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Water Vapor Condensation from Combustion Products and its Usage Possibilities

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Abstract: Moisture condensation from combustion products must appear in the fuel gasses stream of every boiler plant, in some period of operation. Discharging this condensate into environment leads to additional heat loss. Although this amount of heat compared to the total capacity of boiler house is not significant, it is not negligible. At the beginning, this paper deals with causes and sources of water vapor in the combustion products. Then possibilities of usage of formed condensate in the district heating system for improving energy efficiency and decreasing carbon dioxide emission on an example of system in District heating plant "Krivi Vir" in Niš, is presented. After that, some vital factors which have influence on efficiency of considered system are pointed, as well as possibilities for application.

Keywords: carbon dioxide emission reduction, district heating system, fuel saving, water vapor condensation from combustion products;

1. Introduction

Every energy plant which uses fossil fuel as a source of energy contains a boiler as a unit for transformation of fuel energy into heat energy. Because of cold surfaces of chimney, water vapor condensation from combustion products is unavoidable, especially during the system start. The condensate is very acidic, but it contains some heat energy which can be used (regenerated). The subject of this paper is condensation of water vapor from combustion products in the fuel gasses stream and possibilities of its usage in order to increase the energy efficiency and decrease carbon dioxide emission of the district heating system boiler house, through the presentation of the case of district heating plant (DHP) "Krivi Vir" in Niš.

2. Water vapor in combustion products

Under total combustion conditions in general, combustion products consist of $CO_2, N_2, H_2O, O_2, SO_2$, and solid unburnt residue - ash, whose quantity can be determined by analytical formulas obtained from stoichiometric equations.[1] Water vapor generated in the combustion process is of particular interest for this paper. Its quantity depends on the fuel type (moisture of fuel and amount of newly created water vapor as a combustion product from certain components) and, to a lesser degree, on air humidity.

2.1. Humidity from fuel

Depending on the type of fuel, water appears in the form of gross moisture or hygroscopic moisture, to a greater or lesser extent. In the solid fuel as biomass and lignite content of moisture is up to 50%. [1,2,3] In such cases water vapor harms combustion process, since latent heat of evaporation, which is not negligible, is lost. Because of that wet fuel must be dried. In the case of quality solid fuel, like biomass and lignite, the content of moisture is less than 10%[1,2,3]. Liquid and gaseous fuels don't contain moisture, or its amount is negligible. Consequently, in the case of their use, water vapor in the combustion products is result of combustion of particular fuel component.

2.2. Water vapor from combustion process

During combustion of certain fuel components, water vapor is formed. Depending on the type of fuel, the amount of water vapor can vary. Stochiometric equations which describe combustion of some component of fuel define amount of formed water vapor: [1,2,3]:

$$1kg\ CH_4 + 4kg\ O_2 \rightarrow 2{,}75kg\ CO_2 + 2{,}25kg\ H_2O + 49949kJ \quad (1)$$

$$1kg\ C + 2{,}67kg\ O_2 \rightarrow 3{,}67kg\ CO_2 + 33913kJ \quad (2)$$

By carbon combustion water vapor is not generated, while during methane combustion water vapor is the main combustion product, besides carbon-dioxide.

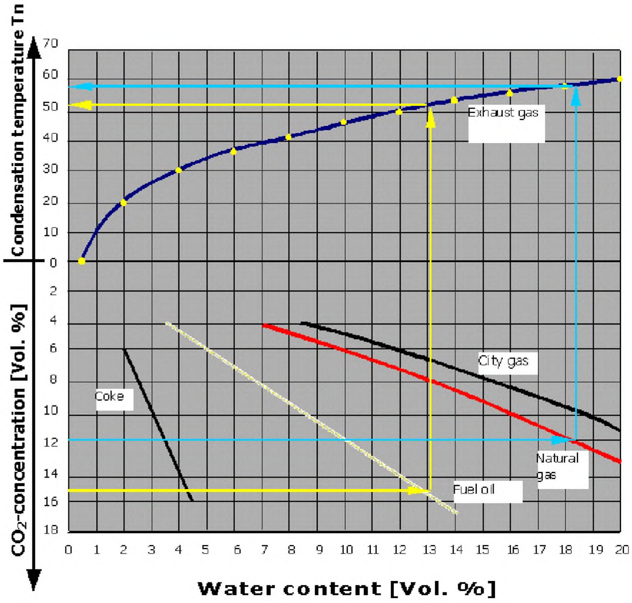

Figure 1. Diagram of dependence of dew point and percentage of water vapor on the share of carbon dioxide in combustion products according to standard DIN 4705 [8]

In case of highquality solid fuels as coke (black line in Figure 1), there is only a few percent of moisture in the products, while during combustion of 1 kg of natural gas, composed mostly of methane, about 2,25 kg water vapor is obtained with moisture up to 20% (Figure 1). It can be concluded that during combustion of fuel based on hydrocarbons, like liquid and gas fuel, amount of water vapor is significant, as well as amount of heat (latent and sensible) which is lost by that.

2.3. The heat in the water vapor of flue gases

The heat loss due to flue gases is a vital loss of boiler plant. The heat lost with water vapor is included in it. The heat lost with water vapor consists of latent heat (condensation) and physically sensible heat [4]. This heat can be used by installation of economizer, as well as by condensate recovery in chimney. The second way is especially important for this paper. In the case of gas, temperature is below than dew point temperature (T_n in the upper part of the Figure 1), for the defined absolute moisture of the combustion products (lower part in the Figure 1) condensation of the water vapor appears on the temperature which depends on the type of fuel. The condensation in chimney of the boiler plant has to appear during the operation start and on walls of chimney, because of cold surfaces. Dew point in case of natural gas, for usual combustion conditions is around 56-58°C. In the case of combustion of lignite, coke, fuel oil and other fuel with lot of impurities, this temperature is significantly lower. Since the temperature of condensate of the natural gas is higher, and condensate has physical and chemical properties suitable for further use, it can be used as feed water of district heating plants boilers with minimal chemical treatment. In this way its heat can be used, because the feed water, used from water supplier or onsite, sometimes is up to 40°C colder than condensate.

3. Condensate properties

The condensate of flue gases is acidic while softened water, where carbon dioxide from gases are dissolved, with pH value in the range between 2 and 6 [8], and in case of natural gas pH value is in the range between 2 and 7 [4,5,6]. It can not be used and also it must not be discharged into the public sewage system because of its aggressiveness. In order to increase pH value to value which can be discharged into the public sewage system it is necessary to pass through the bed of calcium carbonate (or, rarely, magnesium carbonate). In this way it is neutralized. Equation of neutralization is [6]:

$$CaCO_3 + 2H^+ \rightarrow Ca^{2+} + CO_2 + H_2O \quad (3)$$

As it can be seen, during acidic neutralization dissolution of Ca^{2+} occurs and its hardness increases. Since that condensate is very soft, this hardness increase is negligible. Neutralized condensate from the combustion products is practically clean and suitable for application as feed water od district heating system. Condensate from the combustion products of other fuels (first of all solid and liquid: coal, heavy fuel oil, biomass) have to be detailly treated because of other admixtures which are contained before injected in the water tract of the boiler. This kind of plant is carried out in Sweden, in the town Karlskoga. It is a plant for electric energy, heat energy and technological steam production. Fluidized bed combustion boiler is installed, and different types of waste can be used as fuel. Fuel gases and condensate are treated in the special plant with lot of treatment processes. [7] In this paper, the new system for collection and usage of condensate from the chimney for feed water in the district heating plant (DHP) ''Krivi Vir" in Niš will be shown.

4. District heating plant ''Krivi Vir'' in Niš

District heating plant "Krivi Vir'' is the biggest heat source for the district heating system in Niš. Capacity of the district heating plant is 128 MW. Natural gas, the composition of which is given in the Table 1, is used as primary fuel, while fuel oil is the alternative.

Table 1. The usual percentage composition of natural gas, used in DHP ''Krivi Vir'' in Niš [6]

Component	N_2	CO_2	CH_4	H_2S	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}
Volume percentage [%]	0,99	0,47	96,18	0,01	1,62	0,51	0,18	0,04

The boiler house of this DHP has three boilers with capacity of 35 MW, 35 MW and 58 MW. Each boiler has its own chimney. Boilers with 35W capacities have metal chimneys inside of DHP, while third has brick-metal chimney outside.[5] New system for draining condensate is installed in this DHP in 2020 with its possible usage as feed water of the system because of the network losses. Except condensate, well water and water from the city water supply can be used for feeding the system because of water loss in the heating network. Starting from the heating season 2020/21 only well water and condensate are practically used. [9,10] A simplified schematic of this system is shown in Figure 2.

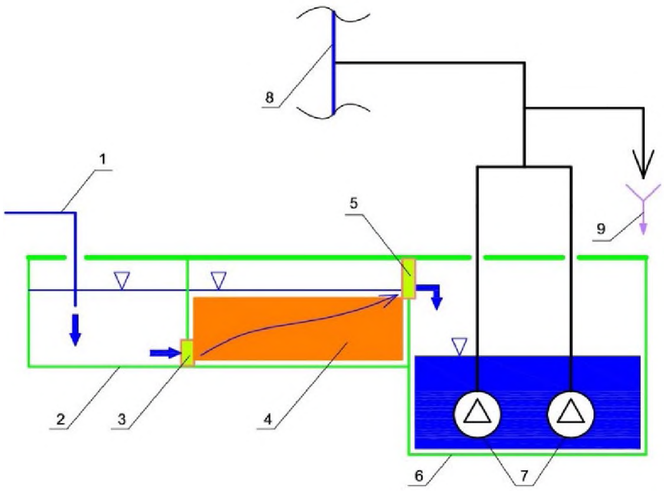

Figure 2. Principle scheme of the system for removal, treatment and use of condensate [6]

Condensate from all chimneys (1) comes into the slow channel (gross impurity settler) (2). After settling of coarse impurities, before passing through the pool with calcite bed (calcium carbonate) (4), it flows through filter for gross impurity (that were not settled) (3). After neutralization in calcium-carbonate, it passes through one more filter for mechanical impurity and enters the collection tank for treated and neutralized water (6). It can be sent by pumps (7) to expansion vessel (8), or to sewage system (9). [5]

4.1. Quality of treated condensate

Condensate treated in this way has lower value of pH (6-7) than needed value for boiler water (9,8+/-0,2) [9]. However, it is added in heat network, where it is mixed with water from the system. Condensate obtained in this way is not a problem, since the amount of condensate is small compared to system water flow which is about 2500 and due to the fact the other parts of system are not sensitive to acidity as is the boiler. Since considerable feed of the system is by using condensate, water in the system would become acidic during time, which results as unallowed mode of operation. In order to prevent this situation, there is a plant for chemical treatment of the water: removing iron from return water and adjusting pH value of water (figure 3).

Figure 3. Device for removing iron and adjusting the pH value of returning water in DHP "Krivi Vir" in Niš

Condensate has greater hardness after passing through calcite bed than before. However, since condensate in the moment of its occurrence until contact with calcite bad has low hardness, increasing of hardness is not of great importance. In certain periods condensate has higher hardness than maximal prescribed value, but sometimes is below upper limit. Consequently, it never causes any problem. Hardness of water in district heating network and in boilers is always below upper limit (0,5 °dH – German degrees of hardness) [9].

5. Analysis of fuel saving and carbon dioxide emission reduction by using new system in ''Krivi Vir'' in Niš

Moisture from fuel gases condensates on the temperature between 56 – 57 °C, and contains certain heat, since return water from the city is often lower temperature, and water used as feed water is well water with adopted temperature of 10 °C. In this chapter savings in natural gas consumption will be described. Of course, condensate generation is not enough to completely replace use of well water at all, but certain part of feed can be done by condensate. The readings of the parameters of the condensate which goes into the system are mostly mornings when the condensate formation is at its peak. Data from internal records of DHP ''Krivi Vir" are used [9]. Values were measured in the morning. Cooling of condensate in the collecting basin is neglected. This principle is possible for reviewing system usage, especially taking into consideration that the biggest amount occurs in mornings and immediately is injected into system. This methodology is acceptable for this paper, because the largest amount of condensate is produced in the mornings and it is in few minutes pumped in heating network, so that it does not have time to cool down. The amount obtained during the rest of a day has minor importance than at starting system.

5.1. The methodology for calculation of natural gas savings

Let assume condensate temperature in collection tank to be t_c, wall water temperature to be t_b, and temperature to which it is necessary to warm up supplementary water to be t , in which case $t_b < t_c < t$. Absolute saving of energy for warming water quantity is:

$$\Delta Q = \rho \cdot V \cdot c_{pw} \cdot (t_c - t_b) \tag{4}$$

Absolute saving of fuel ΔV_g is calculated according to lower heating value and boiler plant efficiency η:

$$\Delta V_g = \frac{\Delta Q}{\eta \cdot H_d} \tag{5}$$

Relative saving is calculated as:

$$\delta V_g = \frac{\Delta V_g}{\Delta V_g + V_g} \cdot 100\% \tag{6}$$

The medium daily temperature is calculated according to expression: [9,11]:

$$t_{sr} = \frac{t_7 + t_{14} + 2 \cdot t_{21}}{4} \tag{7}$$

Values in numerator of the fraction in expression (7) are temperatures measured at 7, 14 and 21 hour. In the way described before, by using data on a daily and monthly basis about fuel saving, next dimensions are determined: absolute heat saving by using condensate, and absolute and relative savings of the natural gas by using of condensate on annual and monthly basis for heating season 2022/23.

5.2. The methodology for calculating the reduction of carbon dioxide emissions

Carbon dioxide in natural gas combustion products comes from hydrocarbons and from fuel. The stoichiometric equations of the combustion of hydrocarbons in natural gas can be represented, per volume unit in general form:

$$C_mH_n{}' \, C_mH_n + \left(m + \frac{n}{4}\right) C_mH_n{}' \, O_2 \rightarrow m C_mH_n{}' \, CO_2 + \frac{n}{2} C_mH_n{}' \, H_2O \tag{8}$$

where $C_mH_n{}'$ is volume ratio of each component. These stoichiometric equation have to be used for each hydrocarbon component in fuel. As can be seen, the amount of released carbon dioxide, from hydrocarbons, per volume unit of fuel is defined by first term on the right side in (8). Amount of carbon dioxide obtained by each component is then:

$$M_{C_mH_n} = m \cdot C_mH_n{}' \cdot \rho_{CO_2} \tag{9}$$

where:

$M_{C_mH_n}$ is amount of carbon dioxide from each hydrocarbon in $[kg/m^3 of\ fuel\,]$, and

$\rho_{CO_2} = 1{,}96\ kg/m_N^3$ is density of carbon dioxide in normal conditions.

The mass of emitted carbon dioxide per volume unit of fuel (specific amount of carbon-dioxide) is obtained by summing the emitted amounts of each hydrocarbon component, and carbon dioxide from fuel:

$$M = \sum_i M^i_{C_mH_n} + CO_2{}' \cdot \rho_{CO_2} \tag{10}$$

where $CO_2{}'$ is volume ratio of carbon-dioxide in fuel.

The total amount of emitted CO_2 for burned volume of fuel V_g is then:

$$M_{CO_2} = M \cdot V_g \tag{11}$$

The absolute CO_2 emission reduction (unemitted amount of CO_2) by using presented system can be calculated according to (5) and (11) as:

$$\Delta M_{CO_2} = M \cdot \Delta V_g = M \cdot \frac{\Delta Q}{\eta \cdot H_d} \tag{12}$$

And relative CO_2 emission reduction is similarly to relative fuel savings:

$$\delta M_{CO_2} = \frac{\Delta M_{CO_2}}{\Delta M_{CO_2} + M_{CO_2}} \cdot 100\% = \frac{\Delta V_g}{\Delta V_g + V_g} \cdot 100\% = \delta V_g \tag{13}$$

5.3. Results

According to described methodologies and data from considered DHP from November 2022 to the last day of heating season in April 2023 fuel and energy saving is defined. Data about condensate production for October was not registered, because of a small number of heating days and small amount of condensate. Heating season 2022/23. is considered then without data about fuel consumption in October, too. Based on data from DHP plant efficiency is 91% that is, 0,91 [9]. Lower heating value of fuel is 34384 $\mathrm{kJ/m_N^3}$[6]. Taking into consideration that efficiency is defined with devices, it can be concluded that without devices efficiency would be smaller. It is assumed efficiency of 90,9% without device, because it is difficult to calculate exactly without this device. Data of fuel savings calculation are shown in the Table 2.

Absolute monthly savings are calculated by summing daily savings. Relative savings of natural gas in every month (and entire heating season) were calculated by using data of natural gas consumption during the whole month and absolute saving for the whole month (or entire heating season). Natural gas saving for the heating season 2022/23. is about 17247,26 m_N^3, i.e. 0.146 %.

Table 2. Results of fuel saving calculation in DHP "Krivi Vir" in Niš for heating season 2022/23

Month	t_{sr}[°C]	t_c[°C]	$V\ [m^3]$	$\Delta Q\ [kWh]$	$\Delta V_g\,[m_N^3]$	δV_g[%]
November	9,77	39,12	820	27639,55	3183,561	0,202
December	6,18	37,49	882	28089,6	3235,398	0,151
January	5,29	39,37	877	29841,95	3437,236	0,146
February	4,1	34,11	552	15747,1	1813,773	0,071
March	9,28	40,2	792	27597,29	3178,693	0,173
April	10,14	37,25	665	20824,53	2398,598	0,172
Heating season 2022/23	7,46	37,92	Σ=4588	Σ=149740,024	17247,26	0,146

The amount of carbon dioxide emitted by burning volume unit of natural gas usually used in DHP ''Krivi Vir'' in Niš is presented in Table 3. The values of absolute and relative unemitted amounts of carbon dioxide are shown in Table 4.

Table 3. Amount of emitted carbon dioxide per volume unit of fuel for each component and total amount of carbon dioxide per volume unit of fuel

	CO_2	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}	M_{CO_2}
m	/	1	2	3	4	5	
Volume ratio	0,0047	0,962	0,016	0,005	0,002	0,0004	
$M\ [kg/m_N^3]$	0,009	1,885	0,064	0,03	0,014	0,004	2,006

Table 4. Absolute and relative reduction of emission by using considered device for heating season 2022/23

Month	November	December	January	February	March	April	Heating season 2022/23
$\Delta M_{CO_2}\ [kg]$	6385,791	6489,769	6894,629	3638,182	6376,027	4811,26	34595,659
δM_{CO_2} [%]	0,202	0,151	0,146	0,071	0,173	0,172	0,146

Absolute carbon-dioxide emission reduction, by using new system in heating season 2022/23. is 34595,659kg. As can be seen, relative carbon-dioxide reduction is identical to relative fuel saving.

5.4. Discussion

From the expression (5) can be seen that absolute fuel savings and carbon dioxide emission reduction is in the direct dependency with absolute saved heat and in indirect dependency with boiler plant efficiency and fuel lower heating value. Based on that it can be concluded that this type of system is more efficient in case of less efficient plants. Diagrams of dependance between fuel savings and efficiency is given in the Figure 4a. Also, diagram of dependance between absolute emission reduction is given in the Figure 4b. These diagrams are nonlinear functions. However, nonlinearity can be neglected in the range of efficiency usual for gas fired plants, as can be seen in Figure 4.

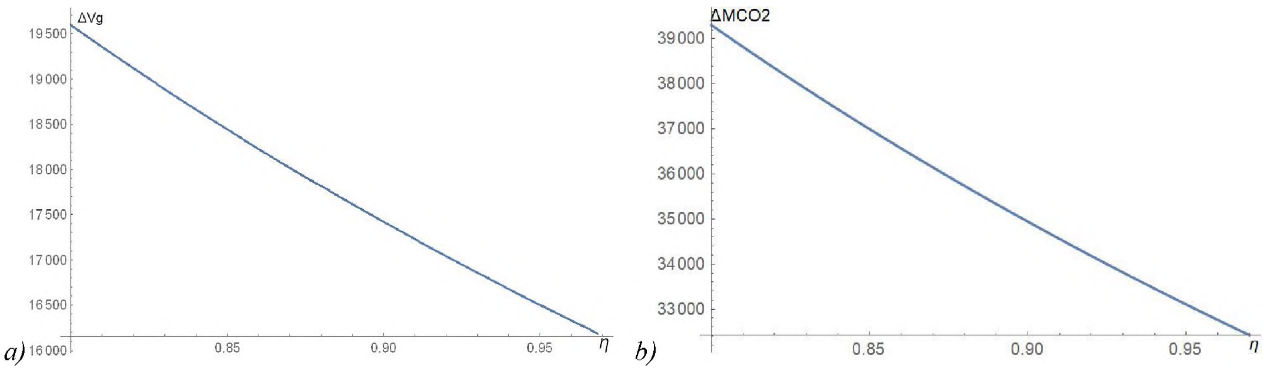

Figure 4. Dependance absolute fuel savings a) and absolute CO_2 emission reduction b) on boiler plant efficiency for efficiency values 0,8 to 0,97. for $H_d = 34384\ kJ/m_N^3$ and $\Delta Q = 149740{,}024\ kWh$

Values of ΔV_g and ΔM_{CO_2} for some values of efficiency are given in the Table 5.

Table 5. Values of absolute fuel savings and absolute emission reduction according to efficiency for same values of ΔQ and as in Figure 4

Efficiency η	0,8	0,85	0,9	0,95
$\Delta V_g\ [m_N^3]$	19597	18444,3	17419,6	16502,8
$\Delta M_{CO_2}\ [kg]$	39311,6	36999,3	34943,7	33104,6

Absolute condensate generation is in direct dependance with fuel consumption which is the highest at the biggest boiler output. However, it is in opposite dependency to fuel gasses temperature which is the lowest in warm weather, because of less boiler output. Since factors influence on condensate generation in different ways, it is necessary to establish mathematical function between condensate generation and mentioned parameters, and then search for maximum of the function, which is possible in the real conditions of boiler operation. It exceeds the scope of this paper.

However, based on data from Table 1 the biggest condensate production is in the warmer months. If linear method of the least squares is applied to data in Table 1, one can notice that with increasing of medium outside temperature production of condensate is increasing too, as well as savings. This approximation, since it is calculated only for 6 values, and because of neglecting other influential dimensions, is not near to real dependence which is difficult to determine, but for the purpose of this paper can show dependence saving on DHP external conditions, as in Figure 5.

Also linear method of the least squares can be implemented on carbon dioxide emission reduction as it is shown in Figure 6. The slope in this case is identical with slope of fuel savings approximation. The linear determination coefficient (r^2) for absolute parameters is 0,053 and for relative parameters is 0,733.

Collecting tank in analyzed plant is not isolated. If the tank were isolated, the savings would be much greater. Condensate temperature in collecting tank in that case is much higher than values in Table 1, and saving is more significant than now. Due to increased fuel savings, then carbon emission is also reduced. It can be solved with negligible financial costs according to befits.

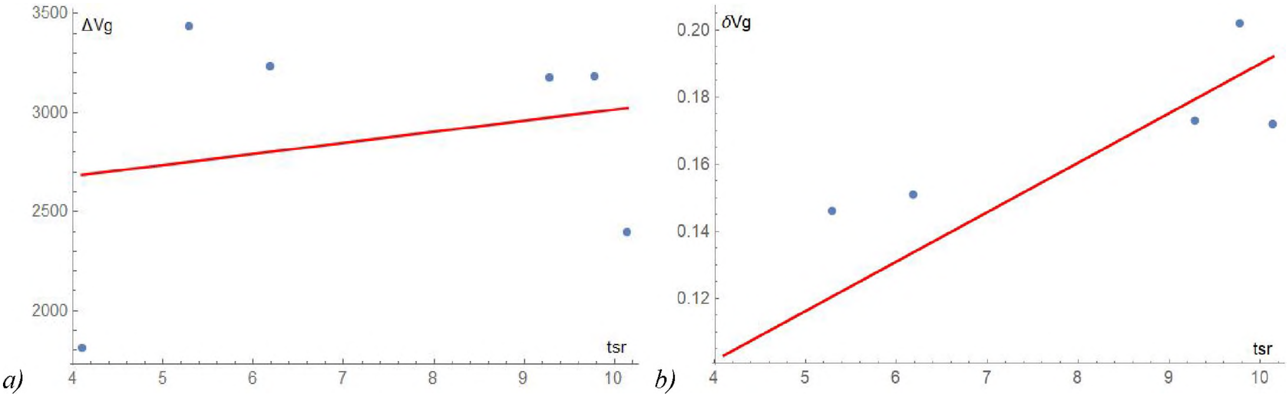

Figure 5. Dependence of savings on outside temperature according to data from the Table 1, by application of linear method of the least squares: a)absolute savings, b) relative savings

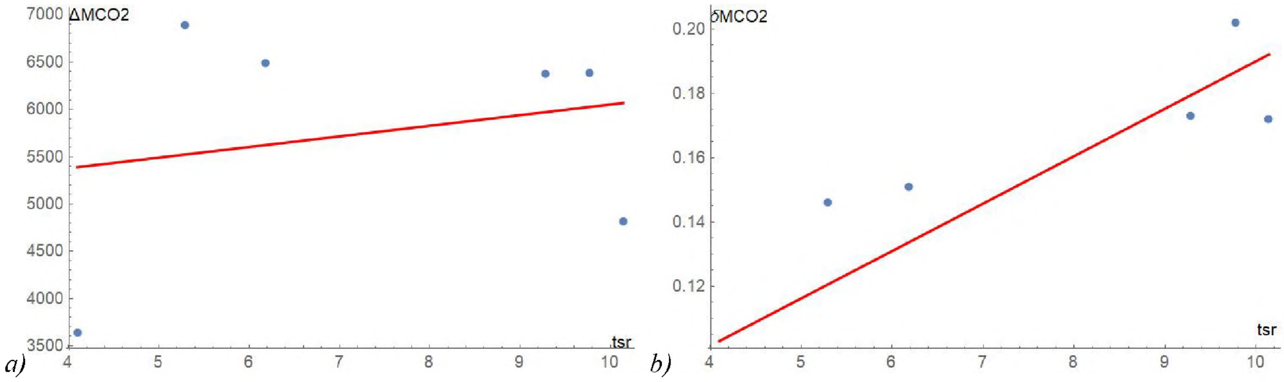

Figure 6. Dependence of CO_2 emission reduction on outside temperature according to data from the Table 1, by application of linear method of the least squares: a)absolute emission reduction, b) relative emission reduction

6. Conclusion

This concept of removal, treatment and use of condensate from fuel gases of gas fired heating plants is a simple and cheap way for efficiency increase. Fuel saving and emission reduction is significant according to financial costs of this device. Because of very low investment costs, it is very useful, especially for old and ineffective plants in case of unfavorable financial situation. A concept like this could be used in the case of other, dirtier fuels. However, in the case of these fuels, percentage of water vapor in combustion products is lower and condensate which is created requires serious chemical treatment. Hence, this way of using condensate does not pay off fast as in case of using natural gas. Since the winters are, on average, becoming more warm and that external temperature is much higher than in previous years, this type of auxiliary systems has greater importance in the future of district heating systems, because under these external conditions a larger amount of condensate is produced.

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