ISSN: 2658–5782

Номер 3

2024

МНОГОФАЗНЫЕ СИСТЕМЫ

mfs.uimech.org

ИМех
им. Р.Р. Мавлютова

ISSN 2658–5782 19 (2024), **3**, 112–118

Многофазные системы

http://mfs.uimech.org/mfs2024.3.016
DOI: 10.21662/mfs2024.3.016
UDC: 62-19

Received: 9.07.2024
Accepted: 26.09.2024

Numerical modelling of the effect of gas temperature non-uniformity on the geometric parameters of the heating element in a cold spraying technology

A.A. Mukhutdinova*, **A.D. Nizamova***, **W.Y. Li****

*Mavlutov Institute of Mechanics UFRC RAS, Ufa, Russia

**Shaanxi Key Laboratory of Friction Welding Technologies, School of Materials Science and Engineering, Northwestern Polytechnical University, Xi'an, Shaanxi Province, China

E-mail: adeshka@yandex.ru

In contemporary mechanical engineering, extending the lifespan of products necessitates heightened standards for the materials used in the fabrication of components and structures. One of the most promising avenues is enhancing material characteristics through the application of functional coatings. This includes boosting the material's corrosion resistance, wear resistance, and protection against mechanical damage, as well as enabling localized repairs without disassembling the structure. Preference is given to technologies that do not adversely affect the surface to which they are applied. Cold spray technology stands out as one of the most rapidly advancing methods for applying protective coatings and imbuing materials with various functional properties. This technique not only safeguards surfaces but also enhances their operational characteristics, ensuring the longevity and reliability of products. Investigation of the influence of the dependence of the gas heating on the geometric parameters of the heating element of the cold spraying technology was considering in this work. This task was considered in two software solvers: the software product "Thermoviscous fluids: a hydrodynamic simulator for modeling flow in annular channels with heat exchange" and ANSYS. The modeling results show that the spiral steel tube can effectively be used for heating gas to high temperatures at high speeds. However, it is necessary to consider that at high speeds, additional hydrodynamic effects such as turbulence and shear flows may occur, which can affect the efficiency and stability of the gas (nitrogen) flow.

Keywords: gas heating, heating element, cold spraying technology, nitrogen

The research work was supported by the state budget funds for the state assignment 124030400064-2 (FMRS-2024-0001).

1. Introduction

In the realm of modern mechanical engineering, extending the service life of products demands elevated standards for the materials employed in the manufacture of components and structures [1–3]. One of the most promising approaches is to enhance material characteristics through the application of functional coatings. This includes augmenting the material's corrosion resistance, wear resistance, and protection against mechanical damage, as well as facilitating localized repairs without disassembling the structure [4]. Technologies that do not negatively impact the applied surface are favored.

Cold spraying (CS) technology is at the forefront of methods for applying protective coatings and endowing materials with various functional properties [5, 6]. This process, broadly known as cold spraying, aims to develop methods and devices for spraying coatings that impart the necessary properties to product surfaces, such as reducing porosity, increasing hardness, strength, and corrosion resistance.

The primary objective of these innovations is to create a method and device for spraying coatings that elevate the surface properties of products to the required levels, ensuring reduced porosity, enhanced hardness, increased strength, and superior corrosion resistance. Over the past 20 years, the greatest inventive activity in the field of CS coating technologies has been observed in Russia, Germany, China and the USA [7]. Also, this coating area is also being developed by developers from Japan, the Republic of Korea, India, Austria and Australia [8].

The forefront of CS technology development is marked by a drive to enhance productivity and automate the coating application process. This is achieved through the creation of novel automated systems and the exploration of modern powder materials, which endow parts and products with diverse functional properties.

The device for applying coatings via the CS method comprises several key components: a dosing feeder, a housing that includes a powder hopper shaped like a drum with recesses on its cylindrical surface, and a mixing chamber equipped with a nozzle designed to accelerate powder particles. The nozzle is connected to both the mixing chamber and a compressed gas source. A powder particle feed controller ensures the desired flow rate during the coating process, while a partition installed at the bottom of the hopper prevents powder particles from entering the space between the drum and the dosing device body, thus avoiding potential jamming.

The nozzle, featuring a profiled passage, enables the gas flow to reach supersonic speeds. To further boost process efficiency and regulate the speed of the gas-powder mixture with a supersonic jet, the device incorporates an element for heating compressed gas, complete with a temperature control system.

Preferably, the heating element should be made from a resistor alloy, which will allow for a reduction in the overall dimensions and weight of the heating means [9–13].

In the work of Wenya Li [14], an experiment was carried out and a 2D model of the entire process of CS technology was constructed, however, numerical modeling of the gas heating element was not performed. Nitrogen is most often used as a working gas.

Nitrogen is an inert diatomic gas without color and odor, the chemical formula of the diatomic molecule N_2, molar mass 28.01 kg/kmol. The nitrogen content in the atmospheric air is about 78.09 % by volume. It is used in technological processes as an inert sealing medium, for example, for dry gas mechanical seals and sealing complexes, in the chemical industry for the synthesis of ammonia. Liquid nitrogen is used as a refrigerant in mechanical engineering for the assembly of non-removable tight joints (cooling of the covered part). Nitrogen is used in special technological processes for applying a thin layer of wear–resistant coating — titanium nitride on the surface of steel parts; in combination with silicon, it forms a wear-resistant promising ceramic material, silicon nitride Si_3N_4 [15].

Numerical simulation of the gas heating process will allow to set the optimal parameters of the heated element to reduce the gas heating time, and, accordingly, optimize the process in the complex.

2. Problem statement

The working gas is nitrogen (N_2), which is supplied to the tube at room temperature, 293 — 298 K (20 — 25 °C), and a pressure of 2 to 10 MPa. The tube walls are maintained at a constant temperature of 1273 K (1000 °C). The inner diameter of the tube is fixed and is 0.008 m, and the wall thickness is 0.002 m. The diameter, number of coils, and length of the tube are parameters that need to be determined for efficient gas heating.

3. Methods

This task was considered in two software solvers:

1. The software product «Thermoviscous fluids: a hydrodynamic simulator for modeling flow in annular channels with heat exchange» [16].

2. ANSYS — a universal finite element analysis (FEA) software system

4. Numerical results

4.1. Part 1. Results of numerical simulation in the own software product

The flow of incompressible nitrogen in a flat channel was considered. The channel diameter was fixed, and the channel length L varied from 1 m to 50 m. The modeling environment used was the own software product «Thermoviscous fluids: a hydrodynamic simulator for modeling flow in annular channels with heat exchange» which was adapted to solve this problem: the inner diameter of the tube — 0.008 m; the length of the tube — from 1 m to 50 m; the pressure drop dp — 1 Pa; the initial temperature of the gas — 293 K; the temperature of the tube walls — 1273 K.

To solve the problem of the incompressible flow of nitrogen in a flat channel, the control volume method was chosen. This approach allows solving the Navier–Stokes equations with high accuracy, which is critical for obtaining reliable results.

The geometric dimensions of the tube, the properties of nitrogen, the boundary conditions for velocity and pressure at the inlet and outlet of the tube, and the temperature at the tube walls were used as input data for modeling.

Based on the calculations, the results for the distribution of velocity, pressure, and temperature along the length of the tube were obtained. The results of the test calculation for a channel with a length of 1 m and a pressure drop of 1 Pa are shown in Fig. 1. The graph shows the distribution of temperature and velocity along the length of the channel in a dimensionless form.

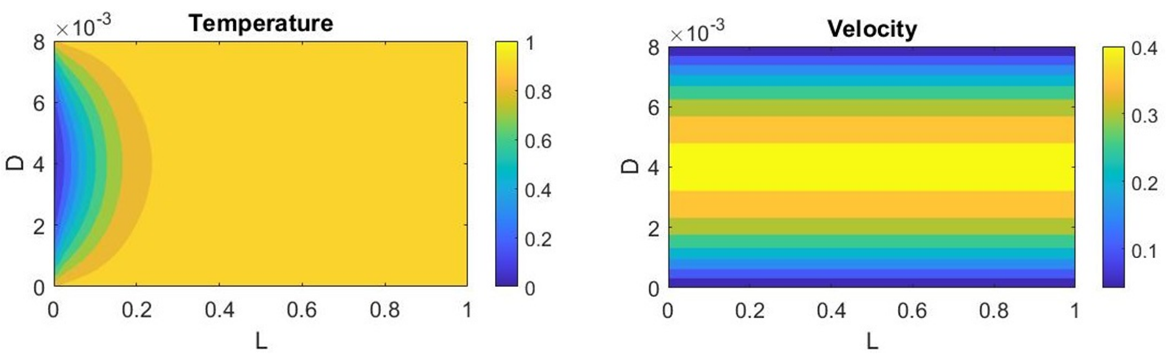

Figure 1. Distribution of temperature and velocity in the computational domain for $L = 1$ m at d$p = 1$ Pa

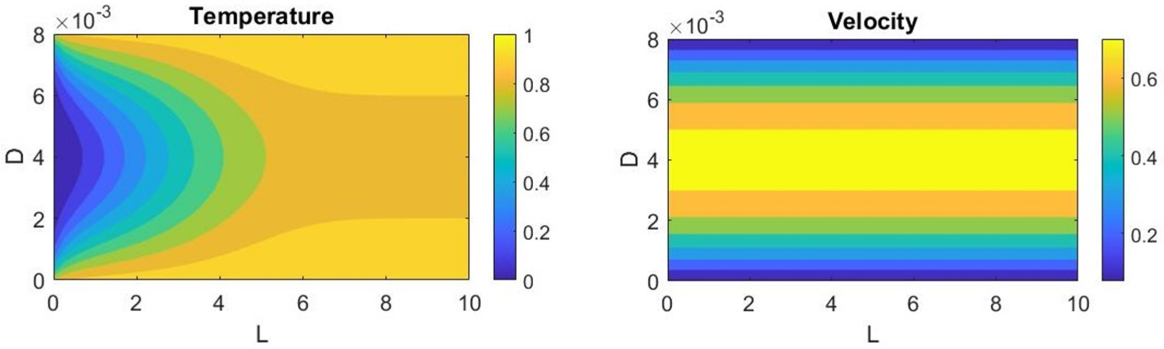

Figure 2. Distribution of temperature and velocity in the computational domain for $L = 10$ m at d$p = 10^4$ Pa

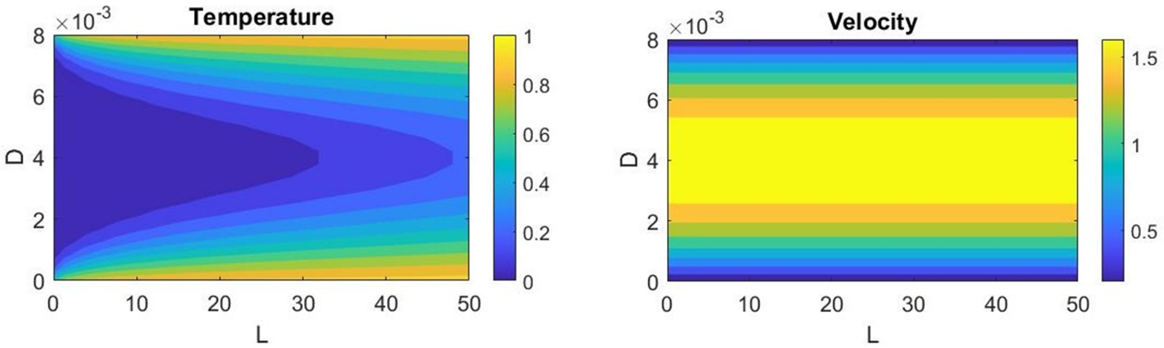

Figure 3. Distribution of temperature and velocity in the computational domain for $L = 50$ m at d$p = 10^5$ Pa

From the obtained results, it follows that the distribution of the nitrogen velocity along the length of the channel has a parabolic shape. The maximum velocity is reached in the middle of the channel and decreases to zero at the tube walls.

The study results showed (Fig. 2) that as the channel length increases to 10 meters and the pressure drop to 10^4 Pa (equivalent to 0.1 atm), the nitrogen is heated closer to the middle of the channel. The maximum nitrogen velocity in the channel is 0.7 m/s.

Further, when the channel length is increased to 50 meters and the pressure drop to 10^5 Pa (equivalent to 1 atm), the nitrogen does not have enough time to heat up in the center of the channel due to the high flow velocity (Fig. 3). Heating occurs only in the near–wall region of the channel. The maximum nitrogen velocity in the channel is 1.5 m/s.

Further research is needed, including the use of more complex channel geometries and experimental studies, to improve the accuracy and validity of the mathematical model and optimize the cold spray process. One option for increasing the complexity of the channel geometry is the use of spiral channels, which have a more complex shape than flat channels and allow for modeling of the flow under more realistic conditions.

4.2. Part 2. Results of numerical simulation in the ANSYS software system

The flow of nitrogen in a spiral steel tube in a 3D configuration is considered to study the features of gas flow in such conditions and to optimize the parameters of the tube to increase the efficiency of gas heating.

Initial parameters: inner diameter of the tube – 0.008 m; length of the tube — 1.154 m; spiral diameter — 0.06 m; wall thickness of the tube — 0.002 m; initial temperature of the liquid — 293 K; temperature of the tube walls — 1273 K; inlet pressure — 2 — 10 MPa; outlet pressure — 0.1 MPa.

The first step of modeling involves constructing the geometry and mesh. Fig. 4 shows the geometry of the computational domain with the constructed mesh. The geometry

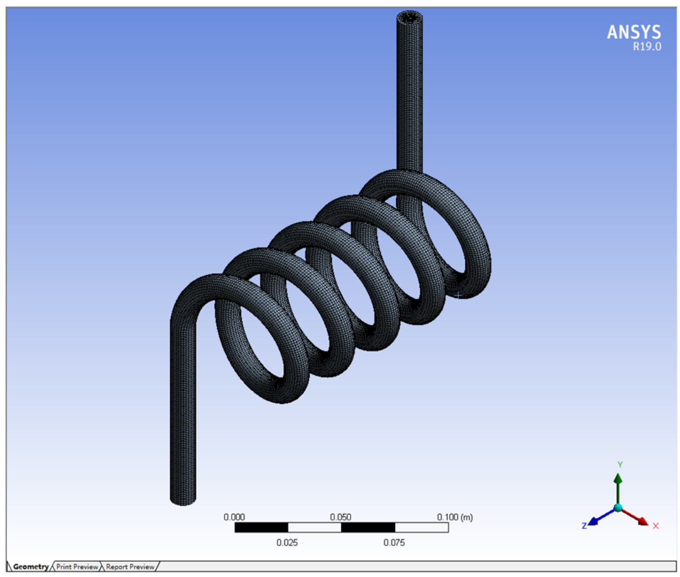

Figure 4. 3D Geometry of the Computational Domain

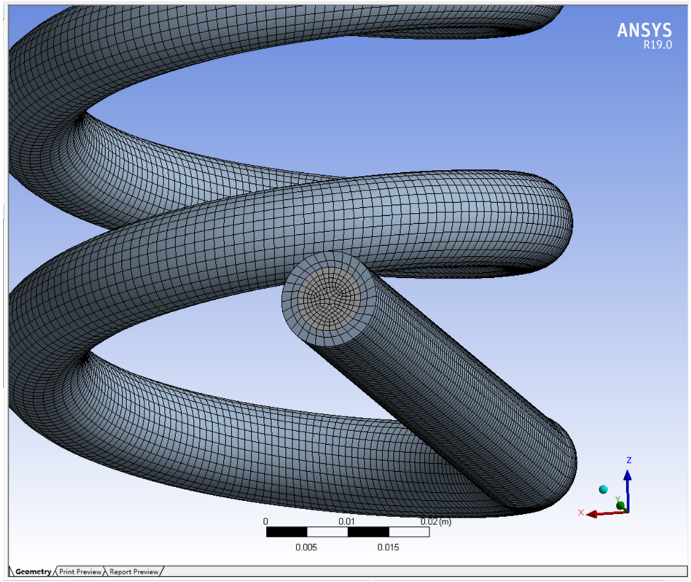

Figure 5. Mesh of the Computational Domain

was created using the ANSYS. Fluent software, and the mesh was built using the AutoMesh module. The computational domain geometry consists of a spiral cylindrical pipe made up of five spirals ($N = 5$) with a distance of 0.03 m between them, into which the working gas is supplied.

Fig. 5 shows the constructed mesh on the inlet of the pipe. The selected cell sizes ($dx = 0.001$ m or 0.0005 m) ensure sufficient computational accuracy while minimizing modeling time.

The next step in modeling is to set up the model, which includes selecting the model equations, materials and properties, as well as boundary conditions on the inlet, outlet, and walls of the pipe.

Fig. 6 shows the ANSYS software's setup module, where the model parameters are *conFig.d*. For modeling the flow of nitrogen in a spiral steel pipe, the Navier–Stokes equations for turbulent flow and the k–ε turbulence model were chosen. The wall of the pipe was selected as stainless steel, and the gas properties were specified according to the modeling conditions.

The boundary conditions on the inlet to the channel include the gas temperature, and the pressure is fixed both at the inlet and the outlet of the channel. The walls of the pipe are considered stationary and have a constant temperature. To account for heat exchange between the gas and the walls of the pipe, a heat dissipation condition was chosen.

To refine the model, additional parameters were also specified, such as the coefficient of roughness of the inner wall of the pipe (roughness height 1e-6 m, roughness constant 0.5), the coefficient of thermal conductivity and heat capacity of the gas according to the properties of nitrogen.

The results of modeling the flow of nitrogen in a spiral steel pipe are presented below. At the inlet to the channel, an initial pressure drop is set, in this case equal to 2 MPa.

Fig. 7 shows the linear pressure distribution in the spiral pipe. From the graph, it can be seen that the pressure in the pipe gradually decreases from the inlet to the outlet, which corresponds to the expected behavior in turbulent gas flow.

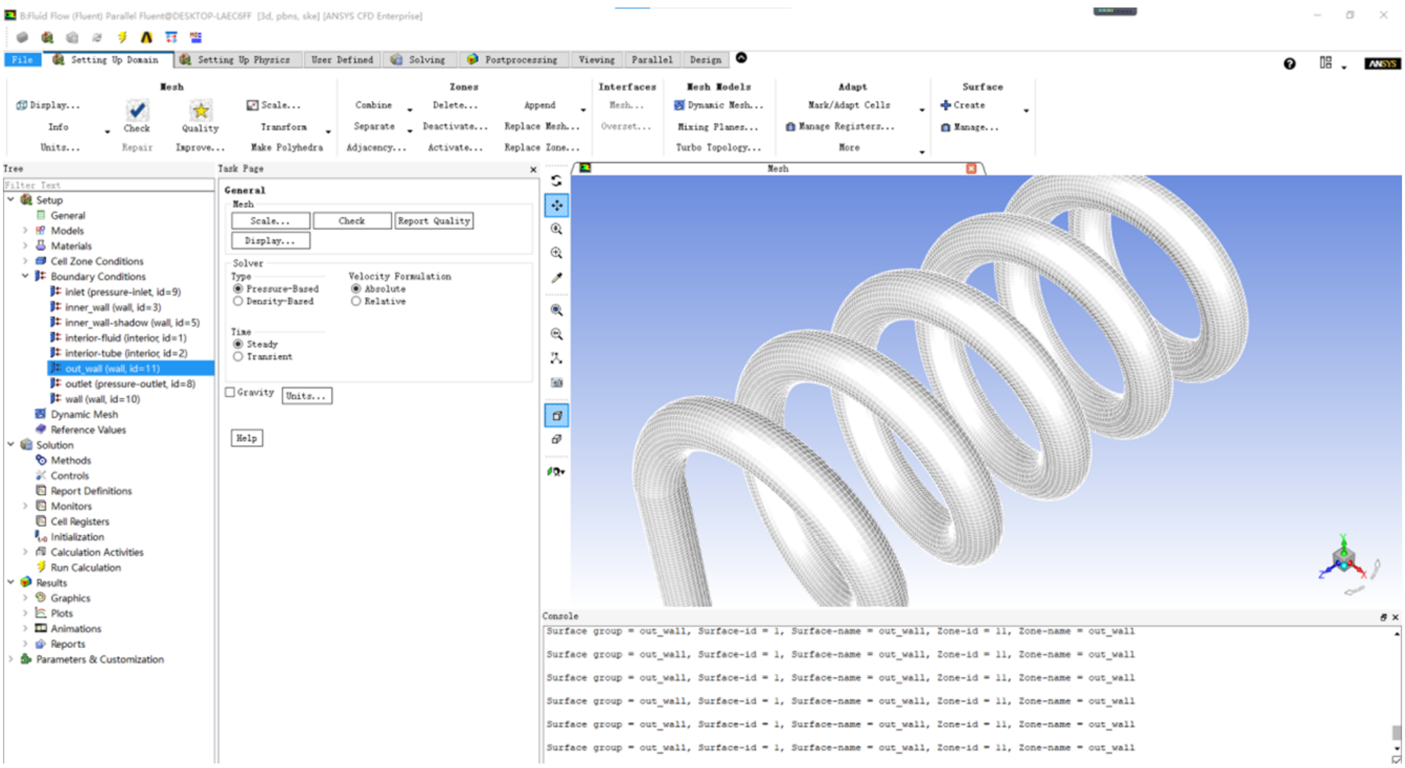

Figure 6. ANSYS Setup Module

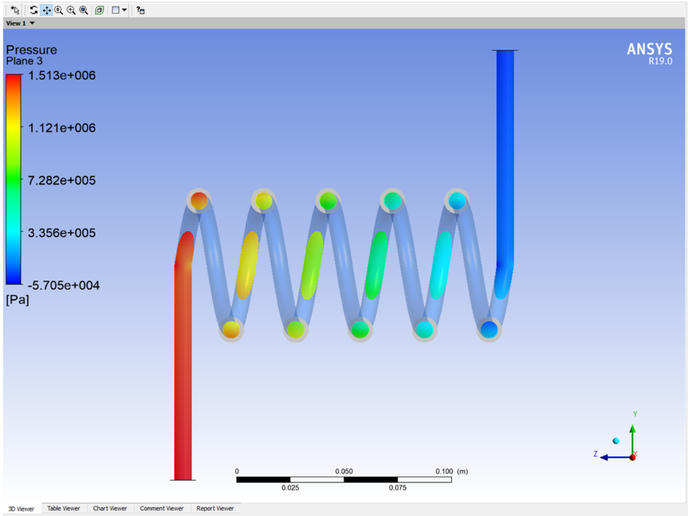

Figure 7. Pressure distribution in the spiral pipe for $N = 5$ at d$p = 2$ MPa

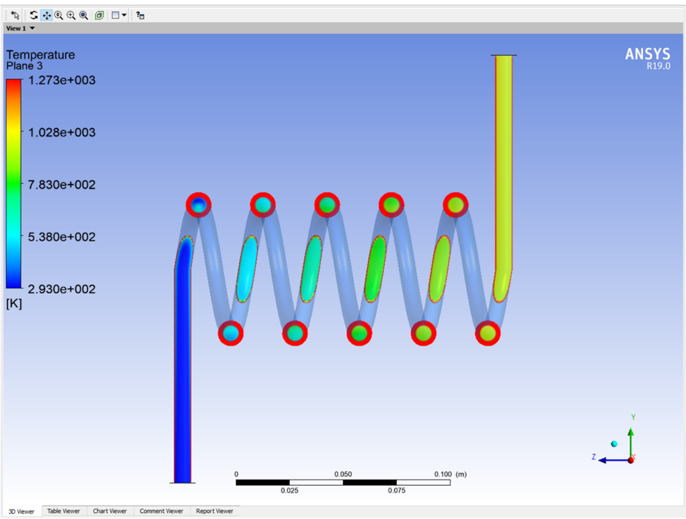

Figure 8. Temperature distribution of the gas in the spiral steel pipe at the given pressure drop for $N = 5$ at d$p = 2$ MPa

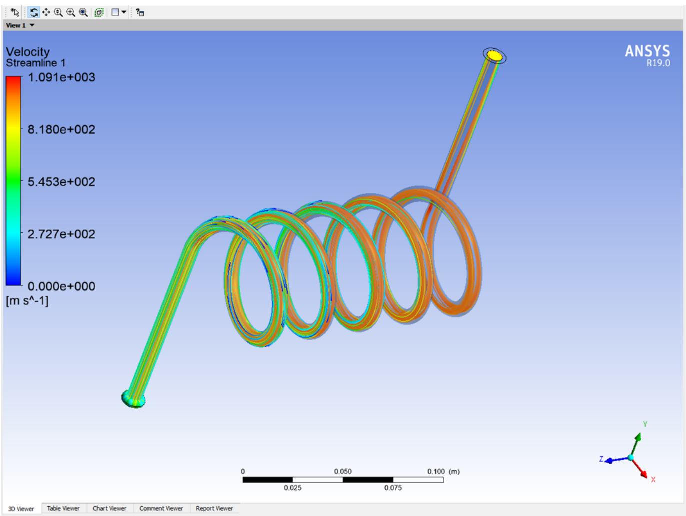

Figure 9. Gas velocity distribution in the spiral tube for $N = 5$ at d$p = 2$ MPa

A constant temperature of 1273 K is set on the walls of the spiral steel pipe. Fig. 8 shows the established temperature distribution in the pipe. It can be seen that nitrogen enters with a minimum temperature of 293 K. As the gas flows through the spiral pipe, it is heated to a temperature of approximately 1000 K.

As can be seen from the Fig. 9, the gas velocity changes along the pipe and reaches its maximum value closer to the outlet of the computational domain. The maximum velocity of the nitrogen is approximately 1.000 m/s.

The results of a parametric study on the influence of pressure differential on the velocity and temperature of the gas at the tube outlet are presented. An investigation into the impact of element mesh size on the solution to the problem at hand has been conducted.

Tab. 1 demonstrates that as the pressure differential increases, the velocity of the gas flow rises, while conversely, the temperature of the gas at the outlet decreases.

Tab. 2 presents the results of calculations with an element mesh size of 0.0005 m.

Upon comparing the results presented in Tabs. 1 and 2, it is evident that the difference between the values is less than 1 %.

When considering the modeling of a spiral tube with a length of 1.154 meters and five rings at fixed parameters based on the pressure differential, it is found that this length is insufficient for the complete heating of the gas at the specified pressure differentials (ranging from 2 MPa to 10 MPa).

Subsequently, the number of spirals was increased to 10 ($N = 10$), with a distance of 0.015 meters between them, while keeping all other parameters unchanged. The overall length of the tube in this case was 2.09 meters.

Fig. 10 shows the temperature distribution at a pressure differential of 2 MPa. It is observed that, starting from the 8th ring, the gas temperature exceeds 1000 K. Upon exiting the tube, the gas temperature reached 1251.15 K.

Tabs. 3 and 4 present the modeling results for various pressure differentials and element mesh sizes. The difference in the results is less than 1 %.

Table 1. Modeling results for $N = 5$ with d$x = 0.001$ m

Pressure, MPa	Velocity, m/s	Temperature, K
2	258.667	1058.12
3	378.155	967.406
4	461.835	951.118
8	565.5605	896.395
10	669.286	841.672

Table 2. Modeling results for $N = 5$ with d$x = 0.0005$ m

Pressure, MPa	Velocity, m/s	Temperature, K
2	258.586	1058.31
3	376.527	968.134
4	459.403	952.506
8	564.6785	896.168
10	669.954	839.83

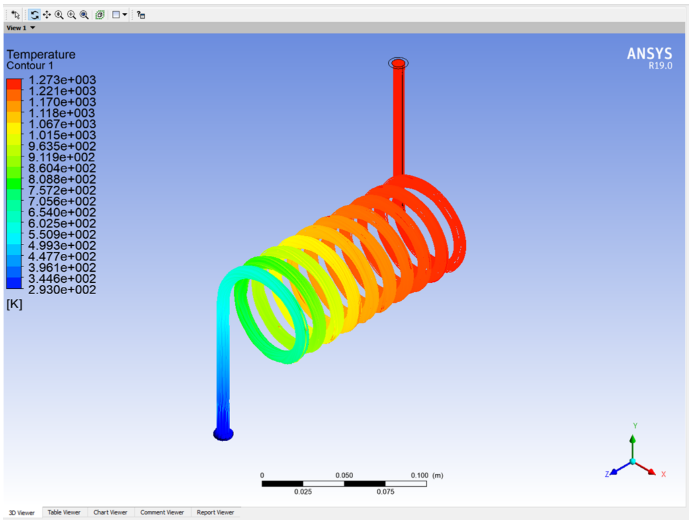

Figure 10. Temperature distribution in the tube with $N = 10$ and $dp = 2$ MPa

At a pressure differential of 2 MPa, the maximum temperature at the outlet is 1251.15 K, which is 193.03 K higher than the calculations with five rings and an increased velocity of 72.171 m/s.

Increasing the pressure differential to 10 MPa results in a temperature decrease of 155.6 K and an increase in velocity by 2.5 times. This is significantly lower than the desired temperature.

The results from Tabs. 1–4 are presented at Figs. 11 and 12 and are qualitatively similar for the meshes 0.001 m and 0.0005 m.

We have modified the spiral diameter from 0.06 m to 0.121 m, increased the channel length to 4 meters, and the number of spirals to 15 ($N = 15$) with a spacing of 0.015 m, using an element size of $dx = 0.002$ m (Fig. 13).

As a result of the modeling with a pressure differential of 10 MPa, the gas velocity was 410.228 m/s, and the temperature was 1257.43 K. This is lower than the desired temperature for the specified pressure differential.

Next, we increased the number of spirals to 17 ($N = 17$) under the same parameters and a pressure differential of 10 MPa. The resulting gas temperature was 1264.76 K, and the flow velocity was 376.234 m/s.

Table 3. Modeling results for $N = 10$ with $dx = 0.001$ m

Pressure, MPa	Velocity, m/s	Temperature, K
2	186.415	1251.15
3	257.071	1227.91
4	302.925	1200.7
8	392.901	1120.41
10	465.696	1095.55

Table 4. Modeling results for $N = 10$ with $dx = 0.0005$ m

Pressure, MPa	Velocity, m/s	Temperature, K
2	183.627	1251.07
3	258.09	1227.9
4	302.539	1200.7
8	393.043	1120.45

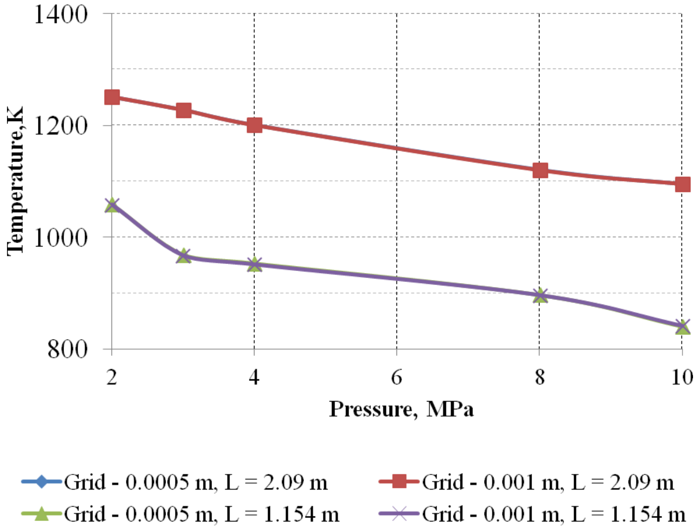

Figure 11. Temperature distribution

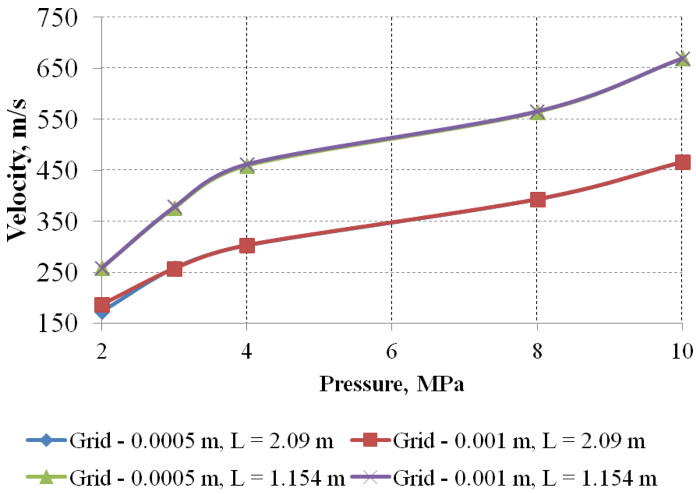

Figure 12. Velocity distribution

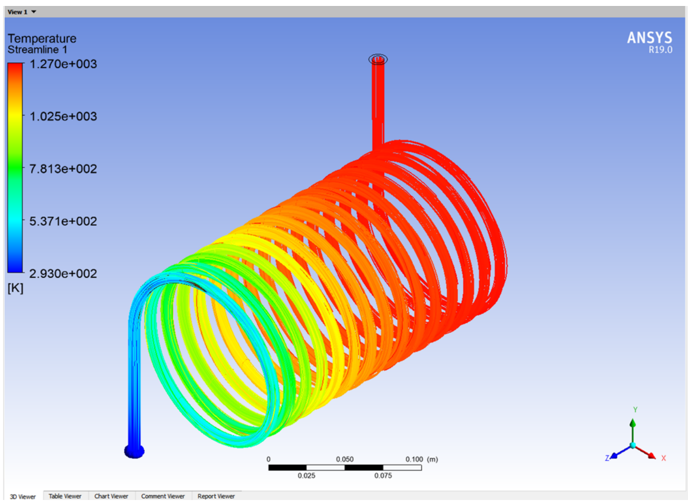

Figure 13. Channel scheme for $N = 15$

5. Conclusion

The modeling results show that the spiral steel tube can effectively be used for heating gas to high temperatures at high speeds. However, it is necessary to consider that at high speeds, additional hydrodynamic effects such as turbulence and shear flows may occur, which can affect the efficiency and stability of the gas (nitrogen) flow.

References

[1] Kozlov I.A., Leshev K.A., Nikiforov A.A., Demin S.A. [Cold gas dynamic coating spraying (review)] *Proceedings of VIAM* [Trudy VIAM]. 2020. No. 8(90). Pp. 77–93 (in Russian).
DOI: 10.18577/2307-6046-2020-0-8-77-93

[2] Kablov E.N. [Innovative developments of FSUE "VIAM" of the State Research Center of the Russian Federation on the implementation of "Strategic directions for the development of materials and technologies for their processing for the period up to 2030"] *Aviation materials and Technologies* [Aviatsionnyye materialy i tekhnologii]. 2015. No. 1(34). Pp. 3–33 (in Russian).
DOI: 10.18577/2071-9140-2015-0-1-3-33

[3] Kablov E.N., Starcev O.V. [Fundamental and applied studies of corrosion and aging of materials in climatic conditions (review)] *Aviation materials and technologies* [Aviatsionnyye materialy i tekhnologii]. 2015. No. 4(37). Pp. 38–52 (in Russian).
DOI: 10.18577/2071-9140-2015-0-4-38-52

[4] Kablov E.N., Starcev O.V., Medvedev I.M. [Review of foreign experience in corrosion research and corrosion protection products] *Aviation materials and technologies* [Aviatsionnyye materialy i tekhnologii]. 2015. No. 2(35). Pp. 76–87 (in Russian).
DOI: 10.18577/2071-9140-2015-0-2-76-87

[5] Kablov E.N., Nikiforov A.A., Demin S.A., Chesnokov D.V., Vinogradov S.S. [Promising coatings for corrosion protection of carbon steels] *Steel* [Stal']. 2016. No. 6. Pp. 70–81 (in Russian).
EDN: WCKVLX

[6] Vinogradov S.S., Nikiforov A.A., Demin S.A., Chesnokov D.V. [Corrosion protection of carbon steels] *Aviation materials and technologies* [Aviatsionnyye materialy i tekhnologii]. 2017. No. S. Pp. 242–263 (in Russian).
DOI: 10.18577/2071-9140-2017-0-S-242-263

[7] Champagne V., Helfritch D. A Demonstration of the Antimicrobial Effectiveness of Various Copper Surfaces. Journal of Biological Engineering. 2013. Vol. 7, article number 8. Pp. 1–8.
DOI: 10.1186/1754-1611-7-8.

[8] Irissou E., Legoux J.-G., Ryabinin A., Jodoin B., Moreau Ch. Review of Cold Spray Process and Technology: Part I—Intellectual Property. Journal of Thermal Spray Technology. 2008. Vol. 17, no. 4. Pp. 495–516.
DOI: 10.1007/s11666-008-9203-3

[9] Moridi A., Hassani-Gangaraj S., Guagliano M., Dao M. Cold spray coating: review of material systems and future perspectives. Surface Engineering. 2014. Vol. 36, no. 6. Pp. 369–395.
DOI: 10.1179/1743294414Y.0000000270

[10] Gärtner F., Stoltenhoff T., Schmidt T., Kreye H. The cold spray process and its potential for industrial applications. Journal of Thermal Spray Technology. 2006. Vol. 15, no. 2. Pp. 223–232.
DOI: 10.1361/105996306X108110

[11] Champagne V., Helfritch D. Mainstreaming cold spray — push for Applications. Surface Engineering. 2014. Vol. 30, no. 6. Pp. 396–403.
DOI: 10.1179/1743294414Y.0000000277

[12] Van Steenkiste T., Smith J. Evaluation of coatings produced via kinetic and cold spray processes. Journal of Thermal Spray Technology. 2004. Vol. 13, no. 2. Pp. 274–282.
DOI: 10.1361/10599630419427

[13] Marx S., Paul A., Köhler A., Hüttl G. Cold spraying: Innovative layers for new applications. Journal of Thermal Spray Technology. 2006. Vol. 15, no. 2. Pp. 177–183.
DOI: 10.1361/105996306X107977

[14] Wan W., Li W., Wu D., Qi Zh., Zhang Zh. New insights into the effects of powder injector inner diameter and overhang length on particle accelerating behavior in cold spray additive manufacturing by numerical simulation. Surface and Coatings Technology. 2022. Vol. 444. P. 128670.
DOI: 10.1016/j.surfcoat.2022.128670

[15] [Physical properties of nitrogen] *Fizicheskiye svoystva azota*. https://www.highexpert.ru/content/gases/nitrogen.html (Accessed: 09.07.2024).

[16] Kireev V.N., Mukhutdinova A.A., Urmancheev S.F. [Thermoviscous fluids: a hydrodynamic simulator for modeling flow in annular channels with heat exchange] *Termovyazkiye zhidkosti: gidrodinamicheskiy simulyator dlya modelirovaniya techeniya v kol'tsevykh kanalakh s teploobmenom*. Certificate of state registration of the computer program No. 2023669294 Russian Federation (application No. 2023668718, registered 12.09.2023, published 13.09.2023) (in Russian).
EDN: JYTNYM

Information about the Authors

Aigul A. Mukhutdinova
Mavlyutov Institute of Mechanics, UFRS RAS, Ufa, Russia
mukhutdinova23@yandex.ru
ORCID: 0000-0002-5009-002X

Adelina D. Nizamova
Ph.D (Physics & Mathematics)
Mavlyutov Institute of Mechanics, UFRS RAS, Ufa, Russia
adeshka@yandex.ru
ORCID: 0000-0002-7772-2672

Wenya Li
PhD, Professor
School of Materials Science and Engineering, Northwestern Polytechnical University, Xi'an, Shaanxi Province, China
liwy@nwpu.edu.cn
ORCID: 0000-0002-5067-843X