

PAPER • OPEN ACCESS

The influence of initial parameters on the process of synthesis gases cooling during plasma-chemical processing of carbon-hydrogen containing raw materials

To cite this article: Yurii Radchenko *et al* 2025 *IOP Conf. Ser.: Earth Environ. Sci.* **1491** 012067

View the [article online](#) for updates and enhancements.

You may also like

- [Study of the efficiency of a gas turbine on CO₂ for the use of secondary heat of mining enterprises](#)
Mykhailo Kirsanov, Inna Slobodiannikova, Olena Gupalo et al.
- [Study of physicochemical relationships accompanying the process of mineral carbonation in basalt rocks from Poland](#)
Anna Pajdak, Mateusz Kudasik, Marta Skiba et al.
- [The impact of gas reserves recovery on the technological and economic performance of gas condensate field minig](#)
Illia Fyk, Serhii Kryvulia, Iryna Sinkevych et al.



UNITED THROUGH SCIENCE & TECHNOLOGY

 **The Electrochemical Society**
Advancing solid state & electrochemical science & technology

**248th
ECS Meeting**
Chicago, IL
October 12-16, 2025
Hilton Chicago

**Science +
Technology +
YOU!**

**Register by
September 22
to save \$\$**

REGISTER NOW

The influence of initial parameters on the process of synthesis gases cooling during plasma-chemical processing of carbon-hydrogen containing raw materials

Yurii Radchenko^{1,2,3}, Volodymyr Shevchenko¹, Serhii Oparin¹, Olena Gupalo^{1,2} and Serhii Davydov¹

¹M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, Simferopolska St., 2a, Dnipro, 49005, Ukraine

²Ukrainian State University of Science and Technologies, Lazaryan St., 2, Dnipro, 49010, Ukraine

³Corresponding author: y.n.radchenko@gmail.com

Abstract. The paper investigates the influence of the productivity of plasma-chemical processing of carbon-hydrogen containing raw material and initial parameters of syngas on the performance of syngas cooler. The syngas cooler consists of a sequentially located radiation section, a preliminary convective section, a steam superheater, a main convective section, an economizer, and an autonomous water cooler. To determine the operating parameters of the syngas cooler, a well-known methodology based on the solution of heat transfer and heat balance equations was used. The main performance indicators of the basic cooler design (steam capacity, superheated steam temperature, heat utilization coefficient of syngas) were determined for the ranges of 100 - 400 m³/h and initial temperature of syngas 2000 °C. The research results were summarized in the form of analytical dependence of the total area of heat-exchange surface of the cooler on the flow rate of syngas in the range from 100 to 400 m³/h, which can be used in optimization of equipment for plasma-chemical technology of hydrogen production at minimum of total costs.

1. Introduction

Currently, the issues of syngas production from carbon-hydrogen containing raw materials are of increasing interest to researchers. Various technologies with appropriate equipment have been developed [1-9]. At the same time, the cooling of produced syngas remains a serious problem, which many researchers are focused [10-15].

Due to the high energy intensity of plasma process, it is necessary not only to cool syngas to a given temperature, which is limited by the subsequent processes of syngas purification from solid particles and syngas separation to obtain hydrogen, but also to maximize the use of extracted heat, which should be returned to plasma-chemical process. An obvious solution to this problem is the use of a syngas cooler (SGC) capable of producing superheated steam.

At the same time, peculiarities of plasma technology of hydrogen production create certain difficulties for practical realization of such a solution. Due to the fact that the main components of produced gas are hydrogen and carbon monoxide, which are diathermic gases, in the radiating part of the cooler heat removal is possible only by radiation from slag particles. This leads to a decrease in the efficiency of the cooling process in the radiation part of the SGC.



The purpose of this work is to determine the influence of initial parameters of syngas and plasma plant performance on the SGC parameters.

2. Methods

For the conditions of the laboratory plasma-chemical gasification unit, the SGC scheme with the layout typical for utilizer boilers (UB) was chosen (figure 1) [10, 14].

The hot syngas from the bottom of gasifier flows down through the radiation section of the cooler (1). High pressure steam is generated in pipes that create a heat exchange surface around the perimeter of cylindrical gas flow zone. The molten slag particles are cooled by gas flow to slag solidification temperature and fall into the bowl (8) at the bottom of the cooler, from where they are removed for further utilization.

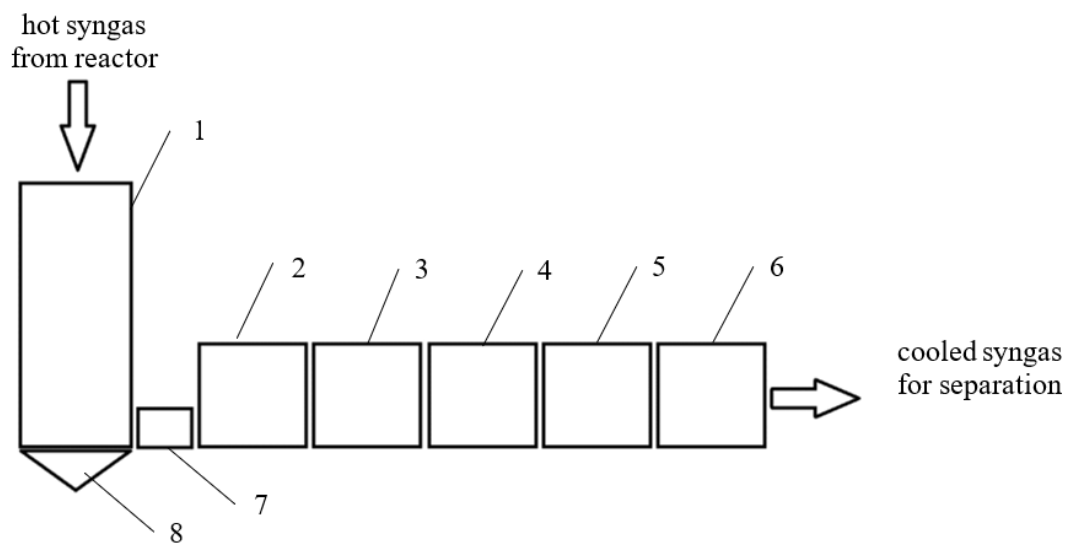


Figure 1. Schematic diagram of the SGC: 1 - radiation section (RS); 2 - preliminary convection section (PCS); 3 - superheater (SH); 4 - main convection section (CS); 5 - economizer (EM); 6 - autonomous water cooler (WC); 7 - connecting channel; 8 - slag bowl.

The syngas flows through the radiation section in connecting pipeline (7) to the convective syngas cooler, where high pressure steam is also generated. To protect the superheater (3) from high temperature, a preliminary convection section (2) is located in front of it. The main convection section (4) is located after the superheater. In the convective sections of the cooler, the syngas flows through pipe packages with a corridor arrangement of pipes.

Chemically purified water in the form of vapor-water mixture circulates in the evaporating surfaces of the cooler and removes heat from the syngas.

The water feeding the SGC is heated in an economizer (5). The final cooling of the syngas takes place in an autonomous water refrigerator (6), which is not intended for steam production. In this refrigerator, industrial water is used as a heat transfer medium. The cooled syngas flows from the SGC to the gas cleaning unit to remove the remaining solid particles and compounds. To determine the SGC operation parameters, the previously approved approach to the calculation of industrial gas coolers based on the solution of heat transfer and heat balance equations was used [16].

As initial data, taking into account the limitations, the following are specified: 1) composition, quantity and temperature of gas before the cooler; 2) maximum temperature of syngas at the outlet from the radiation part of the SGC; 3) maximum temperature of syngas before the superheater; 4) maximum temperature of gas after the cooler taking into account the subsequent process of separation of the gas mixture; 5) pressure of superheated steam produced in the SGC and its temperature.

Due to the fact that most of the heat transfer parameters depend on the value of syngas temperature at the outlet of the calculated section, the calculation is performed by the method of successive approximations.

The syngas temperature t_g at the outlet of the design section is set and the enthalpy change at this section is determined. The heat balance equation for gases determines the heat to be removed from the syngas at this section, and the heat transfer equation determines the required surface area of the section to remove this heat.

To calculate the total heat transfer coefficient on the syngas side, the heat transfer coefficient by radiation is determined, for which the total attenuation coefficient k of syngas in the presence of soot particles is calculated.

In the radiative part of the cooler, convective heat transfer from gases to the screen is negligibly small compared to the radiant heat transfer, so convective heat transfer is not taken into account in the section of radiating surfaces. In the convective part of the cooler, the conditions of heat transfer from syngas to tube surfaces change. In particular, the temperature of syngas decreases significantly, which decreases the heat transfer by radiation, while the turbulization of the flow around tubular surfaces leads to increase in the convective component of heat transfer. As a result, the role of convective heat transfer increases significantly.

The convective heat transfer coefficient for gas-washed tube packages is determined using criterion equations, depending on the conditions of the heat transfer process and the cooling surface layout [17].

The following data are taken as initial data: gas temperature before the cooler is 2000 °C, productivity of the plasma-chemical gasification unit is 200 m³/h of syngas, pressure of the produced superheated steam is 1 MPa with temperature 300-350°C. Steam with such parameters is used in plasma process during gasification, besides it can be used in municipal and domestic sphere.

The design dimensions of individual parts of the SGC were selected taking into account the UB design practice [18]. The diameter of the radiative part of the SGC was taken to ensure sufficient thickness of the dusty radiating gas layer and minimum hydraulic resistance of the channel. For the convective part of the cooler, a corridor arrangement of heat-exchange tubes was used with a step providing the recommended gas velocity in the intertube space.

The area of heat-exchange surfaces was calculated taking into account the recommendations [19] on syngas temperature along the flow. Thus, the temperature of gases before the convective part should not exceed 1300 °C (melting temperature of solid slag particles carried away from the reactor together with gases). The temperature of syngas before the superheater should not exceed 600-700 °C, and the temperature at the SGC outlet should not exceed 60 °C (limiting for the subsequent process of separation of the gas mixture).

Preliminary studies have shown that for the case of the classical SGC layout, when the economizer (EM) is closing, it is impossible to cool syngas to less than 110 °C. This is due to the fact that feed water after thermal deaeration enters the economizer at a temperature of 100 °C. Therefore, an autonomous water cooler was provided after the EM, which is designed to reduce the SG temperature to the temperature of 50-60 °C.

Table 1 shows the design characteristics of the SGC sections, obtained on the basis of the calculation methodology and for the accepted initial data.

Table 1. Design characteristics of the basic SGC design.

Parameter	RS	PCS	SH	CS	EM	WC
Section area, m ²	5.453	1.645	1.645	3.290	3.2899	8.2248
Section diameter/width, m	0.579	0.409	0.409	0.409	0.409	0.409
Pipe diameter, mm	-	32	32	32	32	32
Number of pipe rows, pcs:						
- in width	-	10	10	10	10	10
- in length	-	4	4	8	8	20

3. Results and discussion

Since the heat transfer conditions depend on syngas flow rate and temperature, in order to assess their influence on the SGC performance, the basic design of the cooler was calculated in the range of possible capacities and temperatures of syngas supplied for cooling.

Figures 2-3 show the calculation results of the main parameters of the basic SGC design for the range of plasma-chemical plant productivity from 100 m³/h to 400 m³/h.

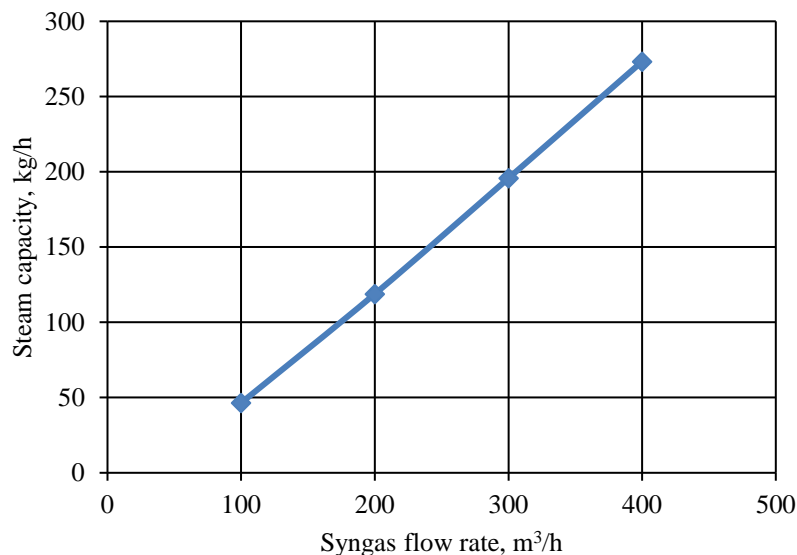


Figure 2. Dependence of steam capacity in the basic SGC design on syngas flow rate.

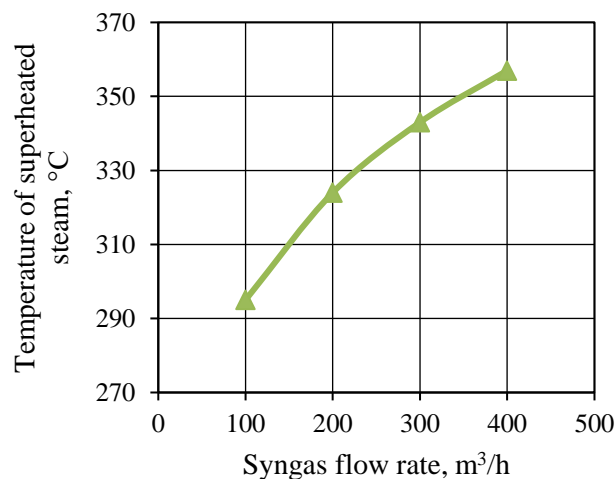


Figure 3. Temperature dependence of superheated steam in the basic SGC design on syngas flow rate.

The analysis of the results showed that the dependence of the SGC steam capacity on syngas flow rate is linear - steam capacity increases with the growth of syngas flow rate (figure 2). At the same time, the temperature of superheated steam increases nonlinearly with increasing syngas flow rate through the SGC and rises from 295°C at 100 m³/h to 357°C at a flow rate of 400 m³/h (figure 3).

In this case, the initial heat utilization coefficient (HUC) of syngas, which is the ratio of enthalpy of superheated steam to enthalpy of syngas at the SGC inlet, has a noticeable maximum area (86.90-87.02%) in the range of syngas flow rate 200-300 m³/h (figure 4).

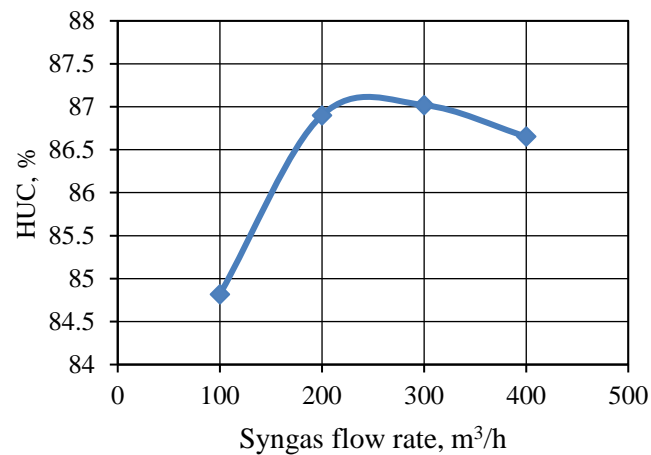


Figure 4. Dependence of the HUC of the basic SGC design on syngas flow rate.

Figures 5-7 show the effect of initial syngas temperature on the performance of the basic SGC design at a nominal gas flow rate of 200 m³/h.

Figure 5 shows the temperature distribution in the basic SGC design at different initial syngas temperatures. As can be seen from the figure, the initial gas temperature has a significant effect only on the RS. This is due to a sharp decrease of the radiant heat flux to the SGC walls as the temperature of syngas decreases. However, already after PCS, the temperature distribution over the sections does not differ much by variants. It is noteworthy that in all cases syngas temperature at the SGC outlet has the same value equal to +54 °C. This is explained by the sufficient heat exchange surface area of the convective part of the SGC and high heat transfer coefficients to the steam-water mixture.

As can be seen from figures 6 and 7, with decreasing initial syngas temperature, the steam capacity and HUC of the basic SGC expectedly decrease, while the superheated steam temperature on the contrary increases (figure 6).

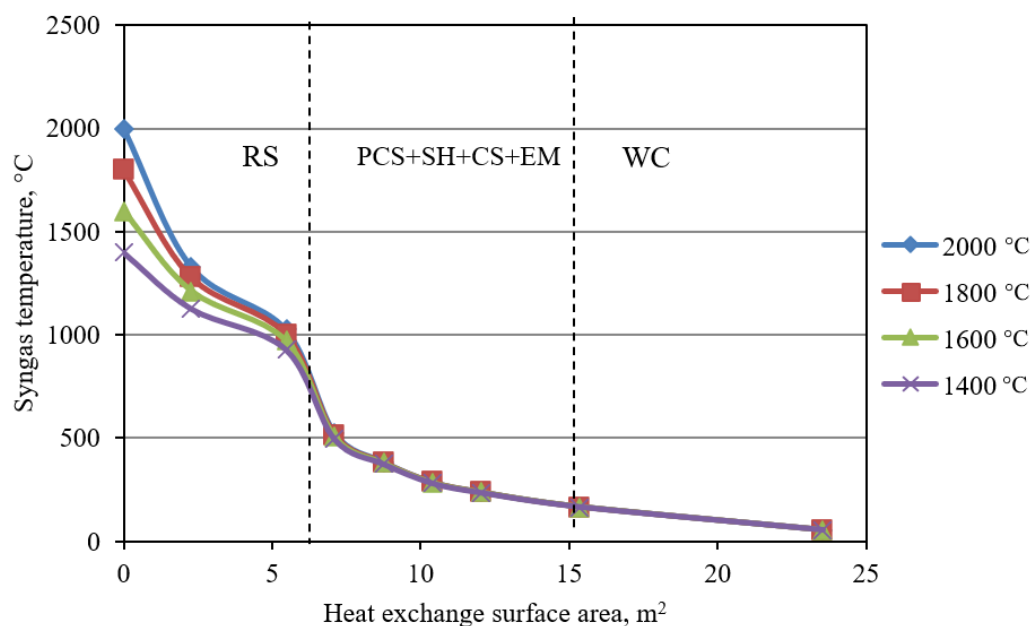


Figure 5. Syngas temperature distribution along the heat exchange surfaces in the basic SGC design depending on the initial temperature of syngas.

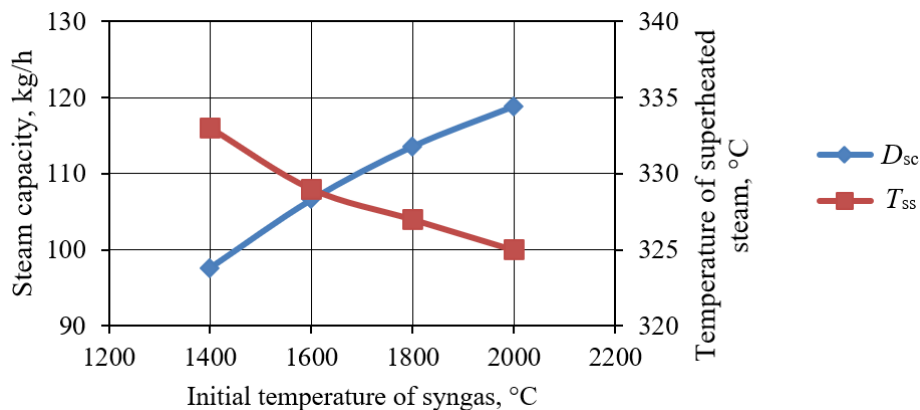


Figure 6. Dependence of the steam capacity of the basic SGC design on the initial temperature of syngas D_{sc} - steam capacity; T_{ss} - superheated steam temperature.

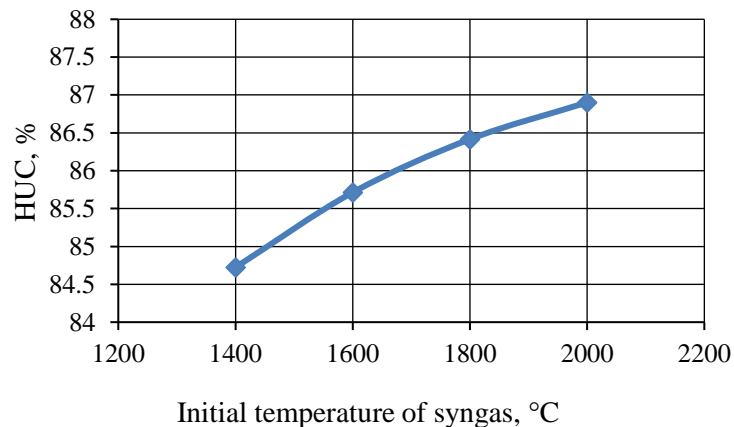


Figure 7. Dependence of the HUC of the basic SGC design on the initial temperature of syngas.

Analysis of the results shows that deviation of syngas flow rate from the nominal flow rate leads to changes in steam capacity and temperature of superheated steam. In turn, this affects both the process and the operation of third-party consumers of superheated steam.

Thus, the study of regularities of the SGC operation showed that when reducing the flow rate from the nominal value (200 m³/h) to 100 m³/h, the temperature of syngas decreases from 54 °C to 46 °C (by 14.81%). Increasing the syngas flow rate from the nominal value to 400 m³/h leads to an increase in syngas temperature behind the SGC from 54 °C to 67 °C (by 24.07%), which may have a negative impact on the efficiency of the separation process of H₂ in the gas separation unit.

With reduction of syngas flow rate from nominal value (200 m³/h) to 100 m³/h, steam capacity decreases from 118.836 to 46.459 m³/h (by 60.90%). At increase of flow rate from nominal value to 300 m³/h steam capacity increases up to 195.755 kg/h (by 64.73%). And at syngas flow rate equal to 400 m³/h steam capacity reaches 273.302 kg/h (increases by 129%). At the same time, it was assumed that the hydraulic resistance of the path does not exceed the capabilities of the draught blowing equipment of the basic SGC design and the flow of gases through the SGC is ensured.

The change of syngas temperature at the inlet to the SGC has no critical influence on the cooler performance. However, at lowering of syngas temperature from 2000 °C to 1800 °C, steam capacity decreases from 118.836 to 113.563 kg/h (by 4.44%). When the temperature is further decreased from 1800 °C to 1600 °C, the steam capacity decreases from 113.563 to 106.575 kg/h (by 6.15%). Finally,

when the temperature changes from 1600 °C to 1400 °C steam capacity drops to 97.633 kg/h (by 8.39%).

At the same time, fluctuations of syngas flow rate and its initial temperature do not significantly affect the superheated steam temperature. It remains practically unchanged (325- 333 °C) and is within the error of this engineering calculation (2.46%).

To assess the possibility of scaling the considered SGC design, calculations of SGC for operation with nominal flow rate in the range of productivity of plasma-chemical plants on syngas from 100 to 400 m³/h at unchanged initial temperature of entering for cooling syngas 2000°C, were performed. The results of calculations are given in table 2.

Table 2. The SGC design characteristics for different nominal capacities and design performance data.

Syngas flow rate, m ³ /h	Parameter*	The SGC structural parts						D_{sc} , kg/h	T_{ss} , °C	HUC, %	D_{sc}/V_0 , kg/m ³
		RS	PCS	SH	CS	EM	WC				
100	t_g	1029	528	386	239	168	54	59.3	326	86.81	0.593
	F	3.817	1.047	1.047	2.094	2.094	5.234				
	F_s	3.817	4.864	5.911	8.005	10.099	15.333				
200	t_g	1025	524	383	237	167	54	118.836	324	86.90	0.594
	F	5.453	1.645	1.645	3.29	3.290	8.225				
	F_s	5.453	7.098	8.743	12.033	15.323	23.548				
300	t_g	1030	529	387	239	168	56	178.651	326	86.83	0.596
	F	6.682	2.540	2.540	5.080	4.838	12.096				
	F_s	6.682	9.222	11.762	16.842	21.68	33.775				
400	t_g	1029	533	390	241	169	55	235.922	328	86.69	0.590
	F	7.911	3.255	3.255	3.255	6.51	16.274				
	F_s	7.911	11.166	14.421	20.931	27.441	43.715				

* t_g – syngas temperature at the outlet from the relevant SGC structural part, °C; F – SGC section area, m²; F_s – total area of heat exchange surfaces of SGC, m²; V_0 – syngas flow rate at the SGC inlet under normal conditions, m³/h; D_{sc}/V_0 – specific steam capacity, kg/m³.

Analysis of the results showed that SGCs designed for plants with different nominal capacity, in all cases provide the specified parameters of cooled syngas, the temperature behind the SGC is not more than 54-56° C. At the same time, the specific steam capacity is in the range of 0.590-0.596 kg/m³ of gas, and the superheated steam temperature is practically unchanged and is 326-328°C, the HUC of the SGC is in the range of 86.69-86.90%.

Depending on the nominal syngas flow rate for which the SGC is designed, the areas of heat exchange surfaces of the radiative and convective parts of the SGC change. Thus, figure 8 shows the dependence of F_s – the total area of the SGC heat-exchange surfaces and F^* – the area of the SGC heat-exchange surfaces (without taking into account the area of autonomous water cooler) on the syngas flow rate. As can be seen from figure 8, both areas increase with increasing plant capacity. At the same time, F_s increases to a greater extent, which is due to the low intensity of heat exchange in the autonomous water cooler section due to the small temperature difference “syngas -water”.

On the basis of calculated data, the analytical dependence of the total area of the SGC heat-exchange surface on syngas flow rate in the range from 100 to 400 m³/h was obtained, which can be used in setting and solving the optimization problem of equipment for plasma-chemical technology of hydrogen production on the minimum of total costs:

$$F_s = -0.3840 \cdot \left(\frac{V_0}{100}\right)^3 + 3.3111 \cdot \left(\frac{V_0}{100}\right)^2 + 0.9695 \cdot \left(\frac{V_0}{100}\right) + 11.4364,$$

where F_s – the total area of the SGC heat-exchange surfaces, m².

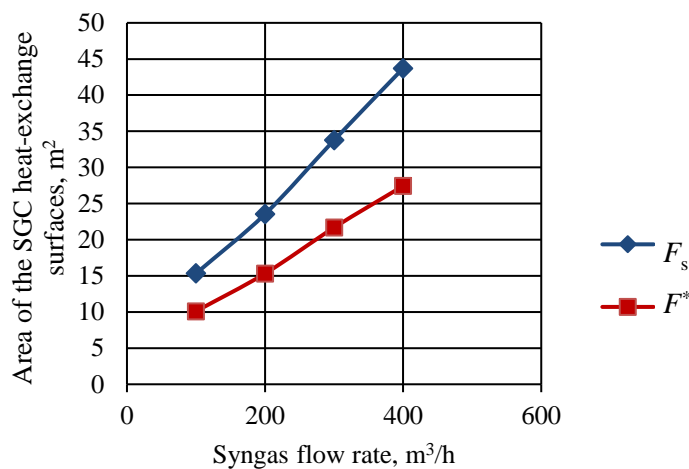


Figure 8. Dependence of the SGC heat-exchange surfaces on syngas flow rate.

4. Conclusions

For the conditions of plasma-chemical processing of carbon-hydrogen containing raw materials and selected cooler layout, the influence of initial syngas parameters and plant productivity on the SGC performance was established.

Rational sizes of separate heat-exchange surfaces of the SGC with account of initial and final parameters of syngas were determined.

The analytical dependence of total area of the SGC heat-exchange surface on syngas flow rate in the range from 100 to 400 m³/h was obtained, which can be used in solving the problem of optimization of equipment for plasma-chemical technology of hydrogen production according to the minimum of total costs.

References

- [1] Mohammed Taher Isse Barshushi, Alkeeb Ahmed M. Mohammed Aljali and Nahla Faiz Abdullah 2019 Current state of development in the field plasma gasification and waste treatment *Integrated Tehnologies and Energy Saving* (2) pp 59-68. Available from: http://library.kpi.kharkov.ua/files/JUR/ite_2019_2.pdf
- [2] Rudyka V I 2017 The analysis of the experience in commercialization of indirect coal liquefaction technologies in the world *The Problems of Economy* (3) pp 13-19. Available from: <http://surl.li/eylumk>
- [3] Bryk D, Podolsky M, Khokha Y, Lyubchak O, Kulchytska-Zhyhaylo L and Gvozdevych O 2021 Substandard carbon-containing raw materials and methods of their thermochemical processing *Geology and Geochemistry of Combustible Minerals* (1-2) pp 89-109 <https://doi.org/10.15407/ggcm2021.01-02.089>
- [4] Salamov A A 2005 Parogazovye ustanovki s gazifikatsiey topliva i sokrashcheniem vybrosov CO₂ *Teploenergetika* (2) pp 78-80
- [5] Rutberg F 2013 Plasma technology for renewable energy *Baltiiskii gorizont* 4 (12) pp 6-9
- [6] Volchyn I, Dunayevska N, Haponych L, Chernyavskiy M, Topal A and Zasyadko Y 2013 *Prospects for the implementation of clean coal technologies in the energy sector of Ukraine* (Kyiv: HNOZIS) 308 p
- [7] Davydov S L 2019 *Substantiation of process parameters of carbon-containing Heterogeneous medium conversion into gas under the influence of plasma energy*. The PhD thesis. (Dnipro: ¹M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine) 185 p

- [8] Bulat A, Kholiavchenko L, Oparin S, Davydov S, Zhevzyk O and Potapchuk I 2022 Energy of low-temperature plasma in the processes of thermal conversions of carbon-containing medium *IOP Conf. Ser.: Earth Environ. Sci.* **970** 012050 <https://doi.org/10.1088/1755-1315/970/1/012050>
- [9] Shevchenko V, Oparin S and Kabakova L 2024 Methodology for determining the design parameters of combined type plasma-chemical reactor for gasification of carbon-containing raw materials. *IOP Conf. Ser.: Earth Environ. Sci.* **1348** 012078 <https://doi.org/10.1088/1755-1315/1348/1/012078>
- [10] Qian Zhu 2015 *High temperature syngas coolers* (London: IEA Clean Coal Centre). Available from: <http://surl.li/gqwidl>
- [11] Uebel K, Guenther U, Hannemann F, Schiffers U, Yilmaz H and Meyer B 2014 Development and engineering of a synthetic gas cooler concept integrated in a Siemens gasifier design *Fuel* **116** pp 879-888 <https://doi.org/10.1016/j.fuel.2013.03.020>
- [12] Syngas Quench Chamber. Web-site *Biofuels Academy*. Available from: <http://surl.li/ppkrxk>
- [13] J. van Rooyen 2018 *Modelling and efficiency improvement of a plasma-arc gasification reactor quench probe* (Potchefstroom, Republic of South Africa: School of Chemical and Minerals Engineering, North-West University Potchefstroom Campus). Available from: <http://surl.li/zffxkt>
- [14] Bruno Bülow 2016 Importance of heat recovery in gasification plants. *7th Annual International Summit & EXPO Gasification India 2016*, February 11 - 12, New Delhi, India. Available from: <http://surl.li/ochqgp>
- [15] Commercial Technologies for Syngas Cleanup. *Web-site of the U.S. Department of Energy National Energy Technology Laboratory*. Available from: <http://surl.li/hnftgt>
- [16] Rumiantcev V 2006 *Teoriia teplo- i massobmenai* (Dnepropetrovsk: Porogi) 532 p
- [17] Kazantcev E 1975 *Promyshlennye pechi* (Moskva: Metallurgiiia) 368 p
- [18] Hichov Yu O, Boiko V M and Adamenko D S 2004 *Kotly-utylizatory ta yikh teplovyi rozrakhunok* (Dnepropetrovsk: Natsionalna metalurhiina akademiia Ukrainy) 46 p
- [19] Voinov A P, Zaitcev V A, Kuperman L I and Sidelkovskii L N 1989 *Kotly-utilizatory i energotekhnologicheskie agregaty* (Moskva: Energoatomizdat) 272 p