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TAILORING SYNGAS ENERGY CONTENT THROUGH COLLOID-CHEMICAL MODULATION OF COAL–WASTE SYSTEMS DURING THERMOCHEMICAL CONVERSION

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Abstract

The current study provides an extensive analysis of the waste-enhanced thermocatalytic system for increasing the calorific value of coal-based syngas produced using Angren and Shargun coals, which originate from Uzbekistan. This research includes systematic assessment of temperature influence within the range from 500 to 700 °C and effect of waste content on the output of syngas and its composition based on the results of gas analysis and microscopic study of the material structure by scanning electron microscopy (SEM). From the standpoint of colloid chemistry, it should be mentioned that such aspects as the processes of structural changes, interfacial interaction, and pore formation play a crucial part in controlling the kinetics and mechanism of mass transfer in the process. It is noted that the formation of a foam-like material with numerous pores contributes to the process of syngas enhancement.

Keywords: *coal gasification; syngas enrichment; industrial waste utilization; thermochemical conversion; calorific value; porous structure; SEM analysis; Uzbekistan coals*

Introduction

An increase in the global need for alternative and efficient sources of energy has brought about a growing interest in syngas production processes (Qurbonov, A., Kucharov, A., & Yusupov, F., 2024). The global syngas market will witness significant growth from a size of USD56.06 billion in 2023 to reach over USD102.21 billion by 2033 due to extensive applications of syngas in power generation, hydrogen fuel production, and chemical synthesis (Maitlo, G., Ali, I., Mangi, K.H., Ali, S., Maitlo, H.A., Unar, I.N., & Pirzada, A. M., 2022; Kucharov, A., Xalilov, S., Alikulova, M., Mamarasulov, T., Turayeva, K., Imanova, G., ... & Farmonov, N., 2025). As far as syngas production is concerned, coal gasification continues to be an important technique allowing conversion of low-grade solid fuels into valuable gaseous compounds rich in carbon monoxide and hydrogen (Griffin, D.W., & Schultz, M.A., 2012). The main challenge with traditional methods of syngas production lies in the comparatively low calorific value of syngas, being in the range of 4–7 MJ/Nm³ and 10–18 MJ/Nm³ for air and oxygen/steam systems, respectively (Kucharov, A., Xalilov, S., & To'Rayeva, X., 2024). Recent research efforts have been devoted to improvement of the calorific value of syngas through process optimization (Xu, D., Zhang, Y., Hsieh, T. L., Guo, M., Qin, L., Chung, C., ... & Tong, A., 2018), reactor design, and modeling, including utilization of machine learning algorithms for syngas composition control (Anuar, S. Z. K., Nordin, A. H., Husna, S. M. N., Yusoff, A. H., Paiman, S. H., Noor, S. F. M., ... & Ismail, Y.M.N.S., 2025). In recent times, efforts have been put towards the application of industrial wastes as reactive agents in thermal chemical reactions, not only to solve environmental issues but to address energy concerns as well (Yang, J., Han, C., Shao, L., Nie, R., Dong, S., Liu, H., & Ma, L., 2024). Earlier studies have proved that syngas yield is greatly affected by fuel properties, operating temperature, and type of reaction (Kucharov, A., Xalilov, S., Farxod, Y., Toshboboyeva, R. N., Bekturdiyev, G., Turayeva, K., ... & Golib, T., 2026); however, there is little evidence on the combined impact of coal and industrial wastes on energy generation (Fan, P., Dai, W., Fan, X., Dong, L., Wang, J., Bao, W., ... & Fan, M., 2024). It should be highlighted that there is not much research done on the contribution of surface and colloid chemistry processes, which could greatly impact mass transfer, kinetics of chemical reactions, and gas dynamics as well (Hu, Y., & Chen, Z., 2025). Hence, the investigation of innovative waste-fueled thermal processes in order to improve the calorific content of syngas would be quite pertinent (Choi, H., Kim, Y. T., Tsang, Y. F., & Lee, J., 2023).

Research method

This study employed Angren and Sharg'un coals from Uzbekistan as representative feedstocks, and a novel thermochemical approach was developed to enrich coal-derived syngas using industrial waste streams from oil and gas processing plants.

Figure 1.

a) b)

(a) Schematic diagram of the syngas enrichment system based on technical waste from oil and gas processing plants a burner (1) and waste heating furnace (2) with a heat circulation zone (3), a gas flow pipelin (4) equipped with check valves (5–7) and a pressure gauge (8), a cooling chamber (9), a gas holder (10), and a waste feed tank (11); flue gases are discharged through an exhaust pipe (12), while syngas is supplied via the inlet pipeline (13) and collected through the outlet pipeline (14); (b) photographic view of the experimental setup., comprising

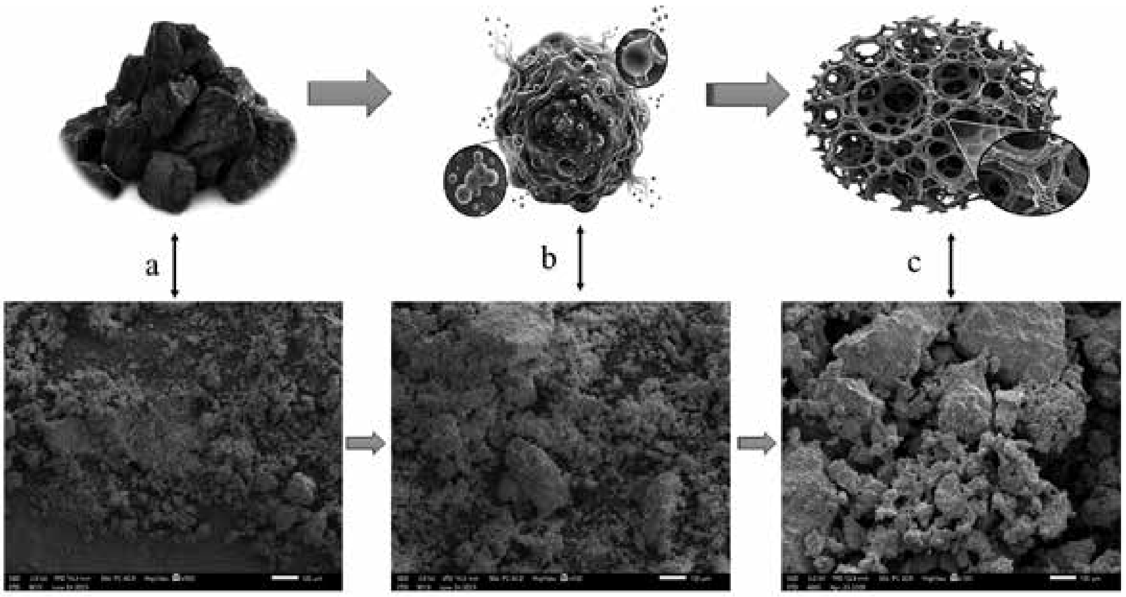
Laboratory-scale thermochemical system that was specifically made to turn technical waste from oil and gas processing plants into synthesis gas to do the experiments. The set-up had a burner (1), a waste-heating furnace/reactor (2), an internal heat-circulation zone (3), a gas-flow pipeline (4), check valves (5–7) to make sure the flow was one way and safe to use, a pressure gauge (8) to keep an eye on the pressure, a cooling chamber (9) to partially condense and lower the temperature of volatile products, a gas holder (10) to temporarily hold gas, and a waste feed vessel (11) (Figure 1). The waste-derived feedstock was heated in the reactor under controlled conditions while it was being used. The resulting gases were then sent through the gas line, cooled, pressure-regulated, and collected in the gas holder.

Flue and residual gases were released through the exhaust line (12), while syngas was sent through the inlet line (13) and taken out through the outlet line (14). This setup made it possible to do stable thermal conversion, control gas handling, and consistently test how well syngas enrichment worked under conditions that were set up in the lab. The proposed methodology demonstrates an effective integration of coal conversion and waste utilization, resulting in enhanced syngas composition and increased calorific value under controlled operating conditions.

Result and discussion

The results and discussion section focuses on the structural evolution of coal during thermochemical conversion and its direct influence on syngas composition and yield, with particular emphasis on the effects of temperature and industrial waste addition.

Figure 2. *Schematic and SEM-based evolution of coal structure during thermochemical transformation:*



(a) raw coal particles, (b) transition to metaplast (plastic) state with bubble nucleation and swelling, and (c) formation of a highly porous char-like structure

The figure shows how the structure of coal particles changes during thermochemical treatment. The top row shows a schematic representation, and the bottom row shows SEM observations that go along with it. In the first stage (a), raw coal has a dense, irregular, and angular shape with surfaces that are mostly smooth and not very porous. When heated, the material changes into a metaplast (plastic) state (b) (Figure 2), where thermal decomposition creates volatile compounds that cause gas bubbles to form in the softened matrix. This process causes particles to swell and internal voids to grow over time. In the last step (c), the quick release of volatiles and the solidification of the plastic phase create a highly developed porous, foam-like structure. SEM analysis shows that the surface roughness and pore density have both gone up a lot, which means that the specific surface area has gone up a lot. This change in structure is a key factor that affects how the material reacts in later processes like gasification and combustion. It makes it easier for mass transfer and reactive sites to be reached.

Table. *Effect of temperature and waste addition on syngas composition and gas yield from Angren and Sharg'un coals*

Feedstock Type	T (°C)	CO (%)	H_2 (%)	CH_4 and other hydrocarbons (%)	CO_2 (%)	Gas yield (%)
Angren coal	500	18.5	12.1	2.5	60.5	25.4
	600	24.4	16.8	2.9	35.2	32.6
	700	28.4	20.9	3.2	28.1	40.4
Shargun coal	500	22.5	14.5	7.5	57.8	28.1
	600	28.4	18.6	9.0	45.4	35.6
	700	32.4	22.4	10.1	35.6	42.1
Angren + 20% waste	500	20.4	14.6	7.1	59.5	40.1
	600	27.4	18.4	18.2	45.8	58.5
	700	32.4	22.3	20.8	34.3	54.4
Shargun + 20% waste	500	25.0	16.2	18.7	51.4	53.0
	600	32.9	20.3	21.8	37.6	50.9
	700	36.4	24.7	33.9	27.5	58.4

The findings clearly show that there is an improvement in the quality and amount of syngas produced as the temperature increases, for both types of coal. The increase in temperature from 500 to 700 °C causes an increase in the amounts of CO and H_2 while simultaneously decreasing the amount of CO_2, implying that there was a greater extent of thermochemical reaction and the presence of secondary reactions such as Boudouard and water-gas reactions. The inclusion of 20% of industrial waste considerably improves the production of hydrocarbons (methane and higher hydrocarbons) and gas production, especially in the case of Shargun coal, with the maximum amount of gas being 58.4%.

While the obtained results confirm the effectiveness of the proposed approach, further studies on reaction kinetics, process optimization, and industrial scalability are required to fully establish the reliability and practical applicability of this technology.

Conclusion

The thermochemical conversion process of Angren and Sharg'un coal has revealed an increase in the quality of produced syngas in accordance with the increase in temperature in the range of 500–700 °C, where there were observed significant growths of CO and H_2 contents as well as a decrease of CO_2 content. The use of 20% of industrial waste in this process has resulted in considerable improvement in production of hydrocarbons (up to 33.9%) and in gas yield (up to 58.4%). It was found that waste volatiles have actively participated in secondary reactions. Based on SEM analysis, it can be noted that the creation of porosity was observed.

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