Raising of fuel utilization efficiency in the contact heat exchange boilers

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Abstract. The relevance of the study is due to low effective utilization of heat of fuel combustion in existing heat generators, in particular, boiler units intended for heat supply to industrial enterprises and residential buildings. Another important research area of the study is the ascertaining ability of a boiler to operate on raw water, which hasn’t undergone a process of preliminary reduction of hardness. The article reveals the use of latent heat of water vapor contained in the exhaust gases in all models of existing boiler units. The authors proposed and described a method for the effective utilization of the latent heat by means of contact heating of the coolant.

1. Introduction
The increase in fuel use in boilers and heat and power plants is now, as heretofore, the most important task for the effective utilization of the heat of power resources combustion [1-3]. The urgency of the problems of the efficient use of fuel is steadily growing, especially in the context of natural gas, the most valuable type of fuel [4, 5]. If we draw up the power balance with the highest heat value of fuel taking into account the so-called latent heat of formation of water vapor contained in the exhaust flue gases, then the amount of heat carried off by the exhaust gases in modern boilers is more than 18 % [6]. Maximal utilization of fuel heat is possible only after cooling combustion products below the dew point, which is 50 ... 60 °C during the natural gas burning, with using of the latent heat of vaporization of water vapor contained in the gases [7]. These specific characteristics of the gas and its combustion products allow, in particular, to use contact heat exchangers where the gases are in direct contact with the heated liquid [8, 9]. Such heat exchangers with quite acceptable dimensions are manufactured with low metal consumption, they provide relatively low power consumption and ensure very deep cooling of exhaust gases to 30 ... 40 °C and 70 ... 80 % condensation of water vapor, which was previously considered an inevitable loss [10].

The main feature of contact water heaters is the fact that they have a high efficiency factor, reaching up to 97 % in heating systems, considering the highest heat value of the fuel [11]. This is because most of the heat is transferred from the combustion products to the water not through the metal wall but by direct contact of water films with high-temperature gases. In this case, the gases cool to a temperature of
30 ... 35 °C, that is, below the dew point, and their latent heat in the form of condensed water vapor is used for water heating. Therefore, under the conditions, the loss of heat carried away with exhaust gases is equal to 1.5 ... 2 % [12]. Depending on the fluctuation coefficient of the excess air when gases are as cold as 30 ... 35 °C, 80 ... 90 % of the latent heat of water vapor condensation is released from them [13]. Therefore, during operation, there is no need to achieve mandatory cooling of the combustion products to lower temperatures.

In the contact apparatus, natural de-aeration of heated water occurs. If gas is completely burnt in the furnace, combustion products do not contain any oxygen [12-14]. In contact water heaters, it is possible to heat hard water without its prior softening. After heating water to 100 °C, only carbonate-hardness salts can settle out in the form of scale and sludge. Non-carbonate salts settle out only when water is oversaturated with these salts. Gas contact water heaters have low specific metal content and are explosion-proof in operation. The contact water heater efficiency factor does not depend on the heat load fluctuation but is subject only to the temperature of feed water. In these devices, when applying fixed loads, the density of water irrigation in the contact chamber increases drastically, and at the same time the velocity of high-temperature gases moving towards the water streams increases. The resulting enhanced turbulization of the gas-liquid medium in the contact chamber gives rise to the intensification of heat and mass exchange of gases and water, so that the temperature of the exhaust gases at the outlet side of the contact apparatus stays the same [15, 16].

Gas contact water heaters might have a broad application comprising several consumer groups, the main of which are housing and utility sector and oil industry. The use of deep-softened mineralized water in power oil-field steam generators is a very promising method of improving oil recovery from a well. As steam irrevocably runs from the field steam generator into the well, there is a need for sufficient volumes of treated feed water. Contact water heaters do not have large thermal inertia, they quickly reach a predetermined operating mode and do not require auxiliary boiler equipment such as boilers, feeding pumps, devices for chemical cleaning [17, 18].

2. Theory

In the design of Valdex (Russia) heat-generating devices, in the boiler units of the KVA series produced by the Borgazoapparat Company (Russia), in the boiler units produced by STM-Oskol (Russia), in the steam-boiler units of the Moderno series (Kazakhstan), in the Viessmann Vitomax (Germany) steam boilers, the convective part is designed as a gas pipe, and heat exchange is carried out through the surface of the fire tubes. The heat transfer intensity is low and, therefore, the metal intensity of the convective part is high (fire tubes are applied).

The authors have developed and patented a new design of a heat-generating device (Figure 1) [19, 20], which allows to obtain saturated water vapor with a temperature up to 150 °C. We obtained the given technical result with a heat-generating device consisting of a boiler, a feeding pump, a hydraulic distribution valve, a metering unit for complexonates, a check valve. The boiler design includes a combustion chamber in the form of a fire tube with a water jacket of water heating or evaporative type, and its convective section is in the form of irrigation chamber of condensation-type with a separator-water eliminator and a cylindrical screen [21].

The heat-generating device operates as follows. Fuel 5 (liquid or gas) is supplied to the burner 4, where it mixes with the supplied air 6 (excess air amount corresponds to the characteristics of the burner depending on the type of fuel burned) and is flared. Reverse delivery water or condensate 12 is supplied from the consumer to the coldest part of the hydraulic distribution valve 8. Circulating water is forced from the coldest part of the hydraulic distribution valve 8 to the irrigation chamber 3 via the irrigation nozzles 11 with a centrifugal circulation pump 10. The feed in of a circulate water spray is cone-shaped, it washes the walls of the irrigation chamber 3 and the cylindrical screen 20 to prevent them from
overheating. The process of heat-mass exchange runs intensively since the products of combustion are brought into contact on an intensive basis with the cooler liquid drops, which are in a finely dispersed state. The combustion chamber has a deadlock design with a cylindrical screen 20 around the flame 7 in the irrigation chamber 3, which provides an increase in the contact time of the vapor-gas mixture and contributes to a more complete condensation of water vapor.

Since in the irrigation chamber of the combustion chamber, heat and mass exchanges of related media, namely, a gas mixture with a temperature of 300 °C to 1000 °C and finely dispersed irrigation water with a temperature within the range of 30 ... 50 °C, which have high mutual adhesion, takes place, then the vapor component of the gas mixture is condensed on the irrigating drops, it exchanges energy with the rest of the water mass and absorbs the heat of the adhesion-condensation transformation. The colder surface of the irrigating drops absorbs the gas component. Thus, the entire energy losses totally convert into the feed water heat. Then the circulating pump energy used for the development of the irrigating drops surface also transforms to the heat of water, at the end of the process it runs into the circulation water flow with concentrated coalescence of the drops, resulting in a complete separation into two macro-phases – liquid and gas.

Figure 1. Scheme of heat generating installation: 1 - combustion chamber in the form of a fire tube, 2 - water jacket, 3 - irrigation chamber of condensation type, 4 - burner device, 5 - fuel supply, 6 - air supply, 7 - sweep of flame, 8 - hydraulic distribution valve, 9 - irrigating heated drops flow, 10 - centrifugal circulation pump, 11 - irrigation nozzles, 12 - reverse delivery water or condensate, 13 - complexonate dispenser, 14 - separator-water eliminator, 15 - water-sludge collector, 16 - heat carrier (hot delivery water or saturated water vapor), 17 - sludge blowing, 18 - exhaust gases, 19 - check valve, 20 - cylindrical screen, 21 - centrifugal feeding pump, 22 - heating medium (hot delivery water).

The heated water flows into the water-sludge collector 15, which is a water trap and a sludge separator. The heated water flows under gravity from the water-sludge collector via the check valve 19 into the
The hottest part of the hydraulic distribution valve 8. The check valve prevents the boiler from overflowing with changes in the load of the boiler unit. Feed water from the hottest part of the hydraulic distributor 8 is fed with a centrifugal feeding pump 21 at a temperature of about 95 °C to the water jacket with a loss equal to the boiler unit performance and is heated to the temperature of 150 °C, and the rest of the heat carrier 22 is forced to the heating system after receiving the saturated steam.

The exhaust gases have a temperature below 70 °C, which is lower than the temperature of the exhaust gases in ordinary boilers (110 ... 140 °C is recommended depending on the fuel characteristics and the heating capacity of the boiler). With that, heat losses occurred due to exhaust gases, decrease and, consequently, efficiency factor increases (a 12 ... 15 °C decrease in exhaust gases temperature increases efficiency factor for approximately 1 %). The increase in the boiler efficiency factor is possible due to utilization of heat of condensation of water vapor of the exhaust gases with use of the highest heat value of the fuel, which can provide further 5 ... 6 % increase in the boiler efficiency factor.

Exhaust gases 18 are cleaned of moisture drops condensed when the gases temperature decreases below the dew point temperature, as well as moisture contained in the evaporated form in the gases in the separator-water eliminator 14 which is located at the outlet side of the combustion chamber, and are released to the atmosphere. Harmful gaseous emissions (CO, CO₂, nitrogen oxides) are absorbed by water. The sludge accumulated in the lower part of the collector, which formation intensifies due to the complexonates added to the feed water, such as HEDP-Zn (Zinc complex of the oxyethylidenediphosphonic acid disodium salt) and NTF-Zn (Zinc complex of the nitrilotrimethylphosphonic acid disodium salt), is removed with blowing. In order to ensure reliable circulation of delivery and feed water, the hydraulic distributor is connected via a check valve at the level of water-sludge collector in a horizontal position, thus preventing drainage (disruption of work of the feeding pump) or overflow of the circulation circuit (flooding of the irrigation chamber due to changes in the device load).

The calculation of heat carrier rate can be made on the basis of heat balance and material balance of the fire tube with a water jacket of water-heating or evaporative type and its convective part in the form of a condensation-type irrigation chamber. The rate of the heat carrier in the heat generator of evaporative type is calculated by:

\[
\frac{W_{ST}(I_{w1} - I_{wf})}{W_{CH}(I_{wf} - I_{w1})} = \frac{I_{A} - I_{1}}{I_{1}}; W_{HS} = W_{CH} - W_{ST}
\]

(1)

where \(W_{ST}\) – Steam capacity of the heat generator, kg/s; \(I_{w1}\) – Specific enthalpy of water in a water jacket of a hot-water or evaporative type, kJ/kg; \(I_{wf}\) – Final specific enthalpy of water at the outlet side of the irrigation chamber of condensation type, kJ/kg; \(W_{CH}\) – Water flow through the irrigation chamber of condensation type, kg/s; \(I_{1}\) – Initial specific enthalpy of water entering of the irrigation chamber of condensation type, kJ/kg; \(I_{A}\) – Respectively the exhaust gases enthalpy at the adiabatic temperature of fuel combustion, kJ/kg; \(I_{3}\) – Respectively the exhaust gases enthalpy at the outlet side of the fire tube with a water jacket, kJ/kg; \(W_{HS}\) – Water flow to the heating system, kg/s.

The calculation of irrigation chamber of condensation type can be made according to the method proposed by E. E. Karpis [22]. The following representative temperatures and efficiency coefficients of the irrigation chamber of condensation-type are used:

\[
E' = 1 - \frac{t_{d2} - t_{w2}}{t_{d1} - t_{w1}}; E_f = 1 - \frac{t_{w2} - t_{wf}}{t_{w1} - t_{wf}}
\]

(2)
where $E'$ – universal efficiency factor of perfect heat exchange in the irrigation chamber of condensation-type; $t_{g2}$ – exhaust gases temperature measured with a dry bulb after the irrigation chamber of condensation-type, °C; $t_{w2}$ – exhaust gases temperature measured with a wet bulb after the irrigation chamber of condensation-type, °C; $t_{d1}$ – exhaust gases temperature measured with a dry bulb before the irrigation chamber of condensation-type, °C; $t_{w1}$ – exhaust gases temperature measured with a wet bulb before the irrigation chamber of condensation-type, °C; $E_F$ – universal efficiency factor of perfect heat exchange in the irrigation chamber of condensation-type for a polytropic air treatment process; $t_{WF}$ – final water temperature at the inlet and outlet sides of the irrigation chamber of condensation type, °C; $t_{WI}$ – initial water temperature at the inlet and outlet sides of the irrigation chamber of condensation type, °C.

In addition to the above efficiency factors, the heat balance equation is used to calculate the irrigation chamber of condensation type:

$$I_{3i} - I_{3f} = 4.187B(t_{WF} - t_{WI})B = \frac{W_{WF}}{L_{WF}}$$ (3)

where $I_{3i}$ – specific enthalpy of gases before the irrigation chamber of condensation-type, kJ/kg; $I_{3f}$ – specific enthalpy of gases after the irrigation chamber of condensation-type, kJ/kg; $B$ – Irrigation coefficient kg/kg; $W_{WF}$ – water flow via the nozzles, kg/s; $L_{WF}$ – gases flow in the irrigation chamber of condensation type, kg/s.

We find the required initial water temperature before the nozzles by equation (2):

$$t_{WI} = t_{w1} - \frac{t_{w2} - t_{WF}}{1 - E_F}. \quad (4)$$

We find the desired final water temperature after spraying at the outlet side of the chamber by equation (3):

$$t_{WF} = t_{WI} + \frac{I_{3i} - I_{3f}}{4.187B}. \quad (5)$$

By solving the simultaneous equations (5) and (6), we get:

$$t_{WI} = t_{w1} - \frac{t_{w2} - t_{WF}}{E_F} - \frac{I_{3i} - I_{3f}}{4.187B}. \quad (6)$$

3. Results and discussion

The results of calculating the required initial water temperature $t_{WI}$ at the inlet side and its final temperature $t_{WF}$ at the outlet side of the irrigation chamber of condensation-type as functions $t_{WF} = f(B)$, $t_{WF} = f(E')$ and $t_{WF} = f(t_{WI})$ are shown in Figures 2, 3 and 4. The calculations are made with the following values of the initial gases parameters: $t_{d1} \approx 450.0 \, ^\circ\text{C}$, $t_{d2} = 69.7 \, ^\circ\text{C}$, $t_{w1} = 94.8 \, ^\circ\text{C}$, $t_{w2} = 68.4 \, ^\circ\text{C}$. 

Figure 2. Dependence $t_{W1} = f(B)$

Figure 3. Dependence $t_{W1} = f(E')$
The obtained results are in good agreement with the experimental data [12–14, 18] which show that the fraction of the evaporated motive fluid for drops of typical size of the sprayed compositions under study does not exceed 60 %, and the values of $\frac{g_{1872}}{g_{3024}}$ and $\frac{g_{1872}}{g_{3024}}$ are close to the calculated values in the article.

4. Conclusion
The use of this method of delivery water heating entails the following main predominant results:
- increase in the boiler efficiency factor due to the use of heat of water vapor condensation contained in the exhaust gases;
- reduction of material consumption of the boiler unit and its cost due to reduction of its dimensions with more intensive heat transfer;
- lowered requirements for the quality of feed water in the context of scale formation on heating surfaces, since the heating surface is water drops and scale in the form of sludge removed with blowing;
- environmental friendliness increases due to washing the exhaust fumes with irrigating water drops which absorb harmful gaseous emissions (CO, CO$_2$, nitrogen oxides). The disposal of resulting hazardous liquid flows is much easier, cheaper and locally compared to gas emissions.

Studies on the quality of water heated due to direct contact with the products of combustion showed that it meets the sanitary and hygienic requirements and can be used for various municipal and domestic uses. Reports on water quality issued by the Moscow Municipal Sanitary-Epidemiological Station and the St. Petersburg Institute of Labor Health and Occupational Diseases indicate that "no significant chemical
or physical changes were found in the water heated with the method of contact heat exchange compared with the basic tap water” [21].

Thus, as a result of applying the developed design of a heat-generating plant able to effectively heat delivery water with contact method using the latent heat of exhaust gases, we can achieve a significant increase in the efficiency of utilization of thermal resources of the primary modern type of fuel - natural gas, as well as reduce the prime costs and increase environmental indicators of thermal energy production.

References
[1] Zhang X, Wu J, Li Z and Chen Y 2019 A hybrid flue gas heat recovery system based on vapor compression refrigeration and liquid desiccant dehumidification Energy Conversion and Management 195 157–166
[2] Yang D, Li J, Wang Y, Tian C and Zhang C 2019 Recent patents on boiler burners for natural gas Recent Patents on Mechanical Engineering 12(1) 55–64
[3] Pinchuk V A, Sharabura T A and Kuzmin A V 2019 The effect of water phase content in coal-water fuel on regularities of the fuel ignition and combustion Fuel Processing Technology 129–137
[4] Eder L V, Provornaya I V and Filimonova I V 2019 Problems of rational use of associated petroleum gas in Russia Geography and Natural Resources 40(1) 9–14
[5] Chen B, Xiong R, Li H, Sun Q and Yang J 2019 Pathways for sustainable energy transition J. of Cleaner Production 228 1564–1571
[6] Sokovikov V V, Tugov A N, Grishin V V and Kamyshev V N 2008 Automatic water-based fire suppression with the use of water mist at power plants Power engineer [in Russian – Energetik] 6 37–38
[7] Bukowska M, Nowak K, Proszak-Miąsik D and Rabczak Sł 2017 Concept of heat recovery from exhaust gases IOP Conf. Ser.: Materials Science and Engineering 245(5) 052057
[8] Yang S R, Seo J and Hassan Y A 2019 Thermal hydraulic characteristics of unstable bubbling of direct contact condensation of steam in subcooled water Int. J. of Heat and Mass Transfer 580–596
[9] Dvoinishnikov V A, Supranov V M and Knyaz’kov V P 2018 Furnaces of the unified-family drum-type gas-fired boilers Thermal Engineering 65(8) 547–554
[10] Prasartkaew B 2018 A novel direct-fired porous-medium boiler IOP Conf. Ser.: Materials Science and Engineering 297(1) 012058
[11] Anangapal H B 2014 Energy and exergy analysis of fuels Int. J. of Energy Sector Management 8(3) 330–340
[12] Vysokomornaya O V, Kuznetsov G V and Strizhak P A 2013 High temperature gas medium J. of Engineering Physics and Thermophysics 86(1) 62–68
[13] Kuznetsov G V and Strizhak P A 2013 The influence of the shape of a water drop on the results of mathematical modeling of its evaporation when moving through the high-temperature products of combustion Heat Processes in Engineering 6 254–261
[14] Vysokomornaya O V, Markov A O, Nazarov M N, Strizhak P A and Yanov S R 2013 Numerical study of the influence of water spray conditions on temperature in the trail of a “Water Bomb” Tomsk Polytechnic University Bulletin 322(4) 24–31
[15] Korolchenko D A, Gromovoy V Yu and Vorogushin O O 2011 Use of water mist to extinguish fires in high-rise buildings Vestnik MGSU 2(1) 331–335
[16] Andryushkin A Yu and Pelekh M T 2012 Efficiency of fire extinguishing with water mist Issues of risk management in the technosphere [in Russian – Problemy upravleniya riskami v tehnosfere] 21(1) 64–69
[17] Kopylov N P, Chibisov A L, Dushkin A L and Kudryavtsev E A 2008 Study of the patterns of
extinguishing the model hot spots with water mist Fire Safety [in Russian – Pozharnaya bezopasnost] 4 45–58

[18] Volkov R S, Kuznetsov G V and Strizhak P A 2012 Numerical estimate of the optimal size of water drops under conditions of its spraying by means of fire extinguishing means indoors Fire and Explosion Safety [in Russian – Pozharovzryvobezopasnost] 5 74–78

[19] Stoyanov N I, Slusarev G V and Gerasimenko S A, RF patent No. 2662757 (30 July 2018) Heat generating device

[20] Stoyanov N I, Slusarev G V and Gerasimenko S A, RF patent No. 2619429 (15 May 2017) The method of contact heat transfer and device for its implementation

[21] Stoyanov N I, Slusarev G V, Khashchenko A A and Smirnov S S 2018 Prospects for the use of gas contact water heaters in modern power engineering Bulletin of the North Caucasus Federal University 3(66) 15–24

[22] Kostin V I and Rakova E A 2018 Constructive schemes of control systems of a microclimate of premises with the constant temperature of internal air News of the higher educational institutions. Construction Industry 4(712) 59–67 (in Russian)