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# Simulation of Solid-Fuel Hybrid Combustion

M. P. Senchuk[1], A. V. Barkovskyi[2]
[1]PhD in Engineering Science, Associate Professor, Kyiv National University of Construction and Architecture, Kyiv, Ukraine, smp_21@ukr.net.
[2] master's student, Heat and Gas Supply and Ventilation department, Kyiv National University of Construction and Architecture. Kyiv, Ukraine.

*Abstract. Solid-fuel utilization in the public energy service is necessary for national supply-demand balance stability. The most efficient combustion process is the hybrid combustion, particularly the three-staged one: combination of stack, fuel-bed firing and overall combustion in swirl chamber. Stability of such combustion model is achieved by relevant design and duty parameters at all stages of fuel combustion with appropriate blasting air reallocation and process flow. A numerical model is proposed in a mechanized boiler with the use of a hybrid process. Analytical equations for calculating the main parameters of the combustion zone in the stack and on the grate are provided. The use of the proposed model for the combustion of solid-fuel provides a definition of parameters of the combustion zone at the stage of designing a boiler plant with mechanized combustion.*

*Key words: solid-fuel hybrid combustion, burning rate, numerical model, stack, grate, mechanical stocker.*

**Introduction.** Solid fuel utilization in the public energy service is necessary for national supply-demand balance stability. Considering the significance of the environmental specifications of solid-fuel heat generators operation, it is important to ensure their improved operational efficiency, including up-to-date environmental safety. It is known that these demands may be met if mechanized process flow is established at all solid-fuel combustion stages (starting from fuel preparation for ash residues removal – ash, slag). The most efficient one is the hybrid combustion, particularly the three-staged one: combination of stack, fuel-bed firing and overall combustion (Fig. 1).
Stability of such combustion model is achieved by relevant design and duty parameters at all stages of fuel combustion with appropriate blasting air reallocation and process flow:

- drying, gasification and fuel particles firing in the stack by using reverse-flow;
- combustion of primarily free carbon on the grate by using cross-flow;
- combustion of volatiles and dust particles in the combustion chamber in the secondary blasting air flow.

Such hybrid model in the solid-fuel boilers design is implemented based on not only the calculation data using well-known methods [1], but on the experimental results of the laboratory research and experimental trials of the combustion unit prototypes.

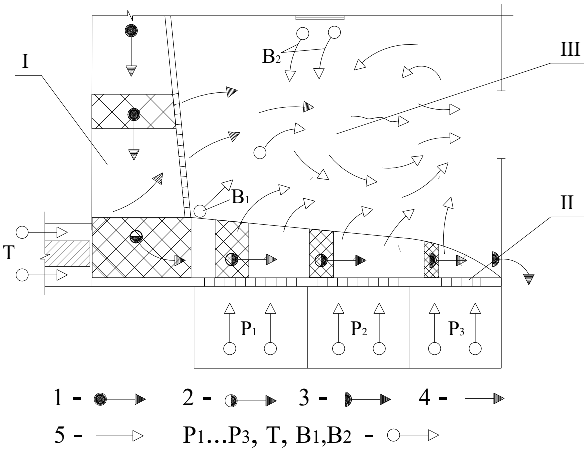


Fig. 1. Solid-fuel hybrid combustion:
1- vertical stack with perforated front wall (holding grate); 2 - grate; 3 - combustion chamber
Designations in the picture: 1 - natural fuel; 2 – coke; 3 - ash residues;
Blasting air flow: $P_1…P_3$ - primary in the zones under the grating; T - primary to stack
$B_1$, $B_2$ – secondary to combustion chamber

To reduce the volume of such research work and tests that involve huge labour and material resources inputs it is necessary to specify design and duty parameters of the combustion zone based on the combustion process simulation according to the response rate of the fuel particles with the blasting air oxygen.

**The objective of the work** is to develop method of complex analytical estimation of the processes in the stack and on the grate of the solid-fuel hybrid combustion in the mechanized boiler.

**A. Combustion process in the stack.** When generating numerical model of the stack combustion process with account for theoretical and laboratory research results [2-4] it is accepted that:

▪ natural fuel particles at the stack inlet have the shape close to spherical one (maximum size is 50 mm), that is kept during the whole combustion process;

▪ fuel in the stack is transported gravitationally, on the horizontal grate – using translational motion under the action of piston pusher;

▪ in the stack the natural fuel particles are dried and volatiles are emitted, and on the grate free carbon is combusted being completely burnt at the grate end;

▪ transportation (sinking) of the particles into the stack is realized using fuel-bed pattern: each cross bed consists of one layer of particles of the same size which thickness is decreased in the process of drying and gasification (Fig. 1).

Calculation of the stack combustion is based on the summary results of the natural fuel-burning rate and test results of engineering and preproduction prototypes of the mechanical stokers. It is assumed that the initial size of the fuel particles at the stack inlet is reduced in the stack height pro rata with the fuel burnt. In the lower zone of the stack the particles size $\delta_{кш}$ , cm, is equal to:

$$\delta_{кш} = \delta_{пш}(1 - b_ш)^{1/3}, \qquad (1)$$

where $\delta_{пш}$ – initial size of the particles at the stack inlet, cm; $b_ш$ – quantity of the fuel burnt in the stack, which is determined with account for experimental data in accordance with the combustion zone burner front load (Fig. 2) subject to moisture exudation and emission of the most of volatiles (about 95%) and ensuring of about 0.8 of the air excess factor at the holding grate outlet.

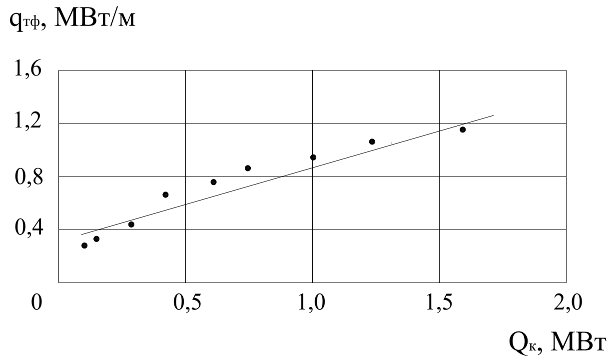


Fig. 2. Fuel burn-up fraction in the stack: $q_{тф}$ - Specific front load of the Furnace; $Q_к$ - Stake heat output; ● - experimental results

Effective height of the particles response in the stack may be determined by using following formulae:

$$H_{рш} = S_{рш}\delta_ш^{сер} / (6mF_ш^{сер}), \text{ cm}, \qquad (2)$$

where $S_{рш}$ – surface area of the particles response, cm$^2$; $\delta_ш^{сер} = (\delta_{пш} + \delta_{кш}) / 2$ – mean particle size in the stack, cm; $m$ – interpartical porosity ($m$=0.5…0.6); $F_ш^{сер}$ – average area of the stack cross section, cm$^2$.

Response surface area in accordance with the fuel-burning rate:

$$S_{рш} = B_{рш} / K_s^n, \text{ cm}^2\text{·s}, \qquad (3)$$

where $B_{рш} = b_ш B_р$ – quantity of the fuel burnt in the stack, g; $B_р$ – aggregate quantity of the fuel burnt in the mechanical stocker, g; $K_s^n$ – specific burning rate of the fuel, g/(cm$^2$·s).

On the basis on solid-fuel, combustion process investigation it was established that the qualitative behaviour of the natural fuel combustion process (anthracitic coal, black coal and hydrogenous coal) in the bed is similar to coke combustion, but if the volatiles content grows the burning rate of the natural fuel rises as compared to the coke burning rate. For rough estimations, one can assume:

$$K_s^n = k_s K_s^c\,, \qquad (4)$$

where $k_s$ – factor of the natural fuel specific burning rate $K_s^n$ excess over coke specific burning rate $K_s^c$ (Fig. 3).

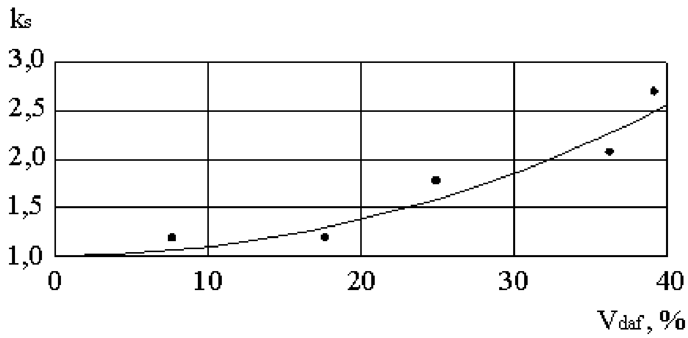


Fig. 3. Factor $k_s$: $V_{daf}$ — volatile matter emission; ● — experimental results

Coke specific burning rate at [4] for Péclet diffusion number $17 \le Pe_D = W\delta_{сер}/D < 320$:

$$K_s^{\ c} = \frac{0.185 \cdot C_{осер} D^{0.5} W^{0.5}}{\delta_{сер}^{0.5}}\,, \qquad (5)$$

where $W$ – reduced blasting air speed which is determined as ratio to the obstruction-free flow area of the bed and temperature in the bed, cm/s; $\delta_{сер}$ – mean particle size the bed, cm; $D$ – reduced diffusion factor, cm$^2$/s; $C_{осер}$ - mean molar oxygen concentration in the bed, g/cm$^3$.

Fuel combustion time in the stack, may be determined as the particle burnout time to the size $\delta_{кш}$:

$$t_ш^ч = \frac{B_ш^ч}{K_s^n S_{шсер}^ч}\,,\ \text{s}, \qquad (6)$$

where $B_ш^ч$ – weight of the particle that burnt out in the stack, g; $S^ч_{шсер}$ – mean surface area of the particle, cm$^2$:

$$B_ш^ч = \pi\rho_ч / 6(\delta_{пш}^3 - \delta_{кш}^3);\ S_{шсер}^ч = 0.5\pi(\delta_{пш}^2 + \delta_{кш}^2)\,. \qquad (7)$$

**B. Combustion process on the grate.** The numerical model of combustion on the grate shall be defined if natural fuel is dried and gasified in the stack and homogeneous fuel with prevailing coke content is accumulated at the grate inlet - start of the burning phase of the coke particles [5]. Process stability is achieved by proper firing of the particles in the bed at the grate inlet, uniform translational delivery of the particles, which burn out along the grate, and appropriate zonal reallocation of the blasting air. At optimum combination of duty and design parameters, the fuel bed burning-out-zone ensures complete burning out of the particles at the end of grate. For the required design, width of the grate and window height at its inlet the length of the combustion zone is equal to:

$$\ell_p = \frac{\delta_{кш}^{2,5}}{2,5A}, \text{ cm}, \qquad (8)$$

where $A$ – constant value:

$$A = \frac{2 \cdot 0,185\, C_0 D^{0,5} W^{0,5} \delta_{кш}}{\rho_ч v_{пр}}.$$

Burning time of the particles in the bed on the grate of length $\ell_p$ :

$$t = \frac{5}{3} \cdot \frac{\delta_{кш}}{v_{пр}} \left( \frac{5}{2} A \right)^{-\frac{2}{5}} \cdot \ell_p^{\frac{3}{5}}, \text{ s}, \qquad (9)$$

where $v_{пр}$ – initial linear speed of the particles:

$$v_{пр} = B_p / (b_p h_{пр} m \rho_ч), \text{ cm/s}, \qquad (10)$$

where $h_{пр}$ – initial bed depth at the inlet, cm; $b_p$ – width if the grate for combustion, cm; ρ – particles density, g/cm$^3$.

Volatiles and dust that are generated during stack gasification process pass to the combustion chamber and burn in the high-temperature gas flow fuel-bed firing. Therefore, full fuel burning time of hybrid combustion may be determined as total time for stack and fuel-bed firing processes of fuel particles combustion.

**Conclusion.** Using of the proposed numerical model of the solid-fuel combustion process enables determination of the design and duty parameters of the combustion zone as early as at the unit design engineering stage. At that, one takes into account special features of the hybrid combustion process implemented in the combustion device design of the mechanized boiler.

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## Моделювання спалювання твердого палива за комбінованою схемою

М. П.Сенчук[1], А. В. Барковський[2]

[1]канд. техн. наук, доцент, Київський національний університет будівництва і архітектури, Київ, Україна, smp_21@ukr.net.

[2]магістрант, кафедра теплогазопостачання і вентиляції,  Київський національний університет будівництва і архітектури, Київ, Україна.

*Анотація. Використання твердого палива в комунальному теплопостачанні необхідне для стабільності паливно-енергетичного балансу. Найбільш ефективним процесом спалювання є комбіноване спалювання, зокрема, триступеневий процес: підготовка палива в шахті, шарове спалювання та повне згоряння в топковій вихровій камері. Стабільність такого спалювання досягається за рахунок відповідних конструктивних і режимних параметрів на всіх стадіях горіння палива з відповідними розподілом повітря й організацією процесу. Запропоновано чисельну модель згоряння палива в механічній топці з застосуванням комбінованого процесу. Наведено аналітичні рівняння для розрахунку основних параметрів зони горіння в шахті і на колосниковій решітці. Використання запропонованої моделі процесу спалювання твердого палива забезпечує визначення параметрів зони горіння на стадії проектування котельної установки з механізованим спалюванням.*

*Ключові слова: комбінована схема спалювання твердого палива, швидкість горіння, математична модель, шахта, колосникова решітка, механічна топка.*

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## Моделирование сжигания твёрдого топлива по комбинированной схеме

М. П.Сенчук[1], А. В. Барковский[2]
[1]канд. техн. наук, доцент, Киевский национальный университет строительства и архитектуры, Киев, Украина, smp_21@ukr.net.
[2]магистрант, кафедра теплогазоснабжения и вентиляции, Киевский национальный университет строительства и архитектуры, Киев, Украина.

*Аннотация. Использование твердого топлива в коммунальном теплоснабжении необходимо для стабильности топливно-энергетического баланса. Наиболее еффективным процессом сжигания является комбинированное сжигание, в частности, трехступенчатый процесс: подготовка топлива в шахте, слоевое сжигание и полное сжигание в топочной вихревой камере. Стабильность такого сжигания достигается за счет соответственных конструктивных и режимных параметров на всех стадиях горения топлива с соответствующими распределением воздуха и организацией процесса. Предложена численная модель в механической топке с применением комбинированного процесса. Приведены аналитические уравнения для расчета основных параметров зоны горения в шахте и на колосниковой решетке. Использование предложенной модели процесса сжигания твердого топлива обеспечивает определение параметров зоны горения на стадии проектирования котельной установки с механизированным сжиганием.*

*Ключевые слова: комбинированная схема сжигания твёрдого топлива, скорость горения, математическая модель, шахта, колосниковая решётка, механическая топка.*

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