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Investigation of two-stage air-blown and air-steam-blown entrained-flow coal gasification

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Abstract. The aim of the paper is to compare effect of coal and steam supply to the second stage of the entrained-flow gasifiers on their main operating parameters. Two two-stage gasifiers of SB RAS Institute of Thermophysics were used as experimental units. The 5 MW unit has air-coal feeding to first and second stages (air-blown gasification). The 1 MW unit has air-coal feeding to first stage and steam feeding to second stage (air-steam-blown gasification). Experimental studies of air-blown and air-steam-blown gasification with various stoichiometric coefficients, flow rates, temperatures and supply points of secondary media (air-coal and steam) are carried out. Experimental and calculated (thermodynamic and CFD) methods have established that: in the air-blown gasification unit the increase of stoichiometric coefficients (secondary coal flow rate reduction) reduces the syngas heating value and increases the carbon conversion rate; in the air-steam-blown gasification unit the increase of the steam supply nozzle immersion to the gasifier leads to increase of the syngas heating value, the carbon conversion rate and decrease of the syngas H_2/CO ratio.

1. Introduction

Coal is the most wide-spread type of fossil fuel on the planet and has one of the first places in the world fuel and energy balances. Today coal is used either to generate heat and electricity, or to produce chemicals. One of the most promising energy technologies for the coal using is the integrated gasification combined cycle (IGCC) plant [1]. The main element of this plant is gasifier, in which coal gasification takes place – coal conversion into combustible gas (syngas). Oxygen or air is usually used as the reagent gas. Oxygen has high reactivity, so the vast majority of oxygen gasifiers have one reaction stage. The air contains 21% oxygen, so the gasification rate is low, which is usually compensated by using two-stage scheme gasifiers [2].

One of the most effective methods of the gasification process controlling is secondary media supply to the gasification chamber. Such media are usually coal, steam, carbon dioxide, combustion products, syngas, etc. The supply of secondary coal or steam is considered to be the most effective and technically simple measure. The use of coal as secondary media makes it possible to approximate the stoichiometric factor to the theoretically necessary value, and thus increase the gasifier cold gas efficiency. On the other hand, decrease of stoichiometric factor reduces the carbon conversion rate, so the method and location of coal supply to the gasifier have great importance. For example, many years development and operation experience of MHI two-stage air gasifier confirmed the effectiveness of radial secondary coal feed into high-heated products of primary coal incomplete combustion [3]. The steam supply is used to lower the temperature in the reaction space (to remove superheating) and to increase the fraction of hydrogen in the syngas due to the water gas shift reaction.

UrFU develop air-steam-blown two-stage coal gasifier for IGCC based on the MHI gasifier [4]. Basically from the MHI gasifier the UrFU gasifier differs by high-temperature steam supplying into the second stage together with the secondary coal, as well as additional heating of air up to 900 ° C.

The aim of the paper is to compare effect of coal and steam supply to the second stage of the entrained-flow gasifiers on their main operating parameters.

In view of the complexity and cost-effectiveness of gasifier experimental research, they are increasingly being replaced by numerical modeling [5]. The most effective is the approach combining experimental studies and the different dimensions (0-, 1-, 2-, 3-D) computational modeling [6].

To achieve this goal, the following tasks have been accomplished:

1) experimental studies of air-blown and air-steam-blown gasification have been carried out with the coal and steam supply into the gasifier second stage, respectively;

2) experiments results were processed and compared using zero-dimensional thermodynamic and three-dimensional CFD modeling;

3) effect of constructive and regime parameters on the gasifier operation is analyzed and compared.

2. Experimental study

Two two-stage gasifiers of SB RAS Institute of Thermophysics were used as experimental units. The 5 MW unit has air-coal feeding to first and second stages (air-blown gasification). The 1 MW unit has air-coal feeding to first stage and steam feeding to second stage (air-steam-blown gasification). Both gasifiers are cylindrical inside lined vessels, at one end of which is swirler of primary coal feeding. Axisymmetric with the reaction chamber into the end of the swirler is nozzle of secondary coal (air-blown gasification) and steam (air-steam-blown gasification) supply at the gasifier (figure 1).

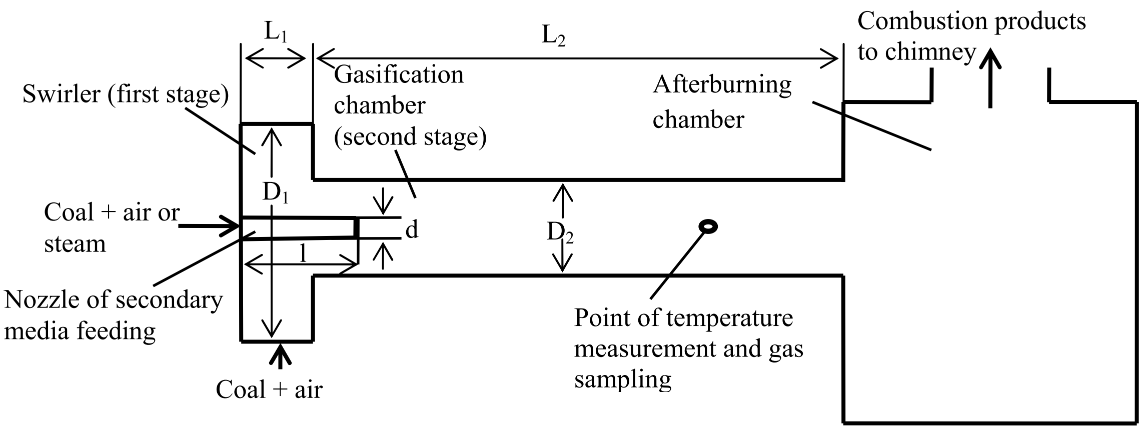

Figure 1. The scheme of experimental gasifiers.

The gasifiers geometry did not differ in principle, but the dimensions were different (table 1).

Table 1. Gasifiers dimensions.

Gasifier	L_1, m	L_2, m	l, m	D_1, m	D_2, m	d, m
Air-blown	0.14	1.5	0	0.5	0.32	0.05
Air-steam-blown	0.1	1.1	0.1-0.25	0.3	0.15	0.03

During air-blown gasification, Kuznetsky bituminous coal, and in the case of air-steam-blown gasification the Pereyaslovsky subbituminous coal was used (table 2).

Table 2. Proximate and ultimate analysis of used coals.

Coal	W^a, %	A^d, %	V^{daf}, %	C^{daf}, %	H^{daf}, %	N^{daf}, %	S^{daf}, %	O^{daf}, %	Q_s^{daf}, MJ/kg
Kuznetsky	5.4	22.3	44.7	75.57	5.66	1.78	0.55	16.44	27.7
Pereyaslovsky	9.1	7.2	46.6	74.6	5.1	1	0.3	19	28.9

To increase the reactivity of primary coal, coal mechanical activation was made by disintegrator mill to average coal particle diameter of 40 microns. Into the second stage of the unit (in the case of air-blown gasification), coal was fed after grinding in ball mill and had average diameter of 100 microns. Measurements of temperature and concentration were performed during quasi-stationary mode of gasifier operation. Further, the measured values were averaged over time of this mode. The gasifiers operation parameters are given in table 3.

Table 3. Gasifiers operation parameters.

Gasifier	Coal flow rate, kg/h	Air flow rate, Nm^3/h	Coal and air temperature, °C	Steam temperature, °C	Stoichiometric factor (α)	Temperature at measuring point, °C
Air	200-300	700-900	20-30	-	0.41-0.67	1400-1500°C
Air-steam	25-35	85-95	20-30	150-200	0.47	1000-1100°C

3. Calculation study

To process experimental data, thermodynamic modeling of syngas components equilibrium concentrations was carried out using the entropy maximization method [7]. The calculation implied idealized case, not taking into account unreacted carbon, incompleteness of reaction and mixing of all syngas components, and considered that the mixture reached complete chemical equilibrium state. Calculation without the above-described assumptions made it possible to estimate the carbon conversion rate by fitting the calculated concentrations to experimental ones.

During air-blown gasification experiment, the stoichiometric factor was varied α 0.41-0.67 (figure 2a), and during air-steam-blown - depth of nozzle immersion into gasifier l=0.1-0.25 m (figure 2b).

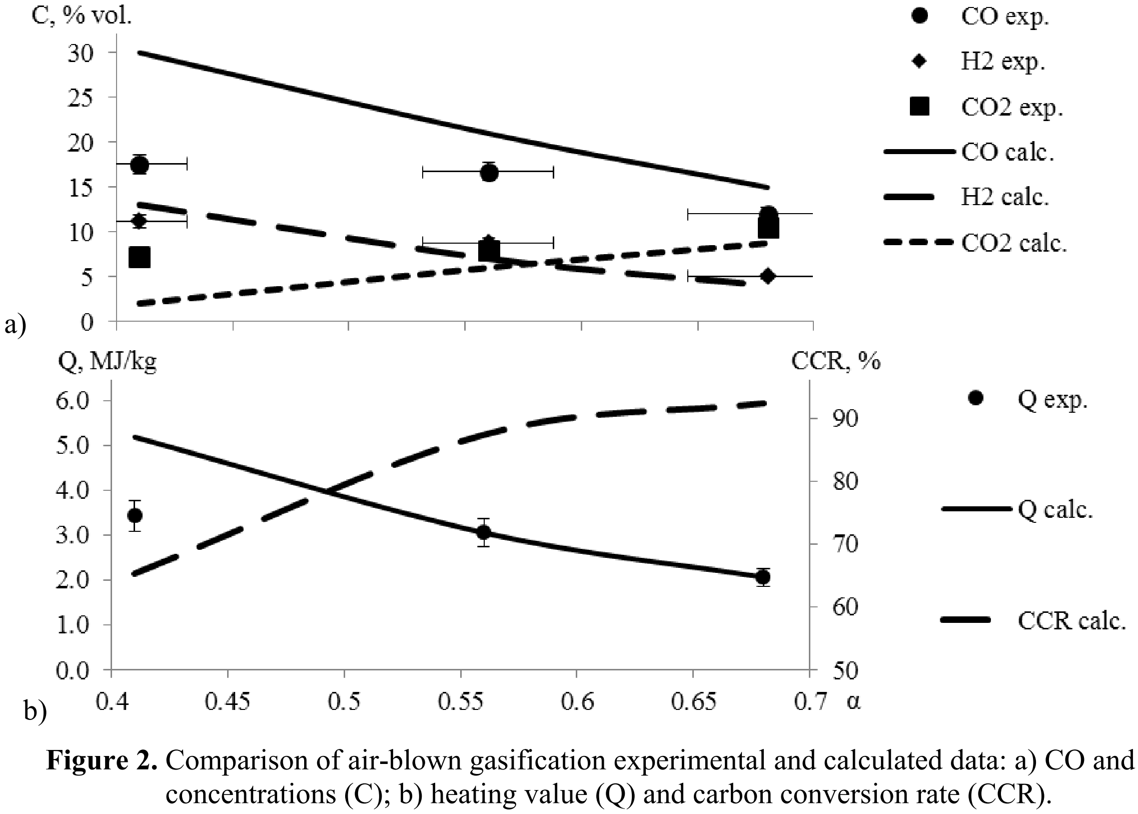

Figure 2. Comparison of air-blown gasification experimental and calculated data: a) CO and H_2 concentrations (C); b) heating value (Q) and carbon conversion rate (CCR).

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Figure 3a shows that the experimental and calculated concentrations of combustible gases decrease with α increasing. The calculation overestimates the concentration of CO, which indicates noticeable amount of unreacted coal carbon. The syngas heating value decreases with α increasing and carbon conversion rate increases (figure 3b). This is due to the burn-out of CO and H_2 part and more complete combustion of carbon by excess oxygen.

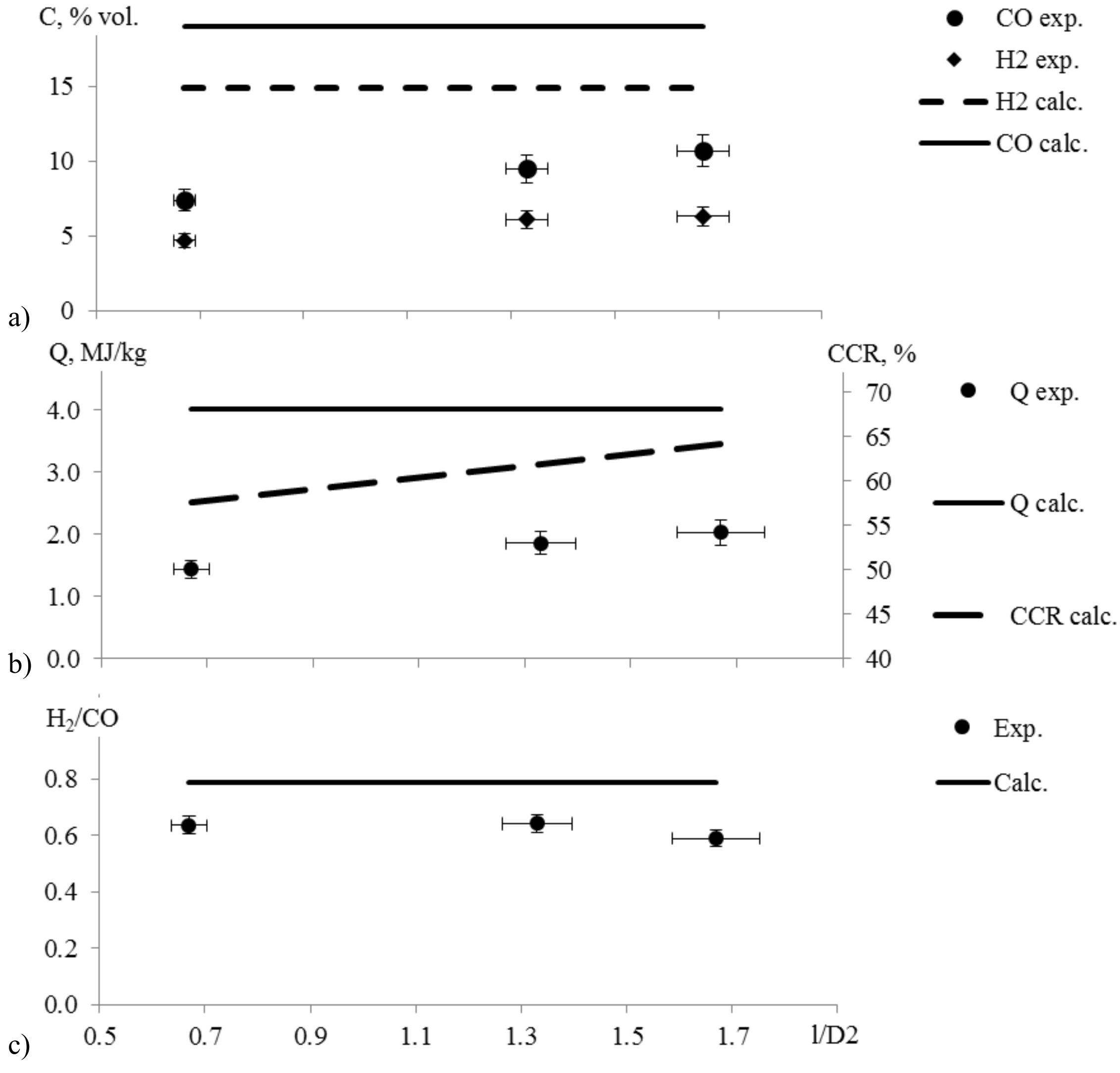

Figure 3. Comparison of air-steam-blown gasification experimental and calculated data: a) CO and H_2 concentrations; b) syngas heating value and the carbon conversion rate; c) syngas H_2/CO ratio.

The experimental and calculated data have differences in the figures 2 and 3 because, as mentioned above, calculation not taking into account unreacted carbon, incompleteness of reaction and mixing of all syngas components, and considered that the mixture reached complete chemical equilibrium state.

The calculation results do not depend on the depth of the steam nozzle immersion into the gasifier, since it does not take into account unreactivity of fuel carbon part. Experimental data show an increase of H_2 and CO concentrations, syngas heating value and the carbon conversion rate (figure 4b) as the depth of the steam nozzle immersion increases into the gasifier. This is due to the decrease of steam and reacting mixture contact time (steam takes less heat). The syngas H_2/CO ratio (figure 4c) decreases with increasing of steam nozzle immersion depth into the gasifier due to a decrease of the reaction time of the steam with fuel coke (steam gasification) and syngas (water gas shift reaction).

In addition to the thermodynamic calculations, CFD simulation of the operation of both gasifiers was performed using the previously verified CFD-model [8-10]. Special feature of the gasifiers is significant gradient of gas concentrations along the gasification chamber radius (figure 4). In the air-blown gasifier, radial CO concentration distribution in the cross section radius was experimentally determined (figure 4c).

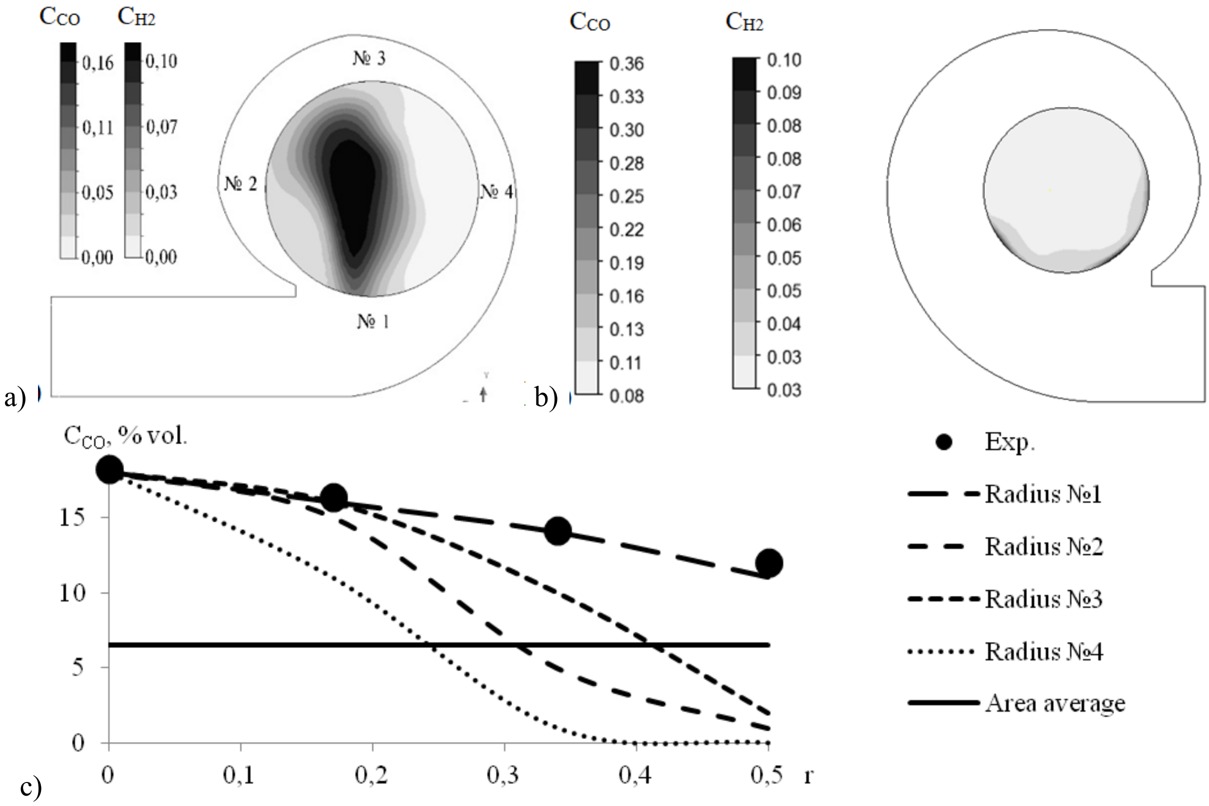

Figure 4. Distribution of CO and H_2 concentrations in the gas sampling cross section: a) air-blown gasifier; b) air-steam-blown gasifier; c) comparison of calculation and experiment CO concentration distribution of air-blown gasifier radius (r).

It can be seen from figure 4 that CO and H_2 concentrations distribution in the cross-section of air-blown and air-steam-blown gasifiers differ significantly. In the air-blown gasifier (figure 4a, c), the maximum values of combustible gases concentration are observed in the paraxial zone as the secondary coal is fed and gasified into the axial region of the gasifier. But in the air-steam-blown gasifier (figure 4b), maximum values of combustible gases concentration can be seen at the periphery of the gasification chamber because coal is fed to the gasifier through swirler that pushes coal to the gasifier periphery.

4. Conclusion

Experimental studies of air-blown and air-steam-blown gasification with various stoichiometric coefficients, flow rates, temperatures and supply points of secondary media (air+coal and steam) are carried out. Experimental and calculated (thermodynamic and CFD) methods have established that: in the air-blown gasification unit the increase of stoichiometric coefficients (secondary coal flow rate reduction) reduces the syngas heating value and increases the carbon conversion rate; in the air-steam-blown gasification unit the increase of the steam supply nozzle immersion to the gasifier leads to increase of the syngas heating value, the carbon conversion rate and decrease of the syngas H_2/CO ratio.

The resulted profiles of gas concentrations in the gasifier cross section indicate complex non-uniform character of the investigated processes dynamics and distribution. This is factor that complicates the experimental and calculated studies, but increases their significance. The investigation indicates the need for additional heating of the reacting media (air, steam) and flow swirling to improve the efficiency of the gasification process.

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References
[1] Clean Coal Research Program, Technology Readiness Assessment - Analysis of Active Research Portfolio (United States Department of Energy, Office of Fossil Energy, December, 2012) / http://www.netl.doe.gov/File%20Library/Research/Coal/energy%20 systems /gasification/TRL-Comprehensive-Report_121112_FINAL_1.pdf
[2] Ryzhkov A F, Bogatova T F, Lingyan Z and Osipov P V 2016 Development of entrained-flow gasification technologies in the Asia-Pacific region (review) *Thermal Engineering* **63** pp 791-801
[3] Hashimoto T, Sakamoto K and Kitagawa Y 2009 Development of IGCC Commercial Plant with Air-blown Gasifier *Mitsubishi Heavy Industries Technical Review* **46-2** pp 1–5
[4] Abaimov N A, Osipov P V and Ryzhkov A F 2016 Experimental and computational study and development of the bituminous coal entrained-flow air-blown gasifier for IGCC *J. of Phys.: Conf. Series* **754** 112001
[5] Vascellari M, Roberts D G, Hla S S, Harris D J and Hasse C 2015 From laboratory-scale experiments to industrial-scale CFD simulations of entrained flow coal gasification *Fuel* **152** pp 58-73
[6] Lee H-H, Lee J-C, Joo Y-J, Oh M and Lee C-H 2014 Dynamic modeling of Shell entrained flow gasifier in an integrated gasification combined cycle process *Applied Energy* **131** pp 425-40
[7] Trusov B G 2002 Software TERRA for computing plasmachemical processes *Materials of 3rd Int. symp. on theoretical and applied plasma chemistry* (Ples: ISUCT) pp 217–8
[8] Abaimov N A and Ryzhkov A F 2015 Development of a model of entrained flow coal gasification and study of aerodynamic mechanisms of action on gasifier operation *Thermal Engineering* **62** pp 767–72
[9] Abaimov N A and Rizhkov A F 2015 Turbulence models verification for numerical Simulation of the cyclone chamber *Proc. of 5th Int. Conf. Heat and mass transfer and hydrodynamics in swirling flows* (Kazan: KAI) pp 429-37
[10] Chernetskiy M Y, Kuznetsov V A, Dekterev A A, Abaimov N A and Ryzhkov A F 2016 Comparative analysis of turbulence model effect on description of the processes of pulverized coal combustion at flow swirl *Thermophysics and aeromechanics* **23** pp 615-26