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DESIGN AND MODIFICATION OF WATER-STABILIZED PLASMA GENERATOR

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1. Introduction

Plasma torches with water-stabilized arcs provide an alternative to the commonly used sources of thermal plasmas based on gas stabilized arcs or RF discharges. The oxygen-hydrogen plasma jet is produced with extremely high plasma enthalpy and flow velocity. Such plasma torches with water-stabilized arc provide special performance characteristics in some plasma processing applications such as plasma spraying or waste treatment. The spraying rates with water plasma torches are almost one order higher than the rates achieved in commonly used gas plasma torches.

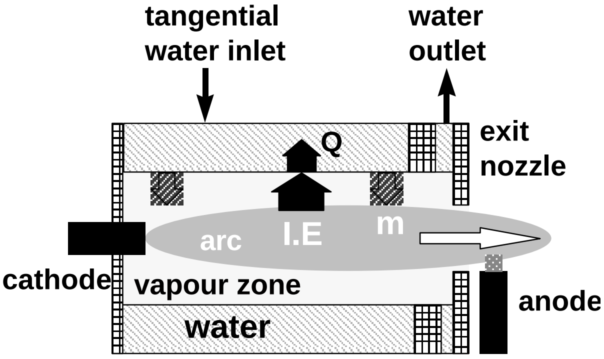


Figure 1. Schema of the water-stabilized arc

The arc chamber of the water torch is divided into several sections by baffles with central holes. Water is injected tangentially into the sections where the vortex is created. The inner diameter of the vortex is determined by the diameter of the holes in the baffles. Water is exhausted at two positions along the arc chamber. The cathode is created either by a graphite rod, which is automatically moved into the chamber to compensate for erosion, or by a tungsten tip protected from contact with water plasma by a stream of inert gas. An anode made of a copper disc with internal cooling is located outside the arc chamber downstream of the nozzle exit. The scheme of the chamber is shown in Fig. 1; a more detailed description of the equipment has been published e.g. in [Jenista 1999] and [Hrabovsky 1998].
All plasma and arc parameters as well as the stability of the torch operation are strongly influenced by the flow of the stabilizing water. This paper is devoted to the modelling of water flow in an arc-stabilizing chamber.

2. Design of the chamber geometry and computational mesh

To achieve an improved design of the water-stabilised plasma generator were use connections among the Theory of Technical Systems and other methods and tools for innovative engineering design e.g. Design for X, FMEA, IMLab (TIPS) etc. The linkage of the Theory of Technical Systems with these methods and tools creates a strong potential for the innovation of existing solutions [Hubka 2001]. Here we used Design Science (Theory of Technical Systems) aided by the IMLab tools.

Invention Machine Lab (IMLab) is an intelligent SW problem solver for engineers, engineering designers, technologist, inventors, scientists, teachers – all those who are professionally engaged in technology, engineering and /or engineering design.

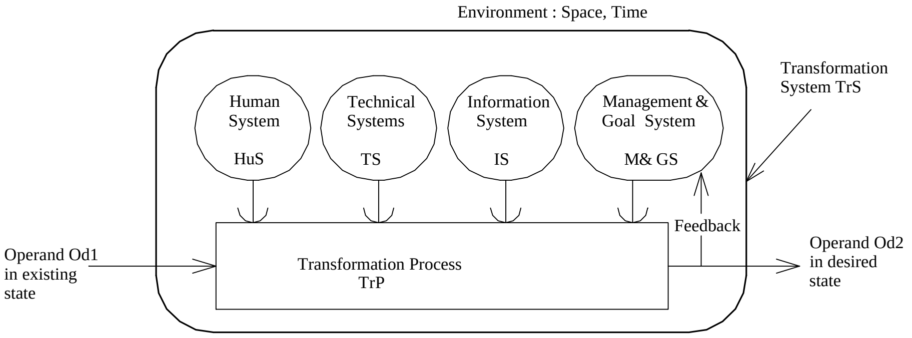


Figure 2. Transformation process in the Theory of Technical Systems

IMLab is based on the Theory of Inventive Problem Solving (TIPS), which was created by accumulating and generalising the inventive ideas from the world's patent collection. It has been established that the best inventive ideas comply with a relatively small number of universal principles and rules. Our understanding of this makes the process of problem solving much more efficient and predicts the development of technical systems and technological processes [Fig. 1].

In this case we first used IMLab in the process of the analysis of properties. Here we created foundations for solving new problems and principles. After an analysing of properties and formulations of the task we used IMLab in the process of creating a design variant of a plasma torch for finding solutions of principles. The next step was to improve the design variant of this plasma generator for computer testing.

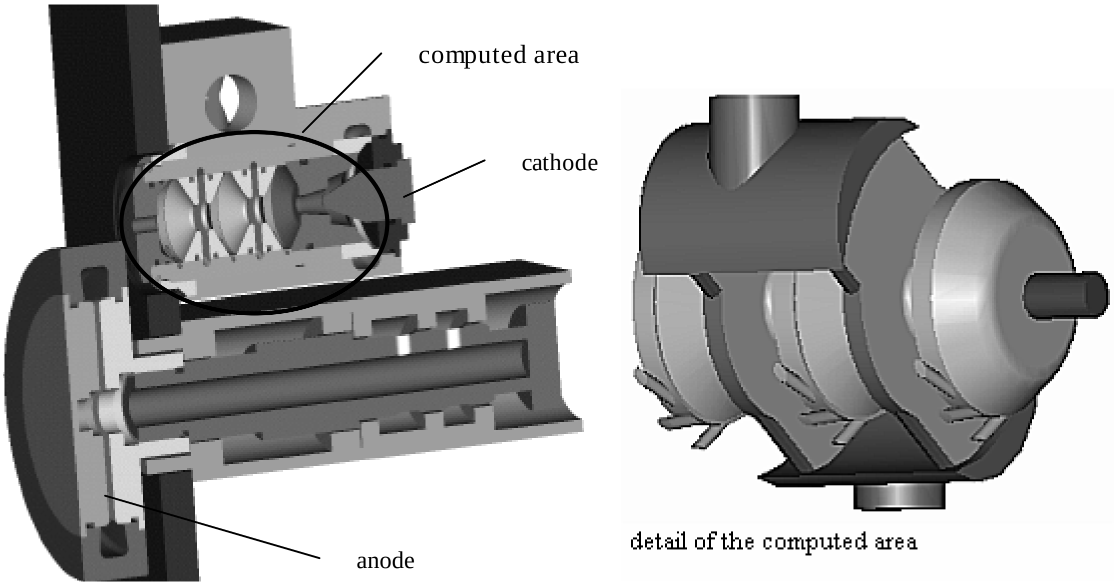


Figure 3. CAD model of the plasma chamber geometry

A 3D model of the geometry of the water-stabilized plasma generator was prepared with several modifications using CAD software I-DEAS MS8. The full parametric model was used to enable simple and rapid modifications of geometry.

A model of the internal space of plasma chamber (selected part of the overall geometry model) together with the 3D geometry model was created to solve two-phase flow field [Fig.3]. This model was partitioned for quick design of the mesh. The models in several modifications in IGES format were read into pre-processor GAMBIT, which had been used to generate the computational meshes.

3. Mathematical model for the multiphase solution

The water flow in the plasma torch of a plasma generator is a very complicated physical phenomenon and the available computing systems do not allow to solve the problem without some simplification, but the quality of the water wall is a main factor in the stabilization.

The system FLUENT 5 for fluid flow and heat transfer computations based on the finite volume method was used to solve partial differential equations. The basic equations of fluid flow follow:

The mass conservation equation

$$\frac{\partial r}{\partial t} + \frac{\partial}{\partial x_i}\left(r u_i\right) = 0 \tag{1}$$

and the momentum conservation equation (Navier-Stokes equation)

$$\frac{\partial}{\partial t}\left(r u_i\right) + \frac{\partial}{\partial x_j}\left(r u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial t_{ij}}{\partial x_j} + r g_i\,, \tag{2}$$

where t_{ij} is the stress tensor.

The segregated solver was used to solve the multiphase models, the discretization schemes of the first and the second order were applied. The turbulent flow was considered, the rng *k-e* two equation's turbulence model was used to close the equations system. The incompressible fluid was considered.

The Volume of Fluid (VOF) model was applied to solve the multi-phases flow field. The VOF formulation relies on the fact that two or more fluids (or phases) do not interpenetrate. In each control volume, the volume fractions of all phases sum to unity. The tracking of the interface between the phases is accomplished by the solution of a continuity equation for the volume fraction of one (or more) phases. For the q-th phase, this equation has the following form:

$$\frac{\partial a_q}{\partial t} + u_i \frac{\partial a_q}{\partial x_i} = 0\,. \tag{3}$$

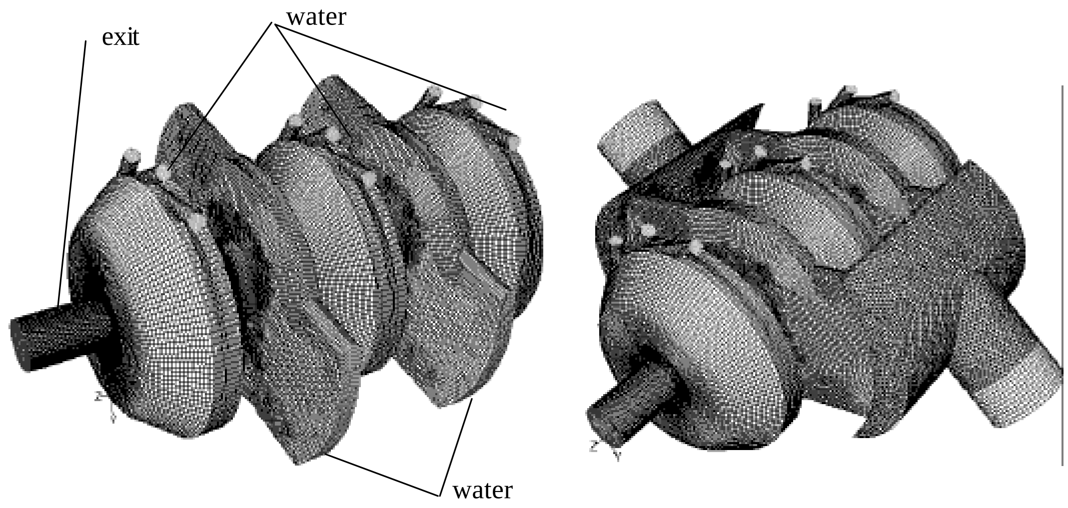
The volume fraction equation is not solved for the chosen phase (so-called primary phase); the primary-phase volume fraction is based on the following constraint:

$$\sum_{q=1}^{n} a_q = 1\,. \tag{4}$$

A single momentum equation is solved throughout the domain, and the resulting velocity field is shared among the phases. The momentum equation results from the volume fractions of all phases – depending upon the properties r (density) and m (viscosity). The implicit method was used to solve the multiphase flow.

4. Performed calculations

The described model and its parameters were tested successfully on a simple model [Matas 2001]. Hexahedral computational mesh was used for the base model. Optimisation of the mathematical model led up to the model with hybrid mesh combining hexahedral and tetrahedral elements [Fig.4]. The number of cells was about 1 Mio. cells for all meshes.



base computed area with mesh **optimised computed**

Figure 4. Example of computational meshes

The following boundary conditions were used to complete the task: the velocity on water inlet 26, 28 and 30 ms^{-1}, the pressure on water outlet from 70 to 100 kPa and the pressure of gas on nozzle exit 100 kPa. Several geometrical modifications of the exhaust channel were compared. The width and the shape of the channel play very important roles in the gas suction [Hrabovsky 2001]. The range of the computed area also plays a very significant role.

The computed results give good basic information about the multiphase flow in the torch chamber without arc. The computed flow fields show the influence of the asymmetric location of inlets on the distribution of flow parameters (pressure, velocity and volume fraction of phases) in the centre of the chamber.

Examples of results are in figures 5 and 6. Fig. 5 demonstrates the unsuitable structure of flow in the outlet area for the older chamber design with keen edges (left part of the picture) and much better flow structure for the new design with rounded edges (right part).

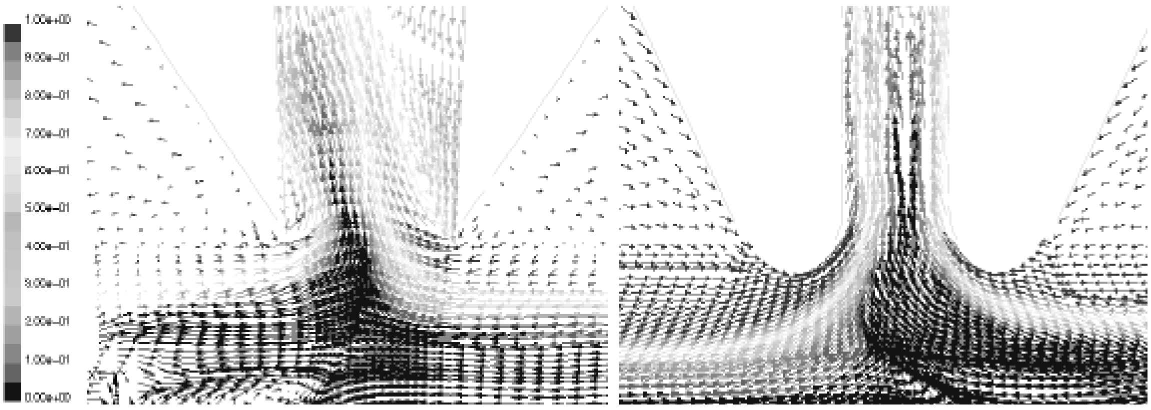


Figure 5. Velocity vectors colored by volume fraction of air on the input to the suction system

Fig. 6 presents the contours of the distribution of the phases - the water-air distribution. It depends on the computational model used and geometry. On Figure 7 the velocity of water in the water vortex on slice at the velocity inlets plane is depicted, the water vortex speed is about 3000 rpm.

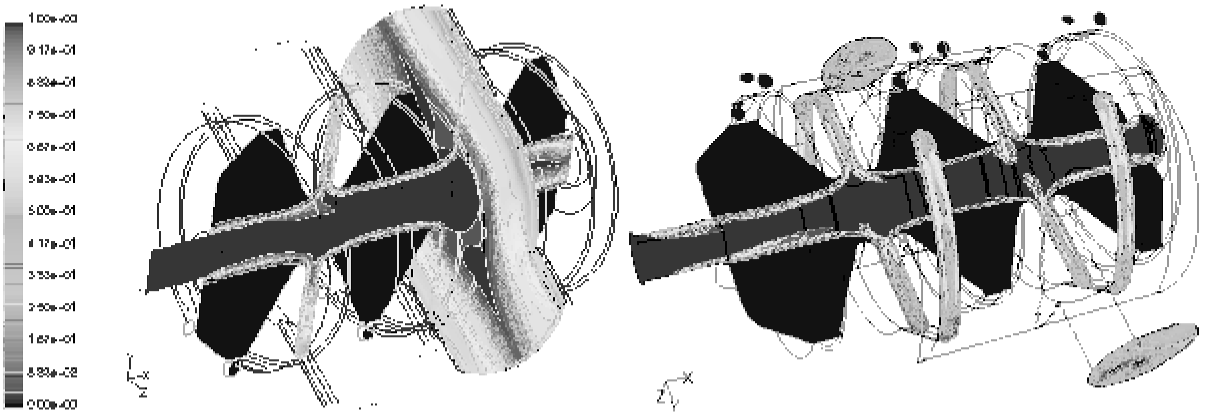


Figure 6. Contours of water fraction on slices through the computational domain for two different ranges of computed area

The comparison with experimental results shows a good agreement of phase interface. It seems that the water-gas interface is stable for various pressures and geometric conditions, the unsteady simulation shows major instabilities only on the input of the suction system. The shape of the water–gas interface is not optimal, the optimisation of the geometry inlet diameters would do for more uniform distribution of phases.

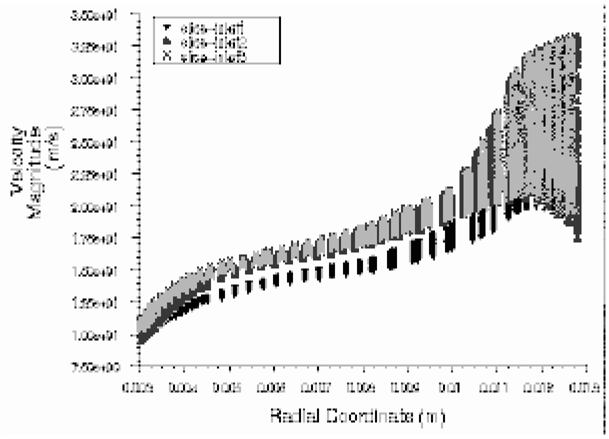


Figure 7. Velocity magnitude of water in water vortex on slice through velocity inlets

The value between 0.5 and 0.7 was computed for the volume fraction of air (argon) on the water outlet in the base models, the optimised models give the value between 0.35 and 0.4 while the experimentally measured value is about 0.3. It has been proved that the computations are very sensitive to the setting of boundary conditions and the range of the computational domain.

5. Conclusions

The aim of the work has been the optimisation of the torch chamber geometry. The new design of the chamber can reduce the suction of the gas (air, argon) by the “water” outlet and improve the stability of water-gas interface. The performed computations confirmed possibility of the simulation of the multiphase flow in arc chamber optimisation. The computed flow field shows the phase distribution of water and air.

The definition of pressure boundary conditions proved to be very important for the calculations and the size of the computational domain has a very significant influence on the computed mass-flow rate of gas.

The results show the significant influence of modifications of the suction system geometry on being flow field distribution. Future computations with improved models of the output system are prepared. They should give more accurate results of the phase distribution and gas flow rate.

Further activities will be directed towards a model with an included heat source – burning electric arc.

Acknowledgement

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