the gases after the bag filter (about 5 °C temperature drop), the mixed flow will reach the required temperature of 70÷72 °C.

As a result of the installation of the air preheater, the annual coal consumption will decrease significantly. The total fuel savings as a result of the implementation of this energy-saving option will be 2800÷7800 t / year, and the boiler efficiency will increase by 1.5÷3.7%.

The implementation of this version of energy efficiency measures will lead to an annual reduction in emissions of sulphur dioxide, nitrogen oxides, dust and ash, carbon dioxide, as well as ash and slag waste storage which values have been calculated for considered cases.

Option 2: Back filter and economizer installation.

This option of measures to improve energy efficiency provides for the installation of an additional economizer simultaneously with the installation of a bag filter. Only part of the gas flow (~85%) should pass through the economizer and emulsifier, and the rest (about 15%) will enter the baghouse filter in parallel flow. A smaller part of the gases passing through the bag filter, after deeper cleaning, will be mixed with the rest of the gas volume. Despite the fact that after cleaning in the emulsifier, the relative humidity of the main gas stream will increase to 100%, and its temperature will drop to 50-60 °C, due to the rather high temperature of the gases after the bag filter, the mixed gases before entering the chimney reach the required 70÷72° C. Fig.3 shows a diagram of the gas path after installation of a bag filter and economizer.

In the economizer in front of the emulsifier, the exhaust gases will be cooled from initial flue gas temperature down to 120÷125°C, and the water flow from the return heating network entering the economizer will be heated from 55°C to a certain value depending on the water flow. The heat output of the economizer is calculated at an average boiler load. As a result of installing an economizer, annual coal consumption will decrease by 1800÷2200 tons. Unlike the previous version with an air preheater, installing an economizer will lead to a slight increase in electricity consumption for water pumps. However, the total fuel savings as a result of energy saving measures will amount to 2,800÷7,800 t / year, and the boiler efficiency will increase by the same 1.5÷3.7%.

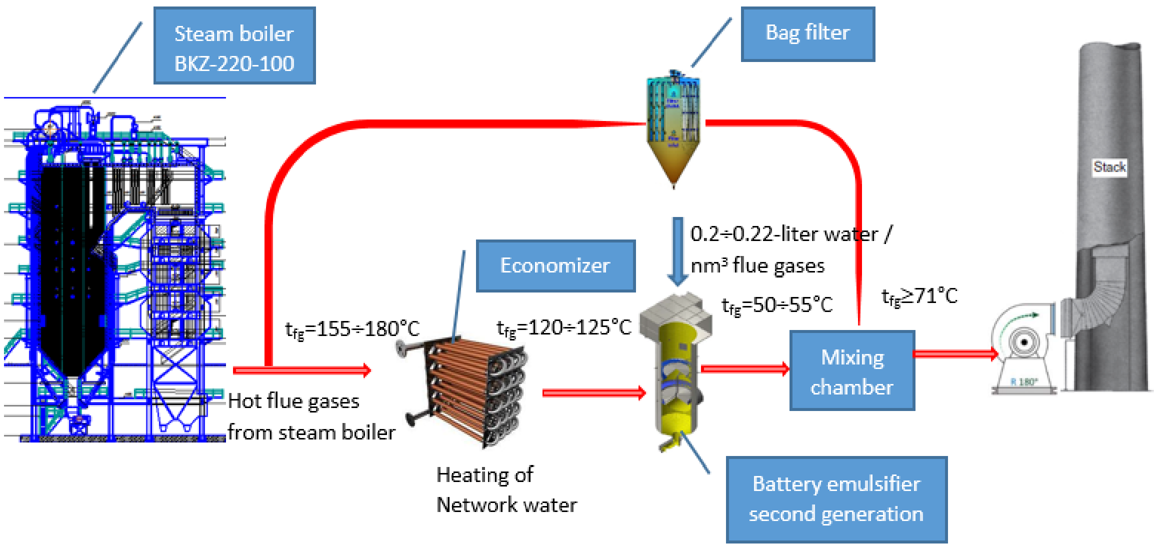

Fig.3. Diagram of the gas path after installation of a bag filter and economizer

The comparative analysis was performed between several variants of waste heat recovery units (air preheater and bag filter) of several different power steam generators (BKZ 420-140; BKZ-220-100 F; BKZ 160-100) operating at different heat loads, with different temperatures of exhaust gases. The analysis also includes a hot water boiler type KTVK-100, located in Ekibaztuzka TPP. In the present analysis the case with the realization of an economizer and a bag filter is not considered, but the results are similar to those with air preheaters and bag filters. In addition, the fuel used for boilers has extremely low prices, which implies poor profitability of measures related to reducing fuel consumption. The calculations were performed for several Kazakh TPPs using second-generation emulsifiers for flue gas purification.

Simulation calculations have been made with the software product „Steam boiler“, which are based on established methodologies for thermal calculations of steam generators [20].

The technical parameters are determined under real conditions, as the values are accepted as average for all boilers in 2020. As the analysis was made for four different cities (Stepnogorsk, Almaty, Pavlodar, Ekibastuz) with different climatic conditions, the initial temperatures of the heated air are different for the different cities. Coal prices and average operating hours also differ and this will have an impact on financial performance (redemption period, NPV, IRR). All boilers are equipped with a second generation emulsifier system for wet flue gas purification. Normative (or measured) temperatures have been adopted in the evaluation of the heat for heating the gases after the emulsifier.

Full thermal calculations of the waste heat recovery units (WHRU) [18, 19, 22, 23, 24, 25] (air preheater in combination with a bag filter) have been made, and the production, installation and commissioning costs have been estimated at European prices. The ecological payments that can be avoided as a result of the realised savings from coal are also estimated.

Comparative analysis of waste heat recovery devices for different steam boilers and conditions

The benchmarks for selection between GTs and GPE at CHPs include:

- Fuel savings;
- Payback period;
- Net present value;
- Internal Rate of Return;
- Specific savings;

One of the most important criteria for assessing the feasibility of an investment related to energy efficiency is the minimum investment per unit of energy saved (EUR / MWh) min. This criterion is characterized by a high degree of objectivity, especially in countries where the price of fuels is many times lower than those on the world market [26]. Fig.4 shows a graphical dependence on this criterion for all analyzed steam boilers.

Fig.4. Specific savings for different boilers

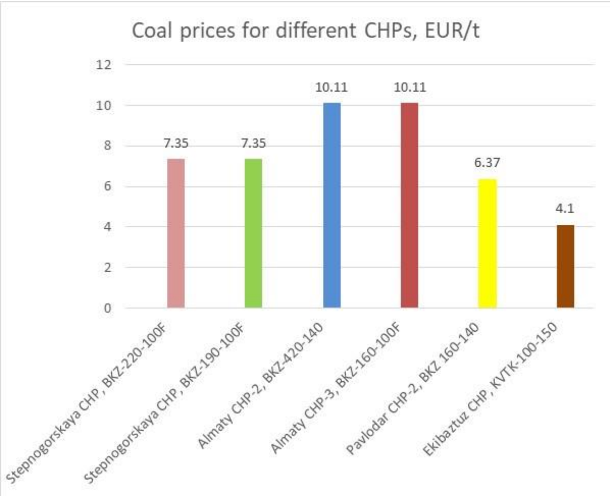

Fig.5. Price of Ekibaztuz coal for the different regions used by all boilers

The analysis shows that the most economically expedient is the investment for boiler BKZ-160-100 F, in TPP-3 Almaty and shows that the investment for 1 MWh of saved energy is 7.92 EUR. This assessment is complex and includes a complex dependence on several criteria: fuel price, operating time of the steam generator, exhaust gas temperature, average boiler load, etc. Undoubtedly, the price of coal has the greatest influence on the economic feasibility of the introduction of energy-saving equipment, because the assessment of savings is based on the most conservative method - the saved heat is estimated through the saved fuel. Because the introduction of a bag filter in the disposal system does not allow the entire gas flow to pass through the emulsifier, but only about 85%, which saves technical water, the price of water will therefore also have an impact on economic efficiency. An important advantage of the method is that the dry ash mass can be collected through the bag filter and even profits from its sale can be realized. In the present analysis, this advantage is not taken into account due to the lack of investor interest in the sale of ash in Kazakhstan. In Europe and other countries such as the USA, Canada and Japan, the ash trapped by dry filters is used as a building material - mainly for the construction of roads and highways.

Fig.5 shows the price of Ekibaztuz coal for the different regions used by all boilers.

Fig.6 shows the price of technical water used in the operation of emulsifiers in different regions.

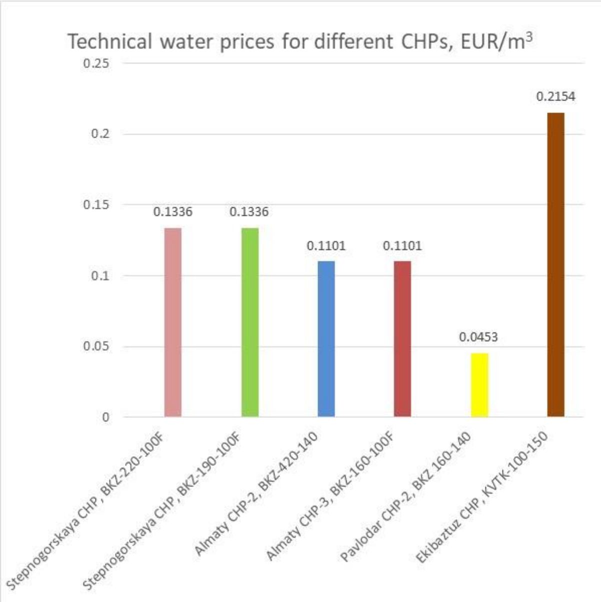

Fig.6. Price of technical water for the different regions used by all emulsifiers

CONCLUSIONS

A new waste heat recovery method is proposed and explained in the article. here are the most important conclusions based on the implemented study:

1. The proposed innovative waste heat recovery method, comprising a combination of an additional air preheater and a bag filter or alternatively an additional economizer and a bag filter, is a topical option for steam generators and boilers using "wet methods" for flue gas purification (scrubbers, emulsifiers first and the second generation). The method makes it possible to use the useful temperature drop of the flue gases, whereby part of the hot gases is purified with higher efficiency in a bag filter and then mixed with the wet gases after the existing emulsifier, without the need for hot air from the boiler air preheater.

2. The technical and financial analysis clearly shows the feasibility of the implementation of WHRU, despite the extremely low price of fuel and technical water, which negatively affect the payback period of the investment. Savings due to harmful emissions reduction (based on the emission charge) are also included in the assessment of the financial indicators. Their impact, however, is insignificant, but should be taken into account. The saved emissions reduce the average payback period of the investment by about 0.5 years.

3. The financial analysis gives an indisputable advantage to WHRU for boiler BKZ-160-100F in Almaty CHP-3. With its highest IRR of 34.7% and Payback period 2.77 years, the project is extremely attractive for implementation. However, it should be noted that all presented variants of WHRU variants are characterized by a low Payback period (2.77-6.78 years) and so are attractive and deserve high investor attention.

4. The realisation of the WHRUs has high environmental impact and is estimated to reduce Ekibaztuz coal use from 2867 to 8034 tons/year, CO_2 emissions from 4153 to 11302 t CO_2/year, SO_2 emissions from 38.8 to 108.1 t SO_2/year and NOx emissions from 18.4 to 51.7 t NOx/year, depending on the selected boilers.

5. The conclusions drawn can be used by experts in the field when making an investment decision regarding the introduction of the relevant technologies in TPP and CHP.

ABBREVIATIONS

CHP - Combined Heat and Power;
IRR - Internal Rate of Return;
NPV - Net Present Value;
NPVQ - Net Present Value coefficient;
PB - simple payback period;
TPP - Thermal Power Plant
WHR - Waste Heat Recovery;
WHRU - Waste Heat Recovery Unit.

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