IRSTI 67.09.45 https://doi.org/10.26577/phst.2022.v9.i2.08

The impact of technological parameters of the torch to physical and chemical properties of a gas-thermal burner for spraying ultra-high molecular weight polyethylene

M.K. Skakov[1], I. A. Ocheredko[2],
M. B. Bayandinova[2,*] and B.T. Tuyakbaev[2]

[1]The Republican State Enterprise «National Nuclear Center of the Republic of Kazakhstan» of the Ministry of Energy of the Republic of Kazakhstan, Kurchatov, Kazakhstan
[2]Sarsen Amanzholov East Kazakhstan University, Ust-kamenogorsk, Kazakhstan
*e-mail:shohmanova_m@mail.ru
(Received 28 June 2022; received in revised form 24 September; accepted 18 October 2022)

The values of the heat flux density, transverse and longitudinal temperature gradients of the gas-thermal burner torch, the type of reaction during the combustion in various modes (reducing, neutral, oxidizing) depending on the mass fractions of the fuel and oxidizer burning have been determined in this paper. The significant role of the torch temperature as one of the most important parameters determining the quality of polymer coatings obtained by the gas-thermal method has been established. A spatial model of a gas-thermal burner has been designed, which allows to obtain thermal modes at specified technological parameters. A physical model of the interactions "torch-polymer particle", "thermal jet – base" has been developed. The necessary density of the torch heat flux for the complete melting of ultrahigh molecular weight polyethylene (UHMWPE) particles not exceeding the temperature threshold of destruction has been determined. The required rate of introduction the UHMWPE powders into the burner flame has been also determined. Based on the calculations of the "torch-polymer particle interaction", the optimal geometry of the torch, the particles trajectory in the torch and the spraying distances have been determined.

Keywords: gas-thermal spraying, ultra-high molecular weight polyethylene, High-Velocity Air-Fuel technology, finite element method, destruction.
PACS numbers: 07.20.−n, 44.90.+c.

1 Introduction

A method of applying polymer coatings to the surface of metal products by gas-thermal spraying in protection purposes is proposed in a number of works [1-5]. The method eliminates the necessity of using volatile organic solvents under hazardous production conditions. However, the proposed method and equipment for the gas thermal spraying has significant drawbacks including low productivity; the heat transfer in the "torch – polymer particle", "thermal jet-base" systems have not been investigated. In our opinion, the systematic studies have also not been carried out to determine the efficient composition of the combustible mixture and granulation of the applied polymer material. In addition, the method is not optimized for the criteria of industrial applicability.

In the result, there are still no unifired recommendations for choosing the optimal value of the heat flow density of the thermal sprayer torch, modes of melting polymer coatings on long-length parts. Moreover, from a technological point of view, the problems of controlling the geometric dimensions of the applied coatings which in turn depends on the accurate modeling of the spraying process have not been solved.

The unstable technological modes adversely affect, respectively, the practically important properties of the obtained coatings.

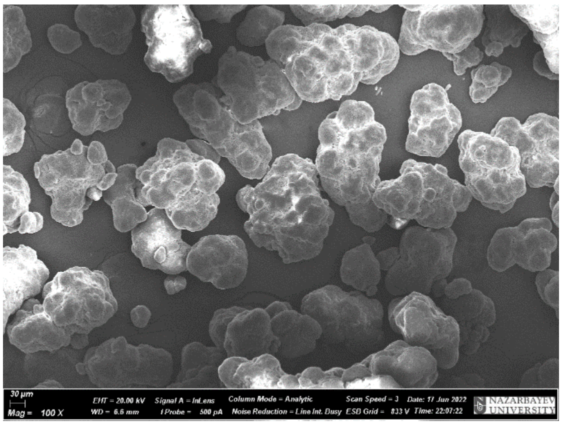
The polymer processing has been carried out using plasma energy [6-8]. However, the high temperature developed in the plasma flow results in the polymer destruction. Besides this, the mechanical properties and chemical resistance of coatings are lower than those of the coatings made by other methods.

This greatly limits the scope of the flame spraying method. In addition, a significant disadvantage of the polymer plasma spraying method is the low values of the thermal efficiency, high energy intensity, and the impossibility of its implementation under non-stationary conditions. The plasma method seems to be appropriate only for the processing of refractory polymers, such as fluorolones.

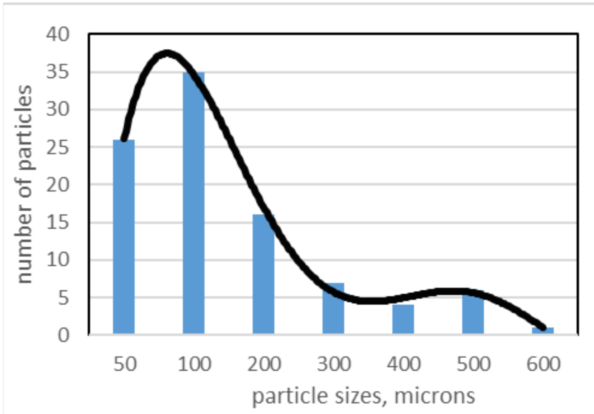
Thus, the purpose of this work is to determine the degree of the parameters of the High-Velocity Air-Fuel (HVAF) method the impact to the physical and chemical properties of the burner torch during the UHMWPE processing.

2 Material and research methods

In order to apply UHMWPE coating in practice, we need to develop and design an experimental high-rate gas-air spraying unit. However, it is necessary to determine beforehand the influence of the technological parameters of the gas-thermal equipment on the physical and chemical properties of the burner torch during the UHMWPE processing. We used 3D modeling methods to solve this problem. Propane was used as a fuel gas, and air was used as an oxidizer (high velocity coating technology – High Velocity Air-Fuel (HVAF). The object of the UHMWPE study, manufactured by Nantong Yangba Polyethylene Co., Ltd., China, the density is 930 kg/m^3, with a molecular weight of $2 \cdot 10^6$ mol^{-1}, is a white powder with an average particle size of 150 microns (Figure 1 a, b), T_{pl} = 135 °C, bulk density >0.4 g/cm^3, p ≥ 0.933 g/cm^3. The shape and size of UHMWPE particles were determined by optical microscopy on Altami Met 5C. The powder mixing was carried out in a Pulverisette 23 ball mill, rotation speed 1500 rpm, grinding time in the range from 6.5 to 15 minutes.



a



b

Figure 1 – Optical image of UHMWPE particles (a), particle size distribution (b)

To study the process of the UHMWPE gas-thermal processing, we have designed a physical model of the system and found optimal solutions by the finite element method (FEM) in accordance with [9,10]. FEM is a numerical method for solving partial differential equations, as well as integral equations arising in solving problems of applied physics. As it is known, FEM is widely used to solve problems of deformable solid mechanics, heat transfer, hydrodynamics, electrodynamics and topological optimization. The domain in which the solution of differential equations is sought is divided into a finite number of subdomains (elements). The type of approximating function is arbitrarily selected in each of the elements.

A spatial model that makes it possible to obtain the thermal modes of the burner torch at the specified technological modes has been designed. The model was designed in the SolidWorks 3D modeling software package according to [11]. The boundary conditions are: heating time of a powder particle is 0.2 s, an average heat flow density is 38 kW/m^2.

3 Results and discussions

3.1 Dependence of the physical and chemical properties of the gas-thermal burner torch on the geometry of the nozzles and the mass fractions of fuel and oxidizer

To determine the dependence of the physical and chemical properties of a gas–thermal burner torch on the geometry of the burner nozzles and the mass fractions of fuel and oxidizer, we designed a 3D model of High-Velocity Air Fuel (HVAF) spraying technology (Figure 2).

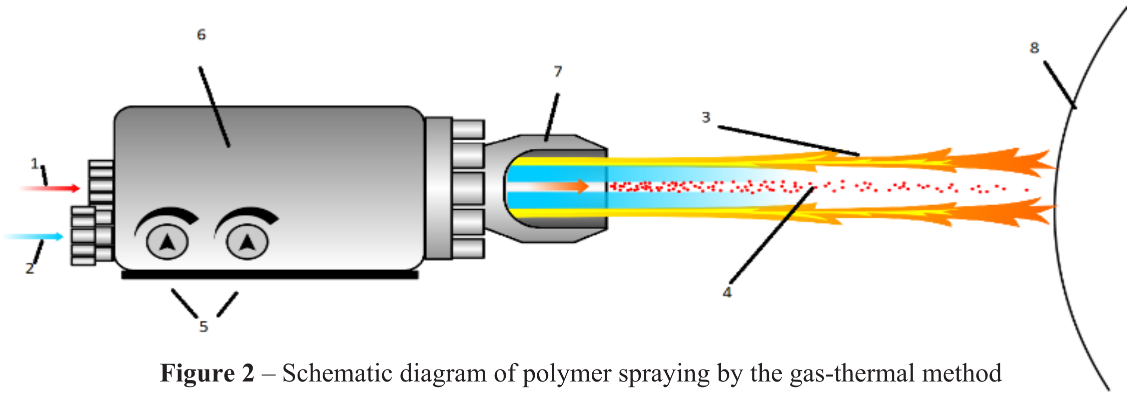


Figure 2 – Schematic diagram of polymer spraying by the gas-thermal method

According to Figure 2, there is a brief description of the technological process: propane 1 enters the gas distribution unit 6, and sprayed through nozzle 7, ignites under the impact of a heat source and forms torch 3; mixture of air and composite charge 2 enters the gas distribution unit and then enters the torch zone through nozzle 7; UHMWPE powders 4 melt under the impact of the temperature and collide with base 8 to form a coating. The ratio of the fuel, oxidizer and working raw materials, i.e. variable technological parameters, are regulated respectively by valves 5. The burner torch must provide the necessary technological mode for the processing of UHMWPE particles. To obtain coatings with the possibility of varying their properties, it is necessary to provide an adjustable temperature gradient of the torch, which can be achieved by changing the geometry of the nozzle and the ratio of fuel and oxidizer.

The most important problem of optimizing the torch burning process is the efficient use of the energy released during the combustion of the combustible mixture. In addition, special attention is paid to the compliance with the spraying temperature mode during the spraying polymer coatings.

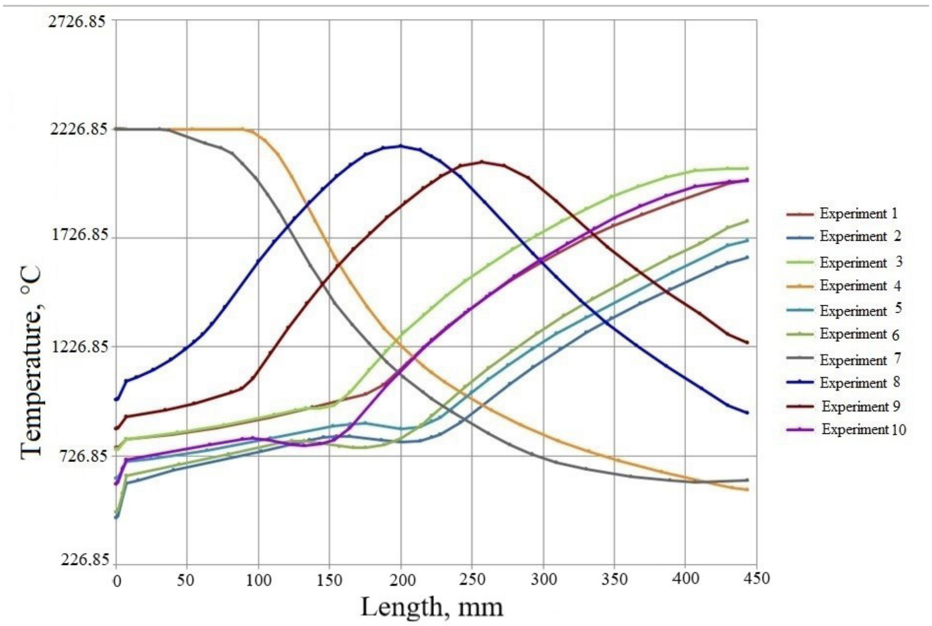


Figure 3 – Dependence of the physical and chemical properties of the torch on the geometry of the nozzles and the mass fractions of the fuel and oxidizer

Figure 3 shows the changes in the physical and chemical properties of the torch depending on the geometry of the nozzles and the mass fractions of the fuel and oxidizer.

Table 1 shows boundary conditions.

It can be seen from the above data, that the temperature distribution along the axes of the torch is sensitive to the ratio of the diameter of the nozzle and the gas flow velocity.

Table 1 – Boundary conditions of the experiment

	Experiment 1	Experiment 2	Experiment 3	Experiment 4	Experiment 5
Jet diameter, mm	0,9	1	1,1	1,2	0,9
Gas consumption (propane)	0,01	0,03	0,05	0,04	0,035
	Experiment 6	Experiment 7	Experiment 8	Experiment 9	Experiment 10
Jet diameter, mm	1	1,1	1,2	0,9	1
Gas consumption (propane)	0,001	0,03	0,01	0,001	0,005

3.2 The dependence of the heat flow density, the temperature gradient of the burner torch, the type of reaction during combustion in various modes on the mass fractions of fuel and oxidizer

According to Figure 2, the ratio of fuel, oxidizer, raw materials (variable technological parameters) is regulated by valves 5

Figure 4 shows the calculated data of the temperature gradient of the gas-thermal burner torch. As can be seen from the diagram, the designed finite element model allows receiving the data at any point in the torch space. Depending on the ratio of the combustible substance and oxygen, the gas flame is divided into [12-14]:

- oxidative – with oxygen excess;
- regular – with a parity ratio of combustible matter and oxygen;
- recovery – with an excess of combustible gas.

The torch flame consists of three components: the neutral zone (red), the recovery zone (green) and oxidizing (light blue color) (Figure 5).

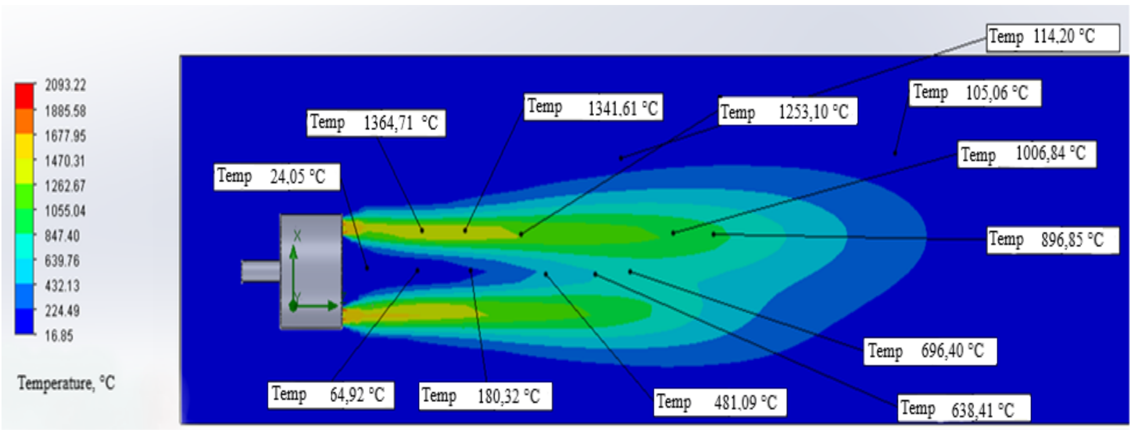


Figure 4 – The torch temperature gradient

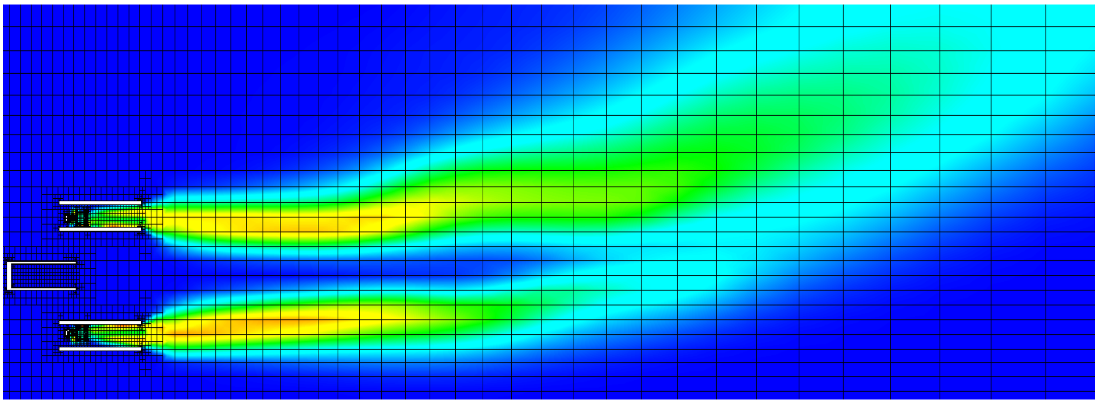
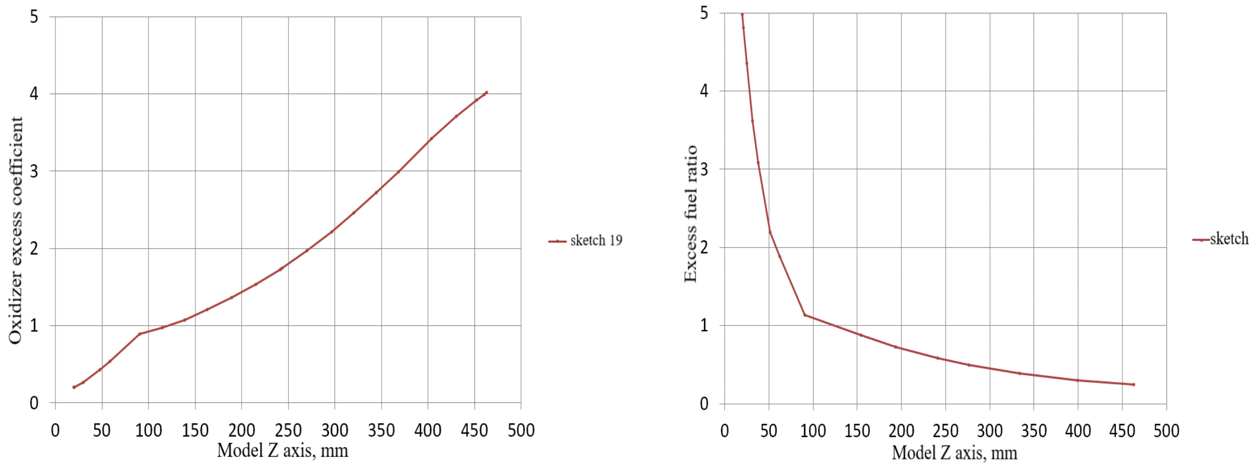


Figure 5 – Colored zones, which show the type of combustion reaction



a) b)

Figure 6 – Change in the excess coefficient of oxidizer (a) and fuel (b) along the flame axis

From the data in Figures 5 and 6, it can be seen that the powder is in the area of the oxidizing flame in the melting zone. In [15,16] it is noted that due to thermal oxidation processes, the coatings even from inert polymers, such as polyethylene, have good adhesion. However, too high flame temperature (up to 1500 ° C) in an unstable mode adversely affects the other, practically important properties of coatings. For example, the mechanical properties and chemical resistance of the coatings are lower than that of the coatings made by other methods [17-19].

The heat flow density is an important technological parameter. The determining of the heat flow density is necessary to determine the optimal trajectories of powder particles in the torch. Figure 6 shows a general picture of the distribution of heat flow density along the torch longitudinal axis.

Figure 8 shows the calculated gradient of the heat flow in the particle deposition area. Figures 7 and 8 show the dependence of the heat flow density on the deposition distance. It can be seen that at a distance of 0.8 m the average value of the flow density is 38 kW/m^2. The heat flow density corresponds to the modes that are calculated when modeling the heat exchange process in the “torch – polymer particle” and “thermal jet-base” systems.It is necessary to study the “torch – polymer particle interaction” because of the low thermal conductivity of the UHMWPE, thermal destruction. Powder losses in this technological process may be caused by:

- the amount of powder that did not melt in the flame,
- the amount of powder that has been destructed due to a high temperature.

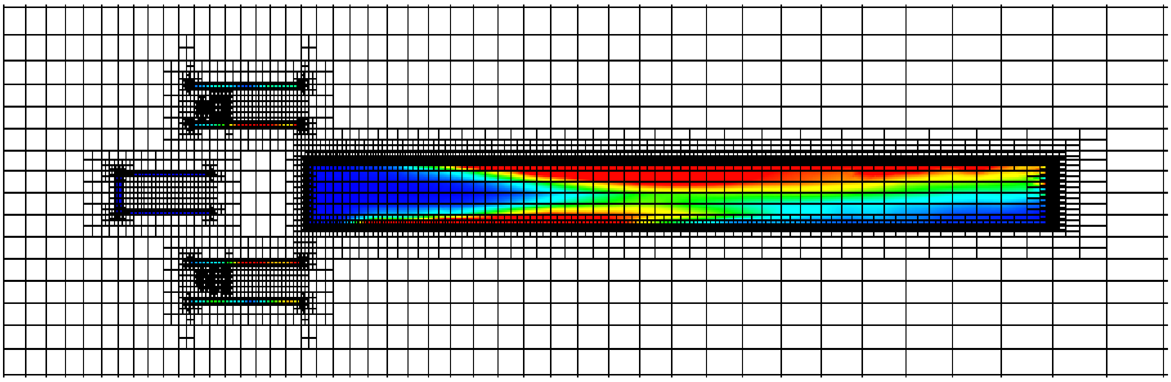


Figure 7 – Picture of heat flow density

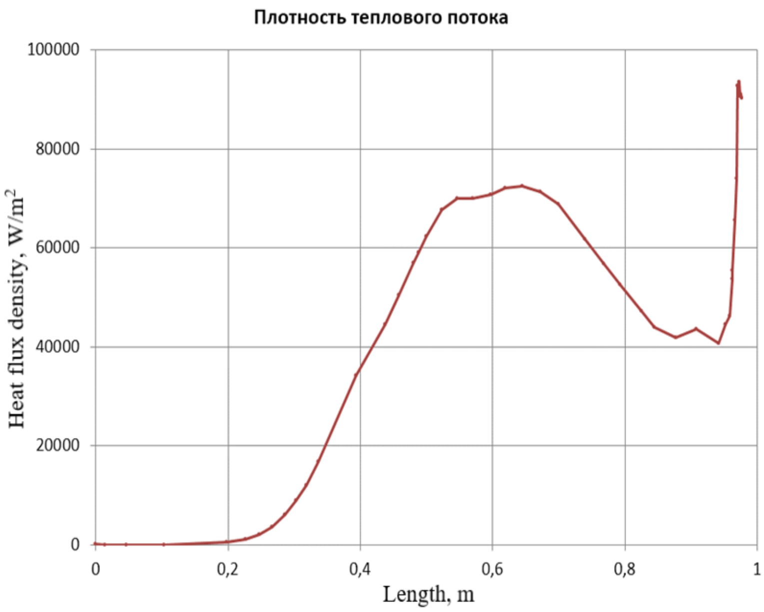


Figure 8 – Change in heat flow density along the torch central axis

This may occur with non-optimal trajectories of the powder particles in the torch. Namely, a particle has a path in the torch that does not correspond to its physical and chemical properties. The particle does not fall into the torch. The thermal power of the torch is less than necessary to melt the entire amount of particles arriving per a unit of time.

3.3 Modeling of heat transfer processes in the "torch – polymer particle", "thermal jet-base" systems

In the result of the calculated work, the trajectories of a particle motion in the torch have been obtained (Figure 9). It can be seen that the powder particles are placed along the cylinder axis and move in the calculated central axis of the flame, the powder heating is uniform and lies within the specified limits of the temperature and destruction.

Picture 10 shows the change in the heating temperature of UHMWPE particles along the trajectory of their movement at a powder feed velocity of 1 kg/min.

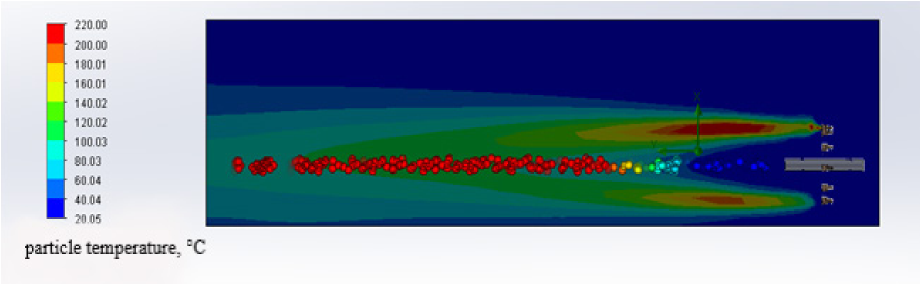


Figure 9 – Picture of the of UHMWPE particles trajectory in the torch

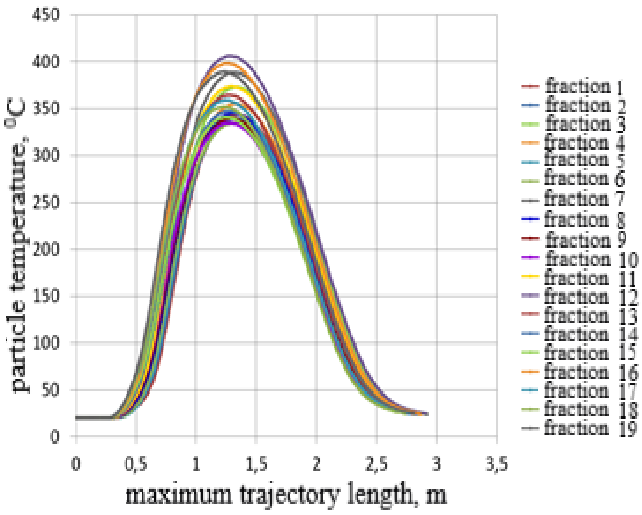


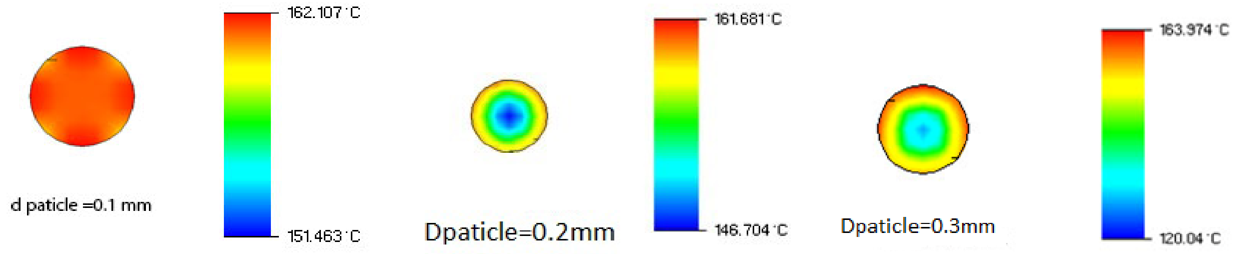
Figure 10 – Particle temperature distribution along the torch length

Figure 10 shows that the particles reach the required temperature at a distance of 0.8 *m*. At the same time, the temperature of the particles is almost the same, which should ensure a uniform structure of the coatings obtained from UHMWPE. The melting point of UHMWPE is 135 – 150^{0}C. Theoretically, the short-term temperature limit without destruction is 1.5 T_{pl}. The values obtained by us satisfy the specified interval. It also follows from the data obtained that it is necessary to choose a spraying distance of 800 *mm*, which ensures the exposure of a given temperature range.

Figure 11 shows the change in the temperature gradient along the particle cross-section depending on its diameter. The boundary conditions are: the heating time of a powder particle is 0.2 *s*, the average heat flow density is 38 kW/m^2

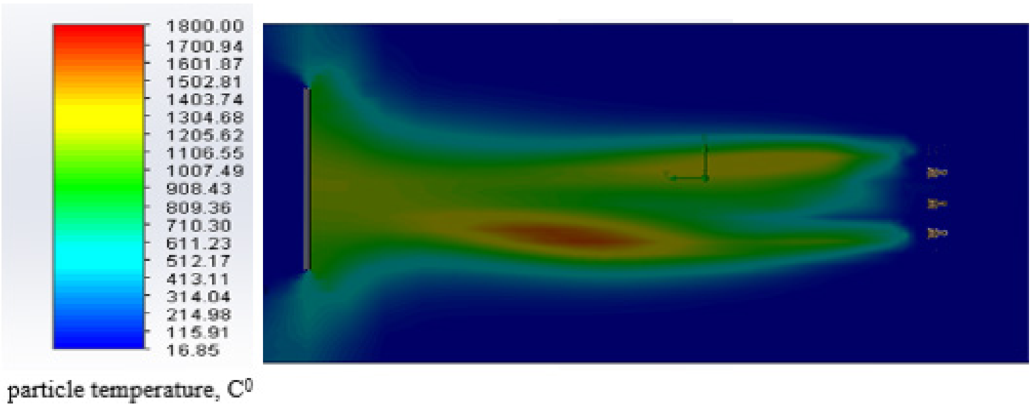
It can be seen that, the particle core has a temperature below melting point by 120 C^0 for a UHMWPE particle larger than 0.2 *mm* at a given heat flow density, which will result in incomplete powder melting. Therefore, it is advisable to use powders with a particle size of about 0.05-0.2 *mm*, which corresponds to the physical and chemical properties of the particles during the spraying [20-21].

Figure 12 shows the "thermal jet-base" interaction. The temperature distribution fields are visible depending on the geometry of the bases. It can be seen from the diagrams that the optimal spraying distance is 0.8-1 *m*, since then the torch is less stable and the particles fall into the turbulent flow.

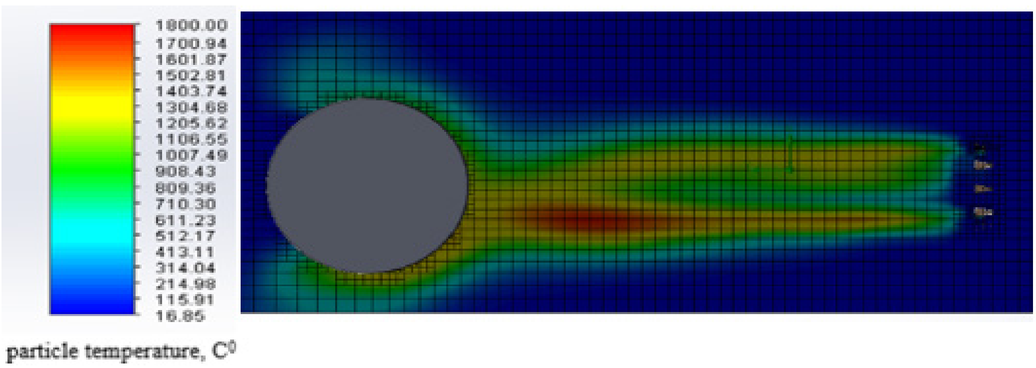


a) b) c)

Figure 11- Temperature gradient along the cross-section of the particle, depending on its diameter: a) d= 0.1 *mm*; b) d=0.2 *mm*; c) d=0.3 *mm*



a



b

Figure 12 – Temperature gradient in the interaction of a thermal jet with a flat (a) and cylindrical (b) geometry of bases

4 Conclusions

Thus, in the result of the conducted research, a significant impact of the technological parameters of the gas-thermal equipment to the physical and chemical properties of the burner torch during the processing of SMPE (HVAF method) has been established. The values of the heat flow density and the temperature gradient of the torch, the type of a reaction during the combustion in various modes (recovery, neutral, oxidizing), depending on the mass fractions of the fuel and oxidizer, have been determined. The significant role of the torch temperature as one of the most important factors determining the quality of the polymer obtained coatings has been established. A spatial model of a gas-thermal burner which makes it possible to obtain the thermal modes at a specified technological parameter.has been designed. A physical model of the interaction "torch-polymer particle", "thermal jet –base" has been developed. The necessary heat flow density for the complete melting of the UHMWPE particles which does not exceed the destruction threshold has been determined. The required rate of the UHMWPE powders input into the burner flame has been determined. The optimal geometry of the torch, the trajectory of particles in the torch and the spraying distances have been determined based on the calculations of the "torch-polymer particle interaction". The obtained results of 3D modeling will make it possible to design an experimental installation of UHMWPE high-velocity spraying.

The work has been carried out within the framework of the grant project of the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan No. AP09259925 "Development and Implementation of a Highly Effective Technology for Applying an Anticorrosive Coating Based on Ultra-High Molecular Weight Polyethylene", 2021-2023.

References

1. Gonzalez R., Ashrafizadeh H., Lopera A., Mertiny P., and McDonald A. A Review of Thermal Spray Metallization of Polymer- Based Structures // Journal of Thermal Spray Technology. – 2016. – Vol. 25(5). – P. 897-919. https://doi.org/10.1007/s11666-016-0415-7
2. Heli Koivuluoto. A Review of Thermally Sprayed Polymer Coatings // Therm Spray Tech. – 2022. – Vol. 31. – Published online. – P. 1750–1764. https://doi.org/10.1007/s11666-022-01404-1
3. Gavrilova R.R., Baldaev L.H., Ilinkova T.A., Baldaev S.L., Mankovsky S.A. Development of a Technique for Applying Protective Coatings to PCM Products by Gas Thermal Spraying // New Technologies, Materials and Equipment of the Russian Aerospace Industry, – 2018. – Conference materials. – P. 149–154.
4. Jing Han, Siyue Ding, Wenge Zheng, Wenya Li and Hua Li. Microstructure and anti- wear and corrosion performances of novel HMWPE/grapheme-nanosheet composite coatings deposited by flame spraying // Polymers advanced technologies. – 2013, Published online in Wiley Online Library. https://doi:10.1002/pat.3161
5. B. Fotovvati, N. Namdari, A. Dehghanghadikolaei. On Coating Techniques for Surface Protection // Journal of Manufacturing and materials processing. – 2019. – Vol. 3(1). https://doi.org/10.3390/jmmp3010028
6. Levchenko I., Shuyan Xu, Baranov O.,Olha Bazaka O., Ivanova E.P., Bazaka K. Plasma and Polymers: Recent Progress and Trends // *Molecules*. A – 2021. – Vol. *26*(13). – P. 4091. https://doi.org/10.3390/molecules 26134091
7. Gatiyatullina R. F., Badrutdinova A. N. Application of Low-Temperature Plasma for the Application of Polymer-Powder Coatings // Bulletin of Kazan Technological University. – 2014. – Vol. 17(20). – P. 45–48.
8. I. Levchenko, S.Xu, O. Baranov, O. Bazaka, E.P. Ivanova and K.Bazaka. Plasma and Polymers: Recent Progress and Trends // Molecules. – 2021. – Vol. 26(13): 4091 https://doi.: 10.3390/molecules26134091
9. Frey P.J. Mesh Generation. Application to Finite Elements // 2nd ed. – London: ISTE Publishing Company. – 2008. – 814 p.
10. Singiresu S. Rao. The Finite Element Method in Engineering // – Butterworth-Heinemann. – 2018. https://doi.org/10.1016/C2016-0-01493-6
11. Alyamovsky A., Sobachkin A., Odintsov E., Kharitonovich A., Ponomarev N. SolidWorks. Computer Modeling in Engineering Practice // BHV-Petersburg, 2008. 1040 p. (in Russian)
12. Hu Xua, Yuqing Bao, David T, Gawne, Tao Zhang. Process control for thermal-spray deposition of thermoset coatings using computer simulation // Progress in Organic Coatings. – 2016. – Vol. 101. – P. 407-415.
13. Baldaev L.H. Gas thermal spraying // Market DS, 2007. 344 p. (in Russian)
14. G.Mauer, C. Moreau. Process diagnostics and control in thermal spray // Journal of thermal spray technology. – 2022. – Vol. 31. – P. 818-828.
15. Ovchinnikov V.V. "Technology of gas welding and metal cutting": Publishing Center "Academy". – 2016. 240 p. (in Russian)
16. F. Awaja, M. Gilbert, G. Kelly, B. Fox, P.J. Pigram. Adhesion of polymers // Progress in Polymer Science. – 2009. – Vol. 34. – P. 948–968.
17. Podzorova M. V., Tertyshnaya Yu. V., Popov A. A., Nikolaeva S. G. Kinetics of thermo-oxidative degradation of polymer blends based on polylactide // AIP Conference Proceedings. – 2019. –Vol. 2167. – P. 020280. https://doi.org/10.1063/1.5132147

18. T. Dayyoub, A.V. Maksimkin, S. Kaloshkin, E. Kolesnikov, D. Chukov, T.P. Dyachkova, and I. Gutnik. The structure and mechanical properties of the UHMWPE // Polymers (Basel). – 2019. – Vol.11(1), Published online https://doi:10.3390/polym11010023

19. Z. Du, J. Wang, S. Wen, P. Wang, D. Zhang, C. Yin. Study on the Properties of UHMW-PE Film // Advances in Materials Physics and Chemistry, – 2015. –Vol. 5. – P. 337-343. https://doi:10.4236/ampc.2015.58033

20. Sutyagin V. M., Kukurina O. S., Bondaletov V. G. "Basic properties of polymers: National Research Tomsk Polytechnic University": Tomsk Polytechnic University. Tomsk, 2010. – 96 p. (in Russian)

21. Y. Bao, T. Zhang, D.T.Gawne. Influence of composition and process parameters on the thermal spray deposition of UHMWPE coatings // Journal of materials science, – 2005. – Vol. 40. – P. 77-85.