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THE STRUCTURE OF THE SWIRLING FLOW IN THE COUNTERFLOW VORTEX REACTOR[1]

ABSTRACT Two promising designs of counterflow vortex reactor were numerically investigated. Such apparatus utilizes reverse flow to withdraw thermal energy and products from interelectrode area. Complex gasdynamic structure of the water-vapor flow was investigated using turbulent three-dimensional simulation employing Reynolds averaged Navier-Stokes equations along with SST $k-\omega$ turbulence model – technique tested in earlier papers. Presented velocity profiles and heat flux reports demonstrate viability of both approaches.

Key words: hydrogen; swirling flows; plasma-vortex generator; computational fluid dynamics; clean energy.

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Introduction

The quest for environmentally friendly energy sources continues and requires development of new solutions and apparatuses. In [1], a group from JIHT proposed vortex-based approach and described plasma-vortex reactor (PVR) – the promising technology capable of simultaneous generation of heat and hydrogen. Such machine exploits swirling flow to hold away hot gas from the walls of the system inside the active area. Experimental and theoretical research into PVR provided several insights about performance of device [2–4]. It can be anticipated that the efficiency depends not distinguishably on the parameters of electric discharge or the structure of the swirling flow but on their complex interaction [5; 6]. From the geometrical point of view there are several factors which can crucially affect the final outcome: the configuration of the working mixture input and output and the design of the electrode system. This statement was tested in [7], which confirmed using numerical simulation of the turbulent vortex flow for an experimental setup that formation of recirculation zone, which eventually determines the direction and intensity of the energy stream, strongly depend on the shape of the electrodes and their location relative to the swirler and the outlet.

The key feature of described system is that products from zone of active plasma-chemical reactions are carried away with the direct flow. However, that is not the only possible conception. In present paper, we propose results of numerical investigation into structure of the flow in alternative vortex reactor which utilizes reverse flow to withdraw thermal energy and desired products.

1. Mathematical modelling

1.1. Numerical model geometry and governing equations

The geometries of the principal part of the device (swirler, tube, and electrodes) is sketched in figure 1 for two cases. The common features both variants share are the following. The swirler has 4 tangential inlets (visible ones are colored in blue) of size in axial direction equal to 10 mm. The system of electrodes consists of coaxial cylindrical cathode (colored in light blue) of 85 mm length and 23 mm diameter and anode (yellow surface and orange base) – 112 mm and 12 mm respectively. There are 2 possible outlets. The primary one is the red annular area at the tube face near the swirler with inner diameter equal to 23 mm and outer one to 30 mm. The secondary optional one is the base of anode (orange). The heat source, which emulates heating in the discharge area, is located between electrodes. The length of the whole system is 267 mm and diameter of the tube 56 mm. Uncolored surfaces are the walls. The difference between two realizations lies in presence or absence of additional coaxial tube with inner diameter of 30 mm and wall thickness of 1 mm which contours are depicted in green color.

Standard unsteady Reynolds averaged Navier-Stokes equations along with SST $k-\omega$ turbulence model, which is well suited for similar system [5], were used to describe the water-vapor flow:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho \nu_i)}{\partial x_i} = 0,$$

$$\frac{\partial(\rho \nu_i)}{\partial x_i} + \frac{\partial(\rho \nu_i \nu_j)}{\partial x_i} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial \nu_j}{\partial x_i} + \frac{\partial \nu_i}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial \nu_k}{\partial x_k}\right)\right] + \frac{\partial}{\partial x_i}\left[-\rho\overline{\nu_i{}'\nu_j{}'}\right],$$

$$\frac{\partial(\rho E)}{\partial t} + \frac{\partial\left[\nu_i\left(\rho E + P\right)\right]}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\kappa + \frac{c_p \mu_t}{Pr_t}\right)\frac{\partial T}{\partial x_j} + \nu_i\left(\tau_{ij}\right)_{eff}\right] + N\left(\vec{x}\right),$$

$$E = h - \frac{P}{\rho} + \frac{\upsilon^2}{2},$$

$$P = \frac{\rho T}{M}$$

where $(\tau_{ij})_{eff} = \mu_{ij}\left(\frac{\partial \nu_j}{\partial x_i} + \frac{\partial \nu_i}{\partial x_j}\right) - \frac{2}{3}\mu_{ij}\frac{\partial \nu_k}{\partial x_k}\delta_{ij}$ is the deviatoric stress tensor, $\left[-\rho\overline{\nu_i{}'\nu_j{}'}\right]$ are the Reynolds stresses which must be modeled using chosen turbulence approach to close the set of equations, $\nu_i, \nu_i{}', \rho, T, P, E$

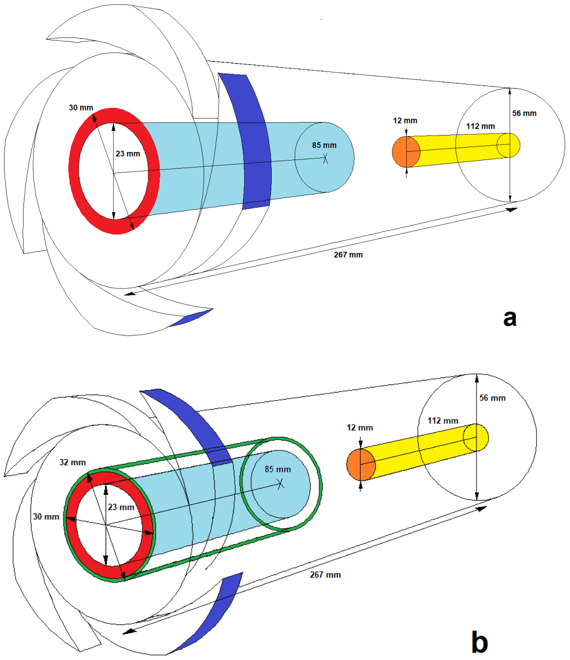

Fig. 1. The geometry of the principal part of the device used for numerical simulation: *a* – without bounding tube, *b* – with bounding tube

Рис. 1. Геометрия главной части устройства, использованная для численного моделирования: *а* – без ограничивающей трубки, *б* – с ограничивающей трубкой

and h are the mean and fluctuating velocity components, density, temperature, pressure, total energy, and enthalpy, respectively; N is the energy source which total power was set to 0 or 500 W, μ, μ_t, μ_{eff} are the molecular, turbulent, and effective viscosity coefficients, respectively; c_p is the molar specific heat capacity at constant pressure; κ is the thermal conductivity coefficient and Pr_t is the turbulent Prandtl number.

The no-slip velocity and fixed temperature boundary conditions were used for solid surfaces. Mass flow rate was set equal to 1 g/sec at every tangential inlet with gas temperature of 300 K. At the outlets, pressure equal to standard atmosphere was set. Temperature at the walls was constant equal to 300 K.

1.2. Numerical procedure

The whole system of equations for the non-stationary 3D turbulent swirling flow was solved using the ANSYS FLUENT 15.0 program package. A second-order upwind scheme was used for spatial discretization of density, momentum, energy and turbulent variables. The higher-order scheme does not provide any considerable change. The diffusion terms are central-differenced and second-order accurate. The pressure values at the faces were interpolated using the PRESTO! scheme developed for the flows of strong swirl behavior.

Transient terms were discretized using the fully implicit scheme of the second-order accuracy. Different pressure-velocity coupling schemes were tested and gave equal results. So, the SIMPLE scheme was chosen as the least resource consuming. The convergence was obtained when the residual reached 10^{-6} for the energy equation and 10^{-4} for the continuity equation, the momentum equation, and the equations for turbulent quantities.

The computational grid consisted of about $2.6 \oplus 10^6$ hexahedral cells. The skewness metric has an average value of 0.15, the minimum value of orthogonal quality metric – 0.10, the mean one – 0.9. The time step was fixed and set equal to $5 \oplus 10^{-5}$ sec in order to achieve convergence at every time step in recommended by ANSYS manufacturer iterations.

2. Results of numerical simulation

Axial velocity profiles of interest are shown in Fig. 2 and 3. Limited velocity ranges are used in order to make pictures more contrast and highlight areas of negative values. For both realizations, with (b) and without (a) additional bounding tube, there is pronounced counterflow which can suck out hot gas and reaction products from the interelectrode zone. However, absolute values of axial velocity in that area when only primary outlet is open are relatively low which could lead to overheating and exceeding limits or the used model. In the case of open secondary outlet (Fig. 2), there is direct flow sufficient to keep temperatures in computationally allowed range (Fig. 3).

Presence of the bounding tube results in two changes of the flow characteristics. The first one, visible from the axial velocity profiles, is narrowing of the stagnation area between electrodes, which in the case of one outlet leads even to two almost splitted zones. The second one is intensification of reverse flow squeezed between the cathode and the bounding tube. When the secondary outlet is open, it leads to shift of heat flux distribution in favor of primary outlet: from $\sim 42\%$ of thermal energy being carried away through it to $\sim 67\%$. Moreover, there is significant decrease in maximum temperature (Fig. 4) which seems to be result of both aforementioned effects.

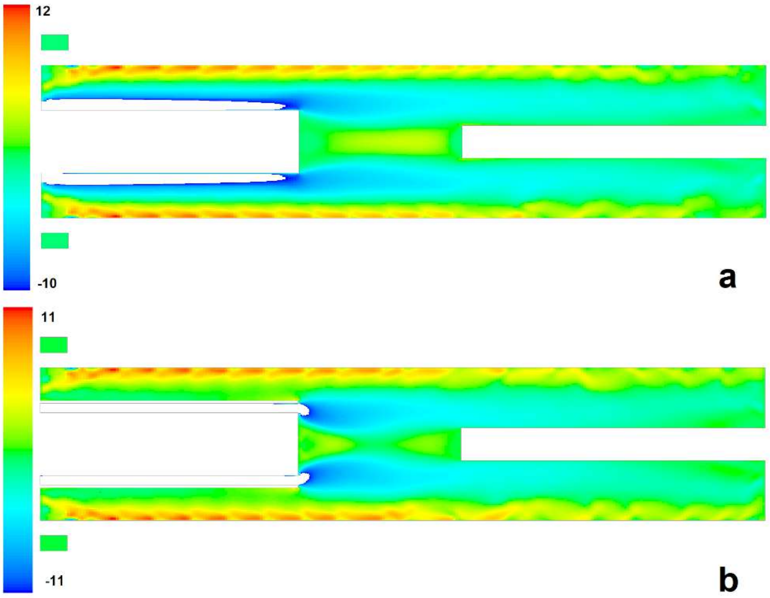

Fig. 2. The axial velocity distributions with (*b*) and without (*a*) the bounding tube. The secondary outlet is closed
Рис. 2. Распределения осевых скоростей с (*b*) и без (*a*) ограничивающей трубы. Вторичный выход закрыт

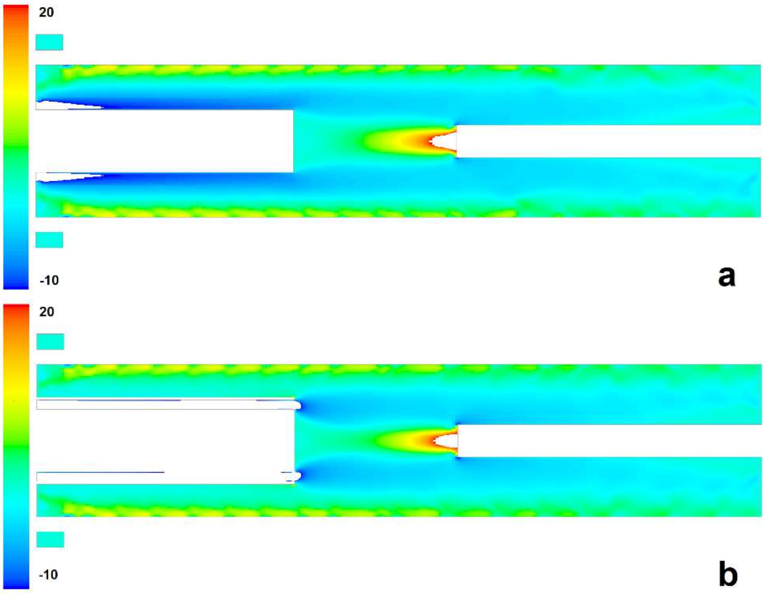

Fig. 3. The axial velocity distributions with (*b*) and without (*a*) the bounding tube. The secondary outlet is open
Рис. 3. Распределения осевых скоростей с (*b*) и без (*a*) ограничивающей трубы. Дополнительный выход открыт

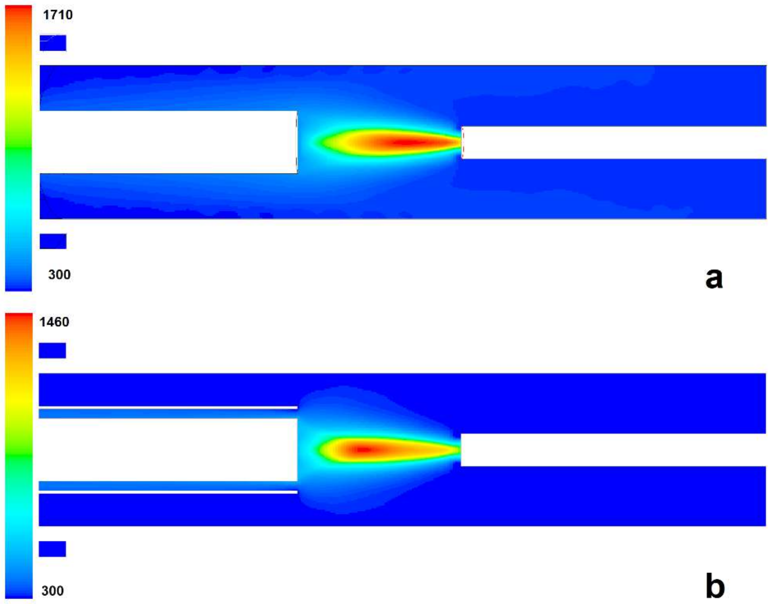

Fig. 4. The temperature distributions with (*b*) and without (*a*) the bounding tube. The secondary outlet is open
Рис. 4. Распределения температуры с (*b*) и без (*a*) ограничивающей трубки. Дополнительный выход открыт

Conclusion

Results of modelling demonstrate viability of vortex reactor with reverse flow. Hot gas from interelectrode area is carried away in both examined cases: closed and open outlet at the base of cylindrical anode. Additional coaxial bounding tube which encircles the cathode significantly affects the flow characteristics. Its presence leads to narrower interelectrode stagnation zone, redistribution of energy fluxes in favor of primary outlet in the face of the whole cylindrical system and lower maximum temperature in the active zone between electrodes. Still, there is a room for optimization. Possible parameters to explore include length of both electrodes, radius and length of bounding tube. However, more experimental data are needed to select criteria and range of search.

References

[1] Klimov A.I. [et al.] Hydrogen Plasma Flow Creation for MHD Power Generation. *42nd AIAA Plasmadynamics and Lasers Conference in conjunction with the 18th International Conference on MHD Energy Conversion (ICMHD)*, 2011, p. 3285. DOI: http://doi.org/10.2514/6.2011-3285.

[2] Bityurin V.A., Klimov A.I., Korshunov O.V., Chinnov V.F. Kinetic model of aluminum oxidation by water vapor in heterogeneous plasma: Gas-phase kinetics. *High Temperature*, 2014, vol. 52, no. 5, pp. 621–626. DOI: http://doi.org/10.1134/S0018151X14050034. EDN: https://elibrary.ru/ufjcmb. (in English; Russian original).

[3] Bityurin V.A., Klimov A.I., Korshunov O.V., Chinnov V.F. Kinetic model of Al oxidation by water vapor in heterogeneous plasma: Heterophase kinetics. *High Temperature*, 2015, vol. 53, no. 1, pp. 21–26. DOI: http://doi.org/10.1134/S0018151X14060042. EDN: https://elibrary.ru/uflcsn. (in English; Russian original).

[4] Kazanskiy P.N., Klimov A.I., Molevich N.E., Porfiriev D.P., Zavershinskii I.P. Numerical simulation of an argon swirling flow in the presence of a DC discharge. *Journal of Physics: Conference Series*, 2018, vol. 980, no. 1, p. 012010. DOI: http://doi.org/10.1088/1742-6596/980/1/012010.

[5] Gorbunova A., Molevich N., Porfiriev D., Sugak S., Zavershinskii I., Klimov A., Moralev I. Precessing vortex core in a swirling wake with heat release. *International Journal of Heat and Fluid Flow*, 2016, vol. 59, pp. 100–108. DOI: https://doi.org/10.1016/j.ijheatfluidflow.2016.03.002. EDN: https://elibrary.ru/wvzodt.

[6] Zavershinskii I.P., Klimov A.I., Makaryan V.G., Molevich N.E., Moralev I.A., Porfir'ev D.P. Structure of RF capacitive discharge in swirl airflow at atmospheric pressure. *Technical Physics Letters*, 2011, vol. 37, no. 12, p. 1120—1123. DOI: http://dx.doi.org/10.1134/S1063785011120157.

[7] Belov N.K., Zavershinskii I.P., Klimov A.I., Molevich N.E., Porfiriev D.P., Tolkunov B.N. High effective heterogeneous plasma vortex reactor for production of heat energy and hydrogen. *Journal of Physics: Conference Series*, 2018, vol. 980, no. 1, p. 012040. DOI: http://dx.doi.org/10.1088/1742-6596/980/1/012040.

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СТРУКТУРА ЗАКРУЧЕННОГО ТЕЧЕНИЯ В ПРОТИВОТОЧНОМ ВИХРЕВОМ РЕАКТОРЕ[2]

АННОТАЦИЯ

Численно исследованы две перспективные конструкции противоточного вихревого реактора. В таком аппарате используется обратный поток для отвода тепловой энергии и продуктов из межэлектродной области. Сложная газодинамическая структура пароводяного потока была исследована с помощью турбулентного трехмерного моделирования с использованием осредненных по Рейнольдсу уравнений Навье — Стокса в сочетании с моделью турбулентности SST $k-\omega$ – методики, апробированной в предыдущих работах. Представленные профили скоростей и расчёты тепловых потоков демонстрируют жизнеспособность обоих подходов.

Ключевые слова: водород; закрученные потоки; плазменно-вихревой генератор; вычислительная гидродинамика; чистая энергетика.

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Литература

[1] Klimov A.I. [et al.]. Hydrogen Plasma Flow Creation for MHD Power Generation. *42nd AIAA Plasmadynamics and Lasers Conference in conjunction with the 18th International Conference on MHD Energy Conversion (ICMHD)*, 2011, p. 3285. DOI: http://doi.org/10.2514/6.2011-3285.

[2] Битюрин В.А., Климов А.И., Коршунов О.В., Чиннов В.Ф. Кинетическая модель окисления AL парами воды в гетерогенной плазме. Газофазная кинетика. *Теплофизика высоких температур*, 2014, Том 52, №. 5, С. 657. DOI: http://doi.org/10.7868/S0040364414050032. EDN: https://elibrary.ru/skiawb.

[3] Битюрин В.А., Климов А.И., Коршунов О.В., Чиннов В.Ф. Кинетическая модель окисления AL парами воды в гетерогенной плазме. Гетерофазная кинетика. *Теплофизика высоких температур*, 2015, Том 53, №. 1. С. 23. DOI: http://doi.org/10.7868/S0040364414060040. EDN: https://elibrary.ru/tfvonr.

[4] Kazanskiy P.N., Klimov A.I., Molevich N.E., Porfiriev D.P., Zavershinskii I.P. Numerical simulation of an argon swirling flow in the presence of a DC discharge. *Journal of Physics: Conference Series*, 2018, vol. 980, no. 1, p. 012010. DOI: http://doi.org/10.1088/1742-6596/980/1/012010.

[5] Gorbunova A., Molevich N., Porfiriev D., Sugak S., Zavershinskii I., Klimov A., Moralev I. Precessing vortex core in a swirling wake with heat release. *International Journal of Heat and Fluid Flow*, 2016, vol. 59, pp. 100–108. DOI: http://doi.org/10.1016/j.ijheatfluidflow.2016.03.002. EDN: https://elibrary.ru/wvzodt.

[6] Zavershinskii I.P., Klimov A.I., Makaryan V.G., Molevich N.E., Moralev I.A., Porfir'ev D.P. Structure of RF capacitive discharge in swirl airflow at atmospheric pressure. *Technical Physics Letters*, 2011, Vol. 37, no. 12, p. 1120–1123. DOI: http://dx.doi.org/10.1134/S1063785011120157.

[7] Belov N.K., Zavershinskii I.P., Klimov A.I., Molevich N.E., Porfiriev D.P., Tolkunov B.N. High effective heterogeneous plasma vortex reactor for production of heat energy and hydrogen. *Journal of Physics: Conference Series*, 2018, vol. 980, no. 1, p. 012040. DOI: http://dx.doi.org/10.1088/1742-6596/980/1/012040.