NUMERICAL SIMULATION OF FLOW IN THE CHAMBER OF THE WATER-ARGON PLASMA GENERATOR

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Abstract. *The paper describes the CFD simulation of the flow of gas and plasma in a plasma generator with a hybrid stabilization of the electric arc. The momentum equations of the model also take Lorentz forces into account. In the energy equation, Joule heat is introduced as an energy source. The introduction of boundary conditions is also explained, as along with plasma transport properties and a method of solution. The paper presents selected results of pressure and velocity fields in the chamber of the plasma generator.*

1 INTRODUCTION

Plasma is utilized in many technical and technological devices. Material cutting, plasma spraying, pyrolysis of waste, etc., can all be mentioned as examples. A basic part of each of the devices listed above is a water plasma generator. This paper presents the model of flow in such a generator and its solution by the CFD methods. The task of the CFD simulation is to optimize the plasma flow and its generation in a high-temperature environment. commercial software Fluent was used for the CFD simulation. The simulation of plasma flow is a complicated multidisciplinary problem. Hence, we cooperated on the solution to this problem with the Institute of Plasma Physics of the ASCR. Data concerning the properties and behavior of plasma were provided to us through this cooperation.

2 MODEL OF PLASMA FLOW

Pictured in figure 1 is the chamber where the process of plasma generation and plasma flow was simulated. This plasma generator is built and operated by the Institute of Plasma Physics of the ASCR. The data necessary for the verification of results are therefore known and have been published [1], [2], [3]. This type of plasma generator utilizes a combination of gas stabilisation and vortex stabilisation. The chamber with the electric arc is split into two parts. The short one represents the cathode and is stabilised by a tangential argon jet, while the longer one is stabilised by the water vortex. This configuration provides sufficient stabilisation and preservation of the cathode. The arc is attached to the external anode. The anode takes the shape of a rotating disc and is cooled by water. It is placed downstream from the generator orifice [2]. Openings are made in the cylindrical chamber, distributed in the tangential direction. The liquid water is injected through the openings into the interior of the chamber. The axes of the openings are at an angle of 120°. The pressure of the injected water is 0,39 MPa at the flow rate 10 l/min. The higher pressure increases the stability of the arc. The model of plasma flow was created on the basis of the following simplifications [1]:

- the numerical model is in 2D with an axis of symmetry
- the plasma flow is laminar and compressible and is in local thermal equilibrium
- argon and water create a homogenous mixture
- only self-induced magnetic fields are considered in the arc
- gravitation is neglected

The omission of the outer part of the plasma chamber (where the water is in a liquid state) in the calculation domain is a very important simplification. This is the reason why there is no liquid phase in the calculation domain and the argon-water mixture is considered homogenous. Hence, it is not necessary to include the phase change (water evaporation) in the model.

Figure 1: Plasma generator chamber – fundamental scheme.

The physical model was input to the software „Fluent“ to obtain a plasma flow solution. The general model contains the following equations:

Equation of continuity for compressible flow:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

where ρ – flowing mixture density, t – time, $\mathbf{u}$ – velocity vector.

Because the flow is considered steady, the time derivation in (1) is zero. Momentum equations also contain body forces due to the existence of a magnetic field. These forces are termed Lorentz forces.

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla(\rho \mathbf{u} \cdot \mathbf{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \mathbf{j} \times \mathbf{B} \quad (2)$$

where p - pressure, $\boldsymbol{\tau}$ – stress tensor, $\mathbf{j}$ – vector of current density, $\mathbf{B}$ – vector of total magnetic induction.

The local acceleration (time derivation) due to steady flow in equation (2) is zero.

The energy equation is expressed as follows:

$$\frac{\partial e}{\partial t} + \nabla \cdot [(e + p)\mathbf{u} - \lambda \nabla T] = \mathbf{j} \cdot \mathbf{E} + \Phi_{dis} - \dot{R} \quad (3)$$

where e – total energy, λ – temperature conductivity, T - thermodynamic temperature, $\mathbf{E}$ – electric intensity field vector, Φ_{dis} – dissipation of energy due to viscous friction, $\dot{R}$ - radiation.

For the internal energy, the following holds:

$$U(p, T) = e(p, T) - 0,5 \rho |\mathbf{u}|^2 \quad (4)$$

The last term in the energy equation (3) was not included in our model; this means that heat loss due to radiation was neglected. This loss is equal to about 20% of total power. The term expressing losses due to viscous friction was also neglected in the energy equation (3). In the case of plasma flow, this term is very small. The current density is calculated according the following relation:

$$\mathbf{j} = \sigma (-\nabla \Phi + (\mathbf{u} \times \mathbf{B}_0)) \quad (5)$$

where σ – electrical conductivity, Φ – potential of electric field.

This equation assumes that the total magnetic induction of an electromagnetic field $\mathbf{B}$ in the vicinity of flowing plasma consists of the outer magnetic field component $\mathbf{B}_0$ and the magnetic induction induced due to currents in a conductor $\mathbf{b}$. Generally, it is assumed that an induced magnetic induction in the vicinity of plasma in which electric current is flowing is very small compared with the magnetic induction of the outer magnetic field $\mathbf{B}_0$. This is why the basic version of the MHD module of Fluent neglects this parameter and takes into account only the component $\mathbf{B}_0$. However, for our purposes this value is important. The addition of the vector $\mathbf{b}$ was implemented by user function (UDF). The value of $\mathbf{B}_0$ was replaced by a tangential component of the vector $\mathbf{b}$ calculated according the formula:

$$b(r) = \frac{\mu_0 I}{2 \pi r} \quad (6)$$

where μ_0 – permeability of the surroundings, r – chamber radius, where induction is calculated, I – total electric current flowing in a cross-section of radius r . It must be noted that the magnitude of the magnetic induction defined in this manner is actually the magnitude of the tangential component given in cylindrical coordinates and it is necessary to transform it to Cartesian coordinates. In the part of calculation domain where the temperature is less then 6000 K electrical conductivity is set to zero, and both current density and magnetic induction are set to zero as well.

The intensity of the electric field is calculated as follows:

$$\mathbf{E}(\mathbf{r}) = -\nabla\Phi - \frac{\partial\mathbf{A}}{\partial t} \quad (7)$$

where Φ - scalar electrostatic potential, $\mathbf{A}$ – magnetic vector potential.

Calculation of the Lorentz forces is carried out according to the following equation:

$$\mathbf{f}_L = \mathbf{j} \times \mathbf{B} \quad (8)$$

The boundary conditions are:

- Input: mass flow rate $m = 0,45$ g/s, temperature profile was calculated by the Elenbass - Heller equation, electric potential constant (153 V).
- Input (vapor): mass flow rate $m = 0,315$ g/s, constant temperature $T=773$ K, linear course of electric potential
- Wall: defined to have a constant temperature. The wall is made from insulating material.
- Output: static pressure, zero electric potential, constant temperature in the case of backflow.
- Electric potential in the domain changes linearly from the input to the output

Transport properties of flowing media (density, specific heat capacity, dynamic viscosity, temperature conductivity, electrical conductivity) were estimated on the basis of kinetic theory. The calculation procedures were developed at the Institute of Plasma Physics of the ASCR. Part of this data was published in [3]. The values of transport properties for a given mass ratio of argon and water were calculated by applying a mixing rule to the data for single components of water and argon. All material properties of flowing mixtures were also calculated by applying a mixing rule to single components. The properties were calculated depending on the temperature. It was assumed that the pressure does not exceed 101 kPa. The results of the calculations show that the pressure in this domain is less than 200 kPa, so this simplification is acceptable.

3 CALCULATION RESULTS

On the left in figure 2, the temperature distribution is calculated and on the right is the distribution of axial velocity. Temperature and velocity are greater then published in [1], but it is assumed that the difference is caused by heat loss due to radiation. It is known that this value is about 20%. We are working on improving the presented model and we expect that the agreement will be better after accounting for the radiation. Calculated static pressure distribution is in the figure 3. Values for this parameter over the whole distribution are very close to the results calculated in [1]. The magnitude of the static pressure at the input is about 0,81 kPa. Also the density agrees closely with expected values and corresponds to the temperature distribution (figure 3).

As was mentioned above, electrical potential has a linear distribution from input to output and corresponds with electrical intensity, the value of which is approximately constant over the whole domain with magnitude about 2700 V/m (figure 4). This value is in agreement with results published in [1].

Figure 2: Temperature [K] (left) and axial velocity [m/s] (right), current $I = \text{cca } 600 \text{ A}$

Figure 3: Pressure [Pa] (left) and density [kg/m3] (right), current $I = \text{cca } 600 \text{ A}$

Figure 4: Electric potential [V] (left) and intensity of electric field [V/m] (right)

4 CONCLUSION

This paper presents an approach to the simulation of multidisciplinary phenomena related to plasma flow in the chamber of a plasma generator. Despite the fact that the model does not include all necessary items, relatively good agreement with results published by the Institute of Plasma Physics of the ASCR was reached. Calculations were made using the commercial CFD software Fluent. The model gives greater values of temperature than are expected. This fact is probably caused by radiation which is not yet taken into consideration in the model.

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