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**THREE DIMENSIONAL MODELLING OF HEAT TRANSFER IN A PLASMA REACTOR WITH THREE TORCHES. COMPARISON WITH EXPERIMENTS**

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*Norwegian Institute of Technology, N-7034 Trondheim, Norway**\*Division of Metallurgy, SINTEF, N-Trondheim, Norway***RESUME**

On présente les calculs numériques concernant un réacteur plasma à trois arcs à courant continu transféré. Le réacteur est cylindrique avec les torches, réparties symétriquement, inclinées à 45°. Une approche à 2 étapes est utilisée en combinant un modèle 2D de la torche avec une simulation 3D des arcs. Les pertes à travers les parois mesurées sur une maquette à l'échelle 1 sont comparées avec les prédictions théoriques. La comparaison est satisfaisante.

**ABSTRACT**

Numerical calculations of a plasma reactor with three DC transferred arcs are presented. The reactor geometry is cylindrical with the torches symmetrically positioned in a conical top section. The tilt is 45°. A two step approach is used where the modelling of the torch itself in two dimensions is combined with the three dimensional simulation of the arcs in the plasma reactor. Wall heat losses measured in a 1:1 scale model are compared with the theoretical predictions. The agreement is quite satisfactory.

**1. INTRODUCTION**

In recent years there has been a growing interest in the use of thermal plasmas for a wide range of processing applications. A plasma research reactor and a 1:1 scale model for calorimetric measurements of wall heat losses have been designed and built in our laboratory. The plasma reactor has been used to run metallurgical experiments of very different characters. It is equipped with three plasma torches that can be operated either in the non-transferred or the transferred arc mode. The total rating of the DC power supply is 300 kW /1/.

In addition to experimental work, modelling of plasma reactors should provide a useful tool in the design as well as the operation of plasma based reactors. Knowledge about heat transfer mechanisms and their relative importance may be of crucial importance for the success of a particular process. The flow simulation program FLUENT has been modified in order to be able to simulate transferred arc(-s), and the first results from this work are presented in this paper.

**2. THE CALORIMETRIC REACTOR MODEL**

In order to get experimental data that can be compared to numerical modelling results, a completely watercooled model of the plasma reactor was constructed. Considering the limited financial resources of our research group, measurements of wall heat losses is one of the few possible methods that can be used in our laboratory to verify our work on mathematical modelling of transferred plasma arc(-s).

Geometrically, the calorimetric model is an exact copy of the

reactor. It is made of copper to ensure good heat conduction from the inner walls to the watercooled outer surface. The water cooling is divided into several sections, thus enabling the heat transferred to different parts of the model to be measured separately. Care is taken to minimize reflection of radiation from the inner walls. The energy in the effluent gas is collected using a heat exchanger mounted on top of the model. The watercooling ensures a uniform and steady inner wall temperature, which is a convenient boundary condition in the numerical models. The next step will be to model the more realistic case of hot thermally insulated reactor walls with a "floating" temperature distribution.

The apparatus used is shown schematically in Figure 1. On the sketch the position of one of the three plasma torches is marked. Of the six ports in the conical section three are occupied by the torches, one by an optical observation unit and the remaining two are closed by watercooled lids. These two ports are used for charging in the real reactor. The optical unit allows visual observation as well as video recording of the interior during operation, e.g. information on arc geometry and stability is obtained directly.

As the model has the exact dimensions of the reactor, the same plasma torches can be used and operated at comparable power levels. The plasma torches are of the PS-400 model supplied by Plasma Systems Ltd., England. These torches are of the classical type with a pencil shaped 2% thoriated tungsten cathode and a copper nozzle. The nozzle also serves as the anode in the non-transferred arc mode.

The anode forms the central part of the bottom and has a diameter of 110 mm. A high pressure, high velocity water jet is used to achieve the intense cooling required. The total inner diameter of the calorimetric model is 340 mm. The vertical height of the conical section is 95 mm and the inclination of the torches is 45°. The height of the cylindrical part is minimum 20 mm and maximum 180 mm depending on the positioning of the bottom which can be moved vertically during operation to obtain various arc lengths. It is also possible to move the torches inwards. This is always done during start-up.

In this study a three torch configuration is used. The height of the cylindrical section is 75 mm, which corresponds to arc lengths of approximately 140 mm. The plasmagen gas used is Argon and the gas flow rate 30 l/min.

Figure 2 shows the three transferred arcs in the calorimetric reactor model. The anode is indicated by the clearly visible white ring of alumina which electrically insulates it from the rest of the bottom.

### 3. MODELLING OF TRANSFERRED ARC(-S)

A modified version of the flow simulation program FLUENT from Create Inc. is used. The differential equations for continuity, momentum, energy and turbulence are solved iteratively using the control volume approach of Patankar /2/.

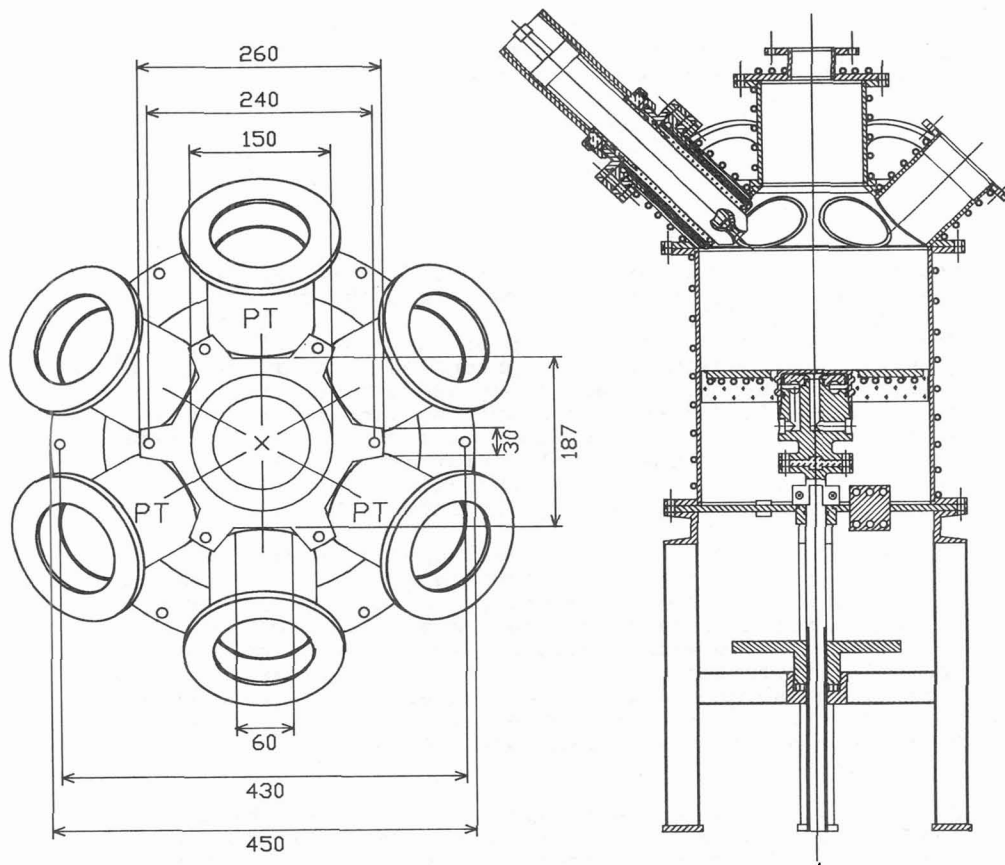


Figure 1. Schematic of the calorimetric model, side and top view.

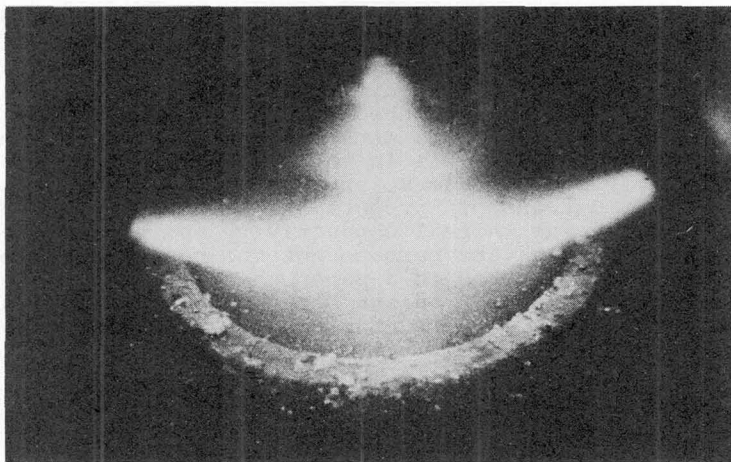


Figure 2. Three transferred arcs

As a first approximation the geometry of the arc is calculated according to the formula proposed by Ramakrishnan for the conducting radius of a free-burning arc /3/:

$$R(z) = R_C \left[ 1 + C \left( \frac{z}{R_C} \right)^{0.5} \right]$$

where  $R_C$  is the cathode spot radius,  $C$  is an expansion coefficient and  $z$  is the distance along the axis of the arc from the cathode tip.

The spatial distribution of the electric current density and magnetic flux density for the predefined arc are then computed analytically assuming that the axial current density distribution is parabolic and solving the current continuity equation together with the Ampere's law relating the axial current density to the magnetic flux density. The arc is assumed to be symmetric about the axis of the plasma torches and in Local Thermodynamic Equilibrium (LTE).

The arc itself is modelled by introducing source terms in the transport equations for momentum and energy. In the momentum equations only the electromagnetic force terms due to the azimuthal magnetic field around the arc are included. Other terms, associated with deviations from axial symmetry or magnetic interaction between the arcs, are presently assumed negligible and consequently not represented in this version. In the energy equation the three source terms representing Ohmic heating, enthalpy transport due to the electron flow and radiation are included.

The plasma is assumed to be optically thin and the radiation losses are modelled by defining a volumetric radiation density. In the 2D case irradiation on the different parts of the surrounding walls is computed using angle factors. The original FLUENT source code assumes a temperature independent heat capacity. This is of course far from correct for a high temperature plasma. The source code is therefore improved by including a new algorithm taking into account the strong variations of the specific heat capacity. It is based on a table containing twenty pairs of values of the enthalpy and the temperature. Values inbetween the given ones are found by linear interpolation. This method may appear to be somewhat rough, but seems to work well in the present computations. The table can easily be extended to improve the accuracy. Data on thermodynamic and transport properties are taken from /4/, /5/, /6/ and /7/. The thermal conductivity and volumetric radiation density data are perhaps not the best available. The subject is further treated in a paper that describes a new method for calculation of radiant heat transfer where also absorption is taken into account (Arntsberg, Gu and Bakken, to be published).

Turbulence is modelled by solving the two transport equations for the turbulent kinetic energy,  $k$ , and the dissipation rate,  $\epsilon$ , /8/, and compute the turbulent viscosity from the parameters of the turbulence model. In the momentum equations an effective viscosity consisting of the molecular viscosity and its turbulent counterpart is employed.

#### 4. MEASUREMENTS AND MODELLING RESULTS

It would require an unrealistically high number of grid lines to satisfactorily resolve the entire calculation domain including the inside of the torch. A two step approach is therefore used where the axisymmetric subdomain inside the torch is modelled using a 2D setup allowing a fine grid mesh (Step 1). The results of this calculation is then used when specifying the input boundary conditions (temperatures and velocities for the inlet cells) for step 2; the 3D simulation of the main reactor chamber. It is required that the total mass flow and the convective heat at the outlet of the nozzle is the same as for the inlet of the reactor, and the part of the arc inside the torch is not included in the 3D simulation. In both cases wall temperatures are set to 300 K except for the cathode tip which is assumed to be at 3000 K. The flow rate is 30 l/min and the current level is 500 A per torch.

##### The torch (Step 1)

This computational subdomain is chosen as the downstream part of the cathode assembly with the surrounding nozzle. The arc is transferred to an external anode. The inside diameter of the nozzle is 10 mm at the cathode tip, and 22 mm at the exit. The arc length inside the nozzle is 15 mm. The radius of the cathode spot is 1.0 mm and the expansion factor is 1.1 /9/. The size of the cathode spot was chosen based on data from the literature as well as from measurement of the cathode tip of our own torches after several hours of operation. The gas enters the computational subdomain at 300 K.

Figure 3 and Table 1 present results from the simulation of the plasma torch. The temperatures near the cathode tip seems to be somewhat high. This might be a result of several factors such as the extremely fine grid mesh in this region, the imposed constriction caused by the nozzle, the predefined arc geometry, the cooling of the fringes by the incoming gas as well as the chosen physical data. In particular, it has been observed that the computations are sensitive to small changes in the electrical conductivity.

Ohmic heating was calculated to be 13.7 kW. Approximately 21.5% of this is radiant heat transfer. The overall heat balance is satisfied within 0.6% of the Ohmic heating.

##### U-I characteristics. Measured heat losses in the calorimetric reactor model for different current settings

Figure 4 shows a plot of I-U characteristics from a silicon metal remelting experiment in the plasma reactor and from the calorimetric model in this study. In both cases the arc voltage increases with increasing current. It is seen that the gross arc behaviour in the calorimetric model and in the real reactor is not very different considering the very different conditions under which they were recorded.

The four sets of bars in Figure 5 give the distribution of the heat losses to eight sections of the model. The heat not accounted for is in all cases less than 1.5% of the power input. It is seen that the upper parts of the model collect a fairly large portion of the total heat loss. This indicates the importance of the reactor geometry and particularly the positioning of the torches as design criteria.

Table 1. Computed radiative and convective heat losses from the arc inside the plasma torch.

	Radiation			Convection		
	kW	%	MW/m <sup>2</sup>	kW	%	MW/m <sup>2</sup>
Inlet	.02	0.6	0.0	.50	4.6	1.6
Inside wall of the nozzle	1.65	56.0	0.7	.95	8.7	0.4
Cathode assembly	.16	5.3	0.2	.02	0.2	0.0
Cathode tip	.15	5.2	27.0	1.29	11.8	227.9
Nozzle exit	.97	33.0	2.6	9.10	83.8	23.9
<b>Total</b>	<b>2.95</b>	<b>100.0</b>		<b>10.86</b>	<b>100.0</b>	

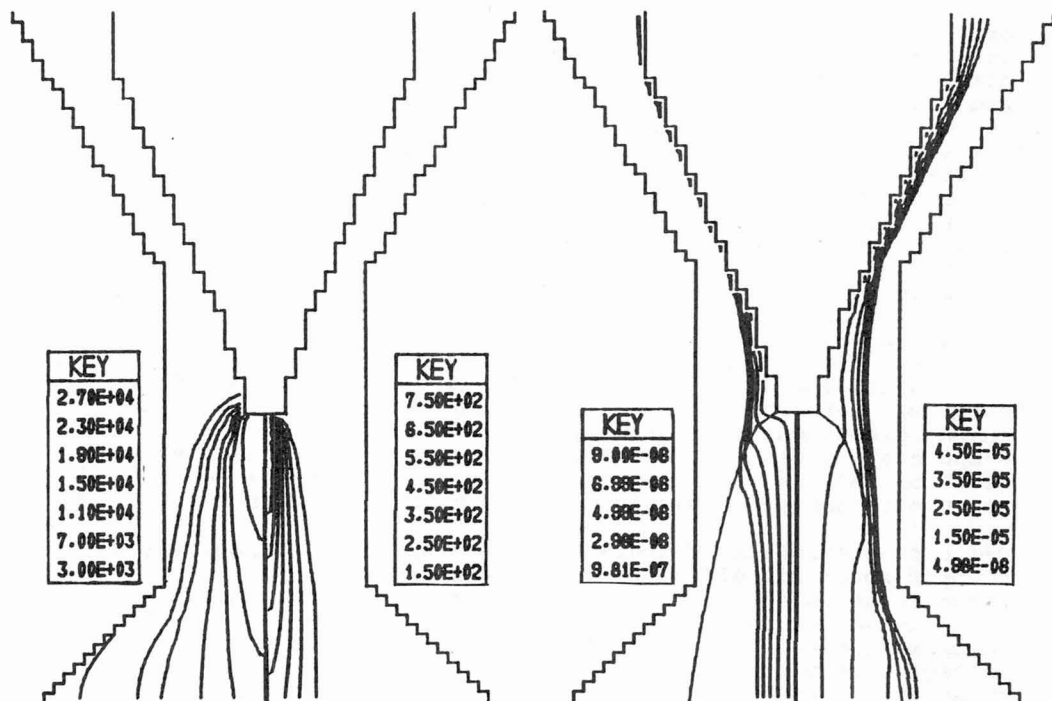


Figure 3. Plot A. The temperature (left side of the symmetry axis) and the axial velocity distribution in the plasma torches.  
 Plot B. Each half is a plot of a subrange of the stream function together with the outline of the arc. The effect of the arc on the gas flow is easily seen. Only a fraction of the total gas flow passes through the high temperature region of the arc.

#### **Combined results of the 2D (Step 1) and the 3D (Step 2) simulations**

The sum of the cathode and the anode fall voltages is assumed to be around 8 V. This value is taken from the literature /10/. The total Ohmic heating calculated by the two simulations is 95 kW. Together with the assumed value for the electrode falls, this gives a total power input of 107 kW. The total voltage drop is then 71 V and is represented in Fig. 4 by a star.

The simulations give a total of 23 kW of radiative heat loss and 72 kW of convective heat loss to the walls (calculated for 2D and 3D separately and then added to give the total). This corresponds to 22% and 69%, respectively, of the total power input. The balance amounts to 9%.

#### **Heat transfer to the anode. Comparison with measured data**

To get an estimate of the total heat loss to the anode that can be compared with the measured value, the computed convective heat transport to the anode (2.4 kW) from the 3D case is combined with the general knowledge that heat transfer by electron drift is by far the most important heat transfer mechanism to the anode, particularly for long arcs. It may account for as much as 85% /11/. For a 50 mm arc 75% of the total anode heat flow is attributed to electron drift /10/. Since the modelled arc is long (140 mm) the first of these referred values is used, and the total anode heat loss is estimated to be 16 kW. Radiation heat transfer is neglected. The angle factor from the nozzle exit to the anode is 0.02. This value increases to 0.4 from a point on the arc axis, 5 mm above the anode surface. In this area, however, the radiation density will be moderate due to the considerably lower temperatures. The total heat flow to the anode is then approximately 15% of the power input, which is remarkably close to the measured anode heat loss in the calorimetric model, 14.6% (left columns in Figure 5).

#### **Concluding remarks**

The 3D simulation as well as the 2D one, are based on a rather simple model for the arc(-s). The 3D case, however, is also complicated by the fact that even a  $23 * 23 * 34$  grid, as the one used here, requires considerable computational time. In addition, the fact that the arcs are tilted relative to the 3D computational grid is unfortunate. In this program version the grid has to be generated based on the cylindrical geometry of the reactor chamber. Only a  $60^\circ$  sector is modelled. This sector is chosen by first dividing the model into three  $120^\circ$  sectors around each torch, each of these is again divided into two due to the symmetry. Even so, the  $23*23*34$  grid of one of these 6 "pies" leaves much to be wanted in geometrical accuracy and resolution of the arc region as can be seen in Figure 6. The demand for a better grid generation is obvious.

In addition to these difficulties, the proposed formula for the arc geometry assumes a cathode jet dominated flow (CJD) as well as a free-burning arc. Violation of these assumptions is likely to occur, e.g. due to the presence of the nozzle



surrounding the arc downstream of the cathode tip. The arc length to diameter ratio is probably too high for a large portion of the arc. An arc model where the geometry of the arc is found as a result of the computations, is highly desirable and is part of the continuing work in our group on numerical modelling of transferred arcs.

3D work is under way to implement calculation of the angle factors in order to get more than just a rough estimate of the radiation distribution. Combined with the convective heat losses to different sections, this will give the total computed heat loss distribution for the reactor which can be compared with the measured one.

The basis and the two step procedure of the present calculations is rather "rough". It is thus even more encouraging for the continuing work on calorimetric and numeric studies of tilted transferred arcs, that the chosen approach actually gives results comparable with measurements.

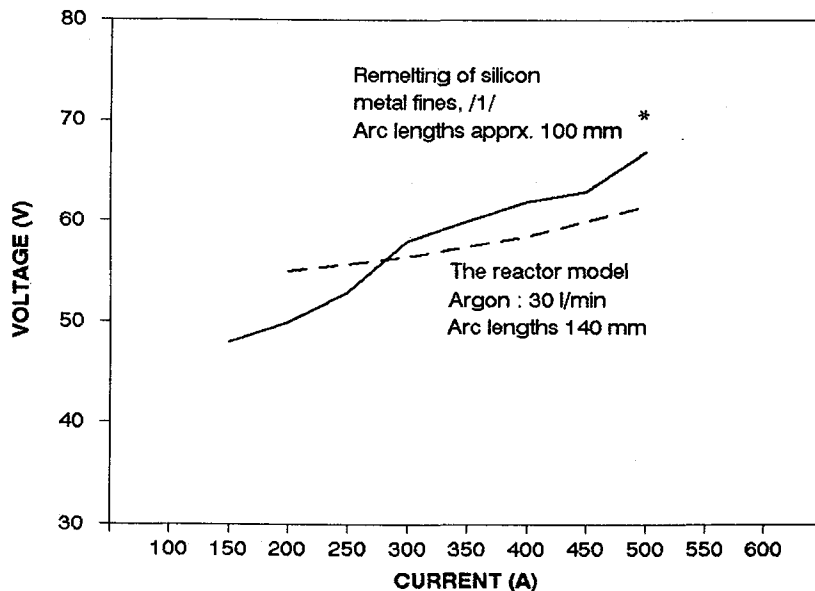
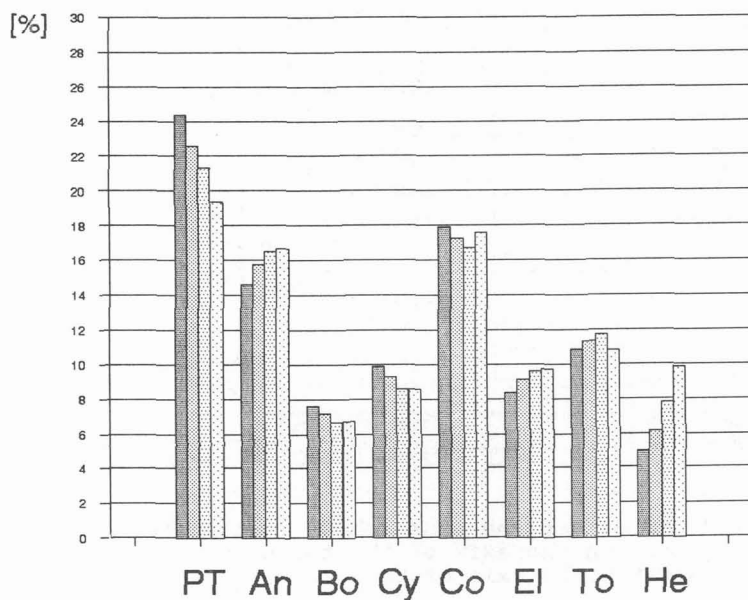


Figure 4. I-U characteristics

**Calorimetric measurements in the 1:1 scale reactor model**  
**Arc lengths approx. 140 mm. Three plasma torches**  
**Argon gas flow rate pr torch : 30 l/min**



Power input 93.2 kW. Current 500 A
  Power input 71.2 kW. Current 400 A  
 Power input 50.8 kW. Current 300 A
  Power input 33.2 kW. Current 200 A

PT = Plasma Torches  
 An = Anode  
 Bo = Bottom minus anode  
 Cy = Cylindrical section  
 Co = Conical section  
 El = Electrical insulation of plasma torches  
 To = Top sections  
 He = Heat exchanger

Figure 5. Experimental data. Heat loss distribution in percentages of power input.

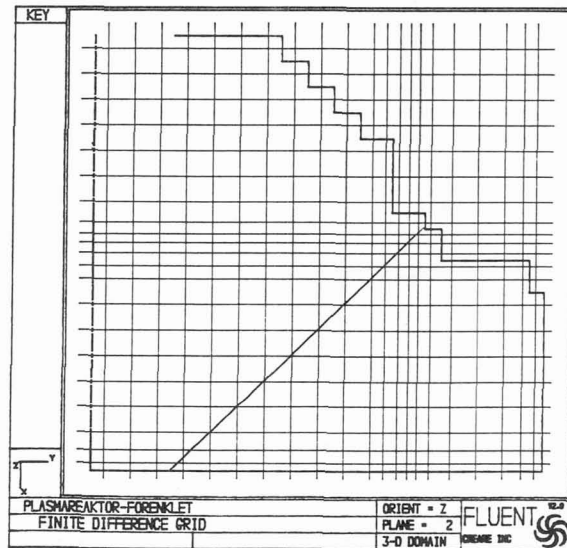


Figure 6. 3D grid. Note that the plane shown is the one cutting through the axis of the torch. The tilted line indicates the axis of the arc.

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