Eindhoven, University of Technology, the Netherlands

Moscow Physical and Technical Institute, USSR

Institute of High Temperatures, USSR

NUMERICAL SIMULATION OF TIME DEPENDENT

PHENOMENA IN THE FLOW TRAIN OF THE

EINDHOVEN BLOW DOWN FACILITY

ERWIN CASTELIJN

Scientific Supervisor
Dr. V. ZATELEPIN

September, 15 - November, 30
1990
Moscow
Summary

My subject during my traineeship in Moscow was the simulation of the gasdynamic phenomena of the EBDF. This facility is used for research concerning the phenomena in MHD-channels and about the possibility to use MHD-generators in large power stations. At IVTAN the institute for high temperatures a mathematical model has been developed to calculate the gasdynamic behaviour of such an installation.

Simulation of the EBDF is interesting because of the highly time dependence of this installation. Therefore it is a good installation to test the developed model.

An attempt for simulation has been done. Much information about the facility was not available at that place at that moment. Therefore some assumptions had to be made which means some entry data were simply wrong. However some specific phenomena are recognisable e.g. the filling of the facility with Ar-gas, the gasdynamic behaviour near the nozzle and the shock waves in the MHD-channel.

New calculations with exact data can lead to further conclusions about the model used. Also it can be interesting to compare these calculations with gasdynamic measurements of certain runs of the installation.
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1 Introduction

At the Eindhoven University of Technology an experimental MHD-generator has been developed. This experimental set-up is called the Eindhoven Blow Down Facility (EBDF). In this facility Ar-gas is used as a working medium. The purpose of this experiment is to understand the phenomena which occur in a closed-cycle MHD-generator and to verify models which describe the working of this type of generator. The main goal is to develop power stations with a high efficiency which make use of MHD as a topping unit.

The total run time of this facility is about 60 sec. During this time gas parameters as pressure, density and velocity in the flow train of this installation change considerably. There are several causes for the strongly time dependence of the phenomena in the flow train of the EBDF. These causes are opening and closing of the valves, inducing of the magnetic field, beginning of cesium injection, dumping of the heat exchanger bed temperature and the value of the magnetic field in the course of the run. This can result in unexpected and unwanted phenomena.

At the Institute for High Temperatures (IVTAN) in Moscow there is also an experimental MHD-plant (U-25). For this system a computer model is designed in order to calculate the gasdynamic response at any time at any place in the flow train of the system.

The aim of my work is to calculate the gasdynamic time dependent phenomena of the flow train of the EBDF with the help of the above mentioned program.
2 The Eindhoven Blow Down Facility

The EBDF is used for research of the physical phenomena inside of the MHD-channel. The main difference with the EUT shocktunnel experiment is that for the EBDF a real heat source (fossil fuel) is used. This is done to obtain a high enthalpy extraction in order to make it possible to use MHD-generators in power stations in future. Therefore the process time is longer (≈10 sec while that of the shock tunnel experiment is in the range of 0.1 sec). Also a higher magnetic field is used (5T instead of 4T). The lay-out of the flow train of the facility is shown in Fig 1.

The installation operates in the following way. Before the run propan is combusted in the combustion system. The blowing of combustion gases are used for heating of the ceramic bed of the regenerative heat exchanger. Next the heat exchanger is evacuated and afterwards it is filled with argon gas at a pressure of about 1.2 bar. High temperature valve and ball valve open then. Near the Ar-tank a valve is placed which is always opened. Inside of the building in the pipeline itself 3 valves are placed not far from each other. The first one (A62) is used to start up the run. This valve opens slowly. Next valve is a control valve which makes sure that the pressure of the Ar-gas is 7 bar downstream of this valve. Then a hermetic seal is placed which is opened during the run. After 30 - 60 sec. valve A62 is closed and at the end of the run the ball valve is closed.

When we pass the flow train from beginning to end we meet the following components:

-Argon gas tank

This is a 4 m³ spherical tank in which the argon is stored at a pressure of 100 bar.

-pipeline

Through a pipeline the gas is transported from the argon tank which is placed outdoors; the installation itself is placed inside of the
building. Length and cross section are unknown for us. Also the material is unknown at this moment. At two or three places of this pipeline some valves are placed but the exact position is also unknown. Two of them are a valve VI for the starting of the run and a control valve which keeps the pressure upstream of the MHD-channel at 7 bar. The pipeline consists of 2 parts. The first has an estimated length of 20 m and a diameter of 0.5 m. The second part contains the valves and has a length of 4 m and the same cross section as the first part.

-regenerative heat exchanger

This component is used for heating the argon gas. It consists of two parts: the bed and the thermal insulation. The bed is made of perforated $\text{Al}_2\text{O}_3$-bricks. When we look at a cross section we see 1711 holes totally. Every hole has a diameter of 8.2 mm. The insulation consists of impermeable $\text{Al}_2\text{O}_3$-bricks. After the bricks in the bed have been heated by the combustion gases they are able to heat the argon which is flowing through the holes. Other parameters of this subsystem are:

- length: 6 m
- diameter (bed): 0.68 m
- Ar mass flow: 5 kg/s
- exit pressure: 7 bar
- Ar exit temperature: 2000 K
- temperature drop: $\Delta$ 60 K in 60 s

-stilling chamber

This is the connection between the heat exchanger and the high temperature valve.

- length: 1.40 m
- cross section:

-high temperature valve

This valve is used to insulate the heat exchanger from the downstream components during the bed heating procedure before the run. Only when
the run is started this valve opens and the hot argon gas can flow through the downstream part of the flow train. Other entries of this valve are:

- maximum cross section:
- equipped for argon gas and flue gas
- opened:
  - medium: argon gas
  - temperature: 2000 K
  - pressure: ≤ 10 bar
  - mass flow rate: ≤ 8 kg/s
  - time: 60 s
- opening time: 10 s
- closing time: 60 s
- isolation: ceramic cement (phlox 188)

- cesium module

In this component the cesium is injected with the help of sprayer. The mixing of cesium with argon has to be as homogeneous as possible. The cross section changes through this part from 0.25m (round) to 0.15m (square). The stagnation pressure and temperature are measured here.

  - length: 0.634 m

- entrance section

This is the part between the cesium module and the nozzle. Actually it's a part of the cesium module, but this part is placed in the magnet. Both parts consist of stainless steel and lined on the inside wall of Al₂O₃ fibre which is a very good thermal isolator.

  - length: 0.958 m
  - cross section: 0.15m x 0.15m

- nozzle

Here the gas is accelerated. The minimum cross section is 0.04mx0.15m (rectangular). Inlet and outlet differ in material and cooling.
nozzle inlet: stainless steel, water cooled
nozzle outlet: boron nitride, heat sink

generator channel

The electrical energy is generated in this component. Important is the thermal isolation of the inner wall and the prevention of cesium reactions with the inner walls. Also the generator should be isolated electrically in the axial direction. The used generator is of the Faraday type with segmented electrodes. Different channels are used for the runs. The entries of the channel used in run 803 are:
- length: 0.70m
- entry cross section: 0.15mx0.05m
- exit cross section: 0.15mx0.18m
- segment pitch: 0.028m
- number of electrodes: 25
- material: Si₃N₄, heat sink

supersonic diffusor

The aim of this component is to decrease the gas velocity to subsonic values. This component is rectangular.
- length: 1.71m
- cross section: 0.154m x 0.180m

Because of the fact that this subsystem partly is placed in the magnet it consists of two parts of different materials.
- supersonic diffusor (1): boron nitride, heat sink
- supersonic diffusor (2): stainless steel, water cooled

ball valve

This valve should actually start the run, but because of possible problems in the heat exchanger and the MHD-channel the run is started now by opening of valve VI which opens in 10 sec. This valve is actually a part of the supersonic diffusor.
-cross section: 0.154m x 0.180m

-subsonic diffusor

This component is used for the further decreasing of velocity. It is a channel diverging in two directions.
- length: 0.972m
- entry cross section: 0.154m x 0.180m
- exit cross section: 0.230m x 0.256m
- material: stainless steel, water cooled

-compensation pipe

This is used to compensate the mechanical forces which are caused by the expanding or shrinking of different components of the facility during the run.
- length: 1.58m
- diameter: 0.393m

-scrubber

This is the last component of the flow train. Here cesium is bound with water to cesiumhydroxide. The argon leaves the system through the stack.
- length: 2.4 m
- diameter: 1.2 m

The different runs have delivered a lot of information about the physical phenomena and problems concerning MHD-channels. With a power generation of 621kW and an enthalpy extraction of 12.9% run 803 is considered to be a quite succesful one. However complete understanding of the MHD-interaction is still not achieved and further research will be needed. Information about especially the last runs is shown in Table 1.
3 Mathematical models for time-dependent processes in the flow train of an MHD-system

A total MHD-system consists of a certain number of different subsystems. These subsystems have different physical phenomena with different time constants. This makes it difficult to create a model for the total MHD-system. At IVTAN, the Institute for High Temperatures a model is developed for calculating the gasdynamic parameters of the main working fluid of the whole system [1]. Models for the different subsystems are used and the response of the whole system is the sum of the responses of the different subsystems. In this model equations of the hydraulic type are used. This model can be used for information about e.g. starting-up, shutting-down or emergency cases of the MHD-system.

Because of the different time constants of the processes three models were developed:

- rapid process model \(10^{-2}\) s
- model of 'slow' gasdynamic processes (1 s)
- model of heat processes (1 hour)

The first model is used here for simulation of the EBDF. The reason for this is that the gasdynamic phenomena in this facility are in the order of \(10^{-2}\) s to 1 s. This is why the rapid process model is further explained here.

-Rapid process model

In order to simulate the gasdynamic response the total flow train of the MHD-system is divided into subvolumes. For every subvolume the unsteady equations of conservation are used. \(V\) is the total volume of the subvolume. \(E\) is the surface of the cylindrical subvolume without the cirkular areas at both ends. The equations are:
\[ \frac{d}{dt} \left( \int_{V} \rho dV \right) + \int_{\epsilon} \rho v_{n} d\epsilon = 0 \]

\[ \frac{d}{dt} \left( \int_{V} \rho v dV \right) + \int_{\epsilon} \rho v v_{n} d\epsilon = \int_{V} \tau_{n} d\epsilon + \int_{V} F dV \]

\[ \frac{d}{dt} \left( \int_{V} \rho \left( \varepsilon + \frac{v^{2}}{2} \right) dV \right) + \int_{\epsilon} \rho v_{n} \left( \varepsilon + \frac{v^{2}}{2} \right) + p v_{n} d\epsilon = -\int_{\epsilon} q_{n} d\epsilon - \int_{V} N dV \]

These equations describe the flow through the flow train of the facility. If we introduce averaged values yielding:

\[ \int_{V} \rho dV = \langle \rho \rangle V \]

\[ \int_{V} \rho v dV = \langle \rho \rangle \langle v \rangle V \]

\[ \int_{V} \rho \left( \varepsilon + \frac{v^{2}}{2} \right) dV = \langle \rho \rangle (\langle \varepsilon \rangle + \frac{\langle v^{2} \rangle}{2}) V \]

We will have three one-dimensional time-dependent equations for every subvolume. These equations can be written as:

\[ \frac{d\rho}{dt} + \frac{1}{V_{i}} (G_{r i} - G_{l i}) = B_{\rho i} \]

\[ \frac{d(\rho u)}{dt} + \frac{1}{V_{i}} (J_{r i} - J_{l i}) = B_{ui} \]

\[ \frac{d\rho (\varepsilon + \frac{v^{2}}{2})}{dt} + \frac{1}{V_{i}} (GH_{r i} - GH_{l i}) = B_{ei} \]

in which the following identifiers are used:
i: number of subvolume

\( V_i \): value of subvolume

G: flow of mass through cross section between subvolumes

J: flow of momentum through cross section

GH: flow of enthalpy through cross section

r: index for flow to the right bound of the subvolume

l: index for flow to the left bound of the subvolume

\( B_{\rho i} \): mass flow rate through side walls

\( B_{ui} \): momentum flow rate through side walls

\( B_{ei} \): enthalpy flow rate through side walls

The meaning of these flows is further explained in Fig 2 for the first equation.

In this model also the equation of conservation of mass for important molecular or atomic components are added to the three conservation laws mentioned.

\[
\frac{d\rho_{ij}}{dt} + \frac{1}{V_i} (G_{rij} - G_{lij}) = M_{ij}
\]

in which index \( j \) indicates the component, \( G_{ij} \) the mass flow rate of this component through the cross sections between the subvolumes, \( M_{ij} \) flow rate of this component through the side walls. For calculating of \( G_{ij} \) the following formula is used:

\[
G_{ij} = G_i \frac{\rho_j^*}{\rho^*}
\]

The asterix indicates that we have to take the density at the boundary between two subvolumes. In case of the EBDF we have added one such equation for the cesium density in the flow train. In this way we have four differential equations with four parameters \((\rho, p, u, \rho_{cs})\).

Important now is how these formulas are used to calculate the gasdynamic parameters. In order to do this the Godunov's approach is used which results in the following schedule:
1) calculation of the right hand terms $B_{\rho i}$, $B_{ui}$, $B_{ei}$
2) calculation of the flows $G$, $J$, $GH$
3) calculation of the timestep
4) calculation of the gasdynamic parameters in the next time moment

1) The calculation of the right hand terms depends upon the component of the flow train in which the subvolume is placed. The way of calculating these terms will be explained in chapter 6. It may be clear that the value of $B_{\rho i}$ is equal to zero in almost every subvolume. Only in the cesium module were cesium is added this value is different from zero. $B_{ui}$ takes into account the friction losses in the subvolumes and for instance the Lorentz-force in the MHD-channel. $B_{ei}$ is used for the calculation of heat- and enthalpy-losses or -sources as f.i. in the heat exchanger.

2) The flows are calculated in the same way for every subvolume. The formulas used are:

$$G_i = \rho \cdot v \cdot y$$

$$J_i = \rho \cdot y + G_i v + p_{i,2}(y_{1,2} - y)$$

$$GH_i = G_i (h + \frac{(v^*)^2}{2})$$

in which:

- $p_1$: pressure at entrance cross section of subvolume
- $p_2$: pressure at exit cross section of subvolume
- $y$: minimal cross-section between two subvolumes
- $y_1$: total inner cross section at entrance of subvolume
- $y_2$: total inner cross section at exit of subvolume
3) In order to calculate the timestep three times are calculated for every subvolume:

\[ T_1 = \frac{L}{u+c} \]

\[ T_2 = \frac{L}{|u-c|} \]

\[ T_3 = \frac{L}{u} \]

in which:

L: length of subvolume
u: velocity in subvolume
c: velocity of sound in subvolume

The minimum value of these times of all subvolumes determines the new timestep.

4) With the help of the equations of conservation we can calculate the gasdynamic parameters in the next time moment. If we integrate the equation of conservation of mass we are able to calculate the density in the next moment:

\[ \rho_i' = \rho_i - \frac{1}{V_i} \int (G_{ri} - G_{li}) \, dt + \int B_{\rho i} \, dt \]

in which:

\( \rho \): density in the next moment
\( \rho \): density in this moment
\( \tau \): time step

If we assume \( G_{ri} \), \( G_{li} \) and \( B_{\rho i} \) to be constant during the time step we can use the following equation:

\[ \rho_i' = \rho_i - \frac{1}{V_i} (G_{ri} - G_{li}) \tau + B_{\rho i} \tau \]

Of course in this way we also take the gasdynamic parameters to be constant during the time step, because with these the terms \( G \), \( J \), \( GH \) and the right hand terms are calculated.
4 Dividing of the EBDF into subvolumes

In order to use the model discussed in the previous chapter for simulation of the EBDF we have to decide what we consider as the flow train. For this we take the components through which the argon gas flows from argon tank to scrubber. We have to chose a division of the components of the whole system into subvolumes. The cross sections and lengths of the components are known from our information about the EBDF or can be estimated. All subvolumes are taken to have a cylindrical form. The cross sections are known, so we only have to determine the lengths of the subvolumes. For this we have 2 criteria:

1) The Strouhal number $S$ has to be much smaller than 1. The following definition for $S_h$ can be used:

$$S_h = \frac{x}{ut}$$

in which:
- $x$: length of subvolume
- $u$: averaged velocity in subvolume
- $t$: typical process time

Actually we can say that $S_h$ is the ratio of the time needed for the working media to cross the subvolume and the typical process time. The time for crossing the subvolume must be much smaller than the typical time. In this way it is quite right to assume a linear distribution of the gasdynamic parameters in the axial direction of a subvolume.

We can calculate the length of a subvolume with the help of the formula for the Strouhal number and the following formulas:

$$u = \frac{G}{\rho F}$$

$$\rho = \frac{P}{RT}$$

in which:
- $G$: mass flow rate
- $\rho$: averaged density in subvolume
p: averaged pressure in subvolume
T: averaged temperature in subvolume
F: cross section
R: gas constant for argon

This gives us the next formula for x:

\[ x = \frac{S_h t G R T}{p F} \]

We take \( S_h \) to be equal to 0.1 and \( t \) equal to 0.1 s. The mass flow rate is taken to be equal to 4.8 kg/s (for run 803). The gas constant for argon is 207.85. The values of temperature and pressure can be estimated though this is of course a rough estimation. As mentioned before we know the values of the cross sections. With the help of this formula we can calculate the length of a subvolume.

2) Another criterium is that in case of large changes of the gasdynamic parameters in some component we take more subvolumes than calculated with the help of the Strouhal number.

Next the chosen division of every component into subvolumes will be explained:

-argon gas tank

The problem here is that the tank is not cylindrical but spherical. In this model we will take a cylindrical tank with the same volume as the real tank. This volume is 4m\(^3\). The radius of this volume is 0.985m. This is taken to be the length of the subvolume. To make sure we have a volume of 4m\(^3\) we have to chose a cross section of 4.06 m\(^2\). The argon tank is taken to be one subvolume only.

-pipeline 1

This is a difficult component in this case, because we don't have any information about it. The estimated dimensions, pressure and temperature are:
\[ l = 20 \text{ m} \]
\[ d = 0.5 \text{ m (diameter)} \]
\[ p = 7.2 \text{ bar} \]
\[ T = 300 \text{ K} \]

With these entries the length of every subvolume has to be 2.6 m. Because we have a total length of 20 m we take 8 subvolumes each with a length of 2.5 m.

-pipeline 2

This is the same kind of pipeline, but there are 2 valves here. The total length is estimated to be 4 m. Unfortunately we don’t know the exact position of these valves. Therefore this part is divided into 3 subvolumes with the valves between them. Later the length of the last subvolume of the pipeline is changed into 3.5 m.

Lengths and subvolumes of the following components are known exactly.

-regenerative heat exchanger

Because of the fact that temperature can change much through the heat exchanger here 10 subvolumes are chosen. This is more than calculation with the Strouhal number delivers (only 2 subvolumes). Also a subvolume for the entrance part and one for the exit are chosen.

-stilling chamber

The following entries are chosen for the calculation of \( S_h \):
\[ l = 1.412 \text{ m} \]
\[ F = 0.203 \text{ m}^2 \]
\[ p = 7.0 \text{ bar} \]
\[ T = 1980 \text{ K} \]

This delivers a subvolume with a length of 0.193 m. Two subvolumes are chosen which is wrong; because of the calculations actually 7 subvolumes had to be chosen.
All entries for calculation of the Strouhal number are the same as in the stilling chamber except for the cross section which is decreasing to the end of this component. This means the averaged cross section is smaller and therefore also $S_h$ is smaller. This component is shorter than the stilling chamber and with the previous considerations one subvolume has to be sufficient.

-entrance section

The entries for calculating $x$ are:

1 = 0.948 m  
$F = 0.023 \text{ m}^2$  
p = 7.0 bar  
$T = 1980 \text{ K}$

The cross section of this component is actually square, but here it is taken to be circular. The calculated length is 1.23 m. and therefore one subvolume is chosen.

-nozzle

The volume concerning the volume of the exit part of the nozzle is also taken to be one subvolume. The entrance cross section of this subvolume is the smallest part of the nozzle. The length of this subvolume is 0.09 m.

-MHD-channel

The entries are:

$l = 0.70 \text{ m}$  
$ar{F} = 0.0195 \text{ m}^2$  
p = 7.0 bar  
$T = 1980 \text{ K}$

This gives a length of 1.45 m. Still 12 subvolumes are chosen, because
we should calculate the electromagnetic interactions in this component in case of large variations of the gasdynamic parameters.

-supersonic diffusor (ceramic)

Entries:
\[
\begin{align*}
I &= 0.648 \text{ m} \\
F &= 0.028 \text{ m}^2 \\
p &= 7.0 \text{ bar} \\
T &= 1980 \text{ K}
\end{align*}
\]
The calculated length is equal to 1.0 m. However 4 subvolumes are chosen.

-supersonic diffusor (stainless steel)

The entries for calculating are the same as in the previous component; Only the total length is different (1.059 m). Also 4 subvolumes are chosen.

-ball valve

It was assumed that this valve has a rather big volume and when it is totally opened there is some extra volume which we didn't want to neglect. The entries are the same as in the diffusors which delivers a length of 1.0 m. The total length is 0.655 m so one subvolume is chosen.

-subsonic diffusor

Following entries are used:
\[
\begin{align*}
I &= 0.972 \text{ m} \\
F &= 0.059 \text{ m}^2 \\
p &= 7.0 \text{ bar} \\
T &= 1980 \text{ K}
\end{align*}
\]
x is equal to 0.5 m and 3 subvolumes are chosen.
-compensation pipe

Entries:

\[ l = 1.585 \, \text{m} \]
\[ F = 0.393 \, \text{m}^2 \]
\[ p = 7.0 \, \text{bar} \]
\[ T = 1980 \, \text{K} \]

The calculated length of a subvolume is 0.23 m; 3 subvolumes are chosen.

-scrubber

As mentioned before this is the last component. It has a cylindrical form, but the inlet is somewhere in the middle of the side wall of the cylinder. This means that the chosen dimensions are different from the real dimensions of this cylinder. As in the argon tank the dimensions are chosen in such way that the total volume of the chosen subvolume is equal to the real subvolume. The dimensions are:

\[ l = 1.77 \, \text{m} \]
\[ F = 0.55 \, \text{m}^2 \]

One subvolume is chosen.

It may be clear that the division on base of the Strouhal number is not followed correctly in every subvolume. But this procedure is not a very strict one, so small differences in division don’t create large problems. The total chosen dividing of the flow train with which our calculations are made is shown in Fig 3.
5 Entry data

The IVTAN computer model has to be changed in order to use it for simulation of the EBDF. The most important equipments are the entry data with information about the EBDF. Each subvolume of the flow train has its own properties concerning dimensions, shape, material etc. Special data for this computer code are shown in Fig 4. The first column consists of different identifiers for different properties. The second row contains all the numbers of the subvolumes. Every property is explained by a number which can have the meaning of a real dimension e.g. p for pressure. It can also have a special meaning for a certain property in the program itself e.g. IRAT which is used for different ways of calculating friction losses. First of all now the different identifiers will be explained:

IG: type of cross section between two subvolumes
Because we have 57 subvolumes we have (with beginning and end) 58 cross sections.

IRAT(1,2,3): shape of subvolume
This is needed to calculate the friction in the subvolume. Some basic shapes are included here. It is taken into account that there can be 3 different factors which act on the value of friction.

IE: type of heat losses and sources
This identifier is needed for calculating the heat exchange between wall and gas which of course depends on the material of the wall.

IS: buoyancy force
In subvolumes in which the gas is flowing in horizontal direction this identifier is equal to zero indicating that there is no buoyancy force. When the flow is in vertical direction the value is +1 or -1 which means that this force is calculated. The sign depends on the direction of the flow.
Hi: length of the subvolume

YHS1, YHS2, YHS: cross sections of subvolumes
The meaning of these different cross sections is explained in Fig 5. Different cross sections are used because they are needed in different calculations. In the previous chapter the choice of the lengths and cross sections of the subvolume is already discussed.

G: initial mass flow rate
In case of the EBDF this identifier is zero for every subvolume.

P: initial pressure
T: initial temperature
T_wl: initial wall temperature
The value of the last 3 identifiers had to be guessed at some places. At some points we know these initial values. Here often for other points these values are taken to be the same.

All of these identifiers with their values for all subvolumes are placed into a special data file. At the start of the program these values are read from this file and further used in the program. This way of working has the advantage that for the simulation of other flow trains it is easy just to use another data file. In case of new features of special components of course also new subroutines have to be added.
6 Calculation of losses and sources

As mentioned in chapter 3 we calculate the righthand terms of the equations of conservation of mass, momentum and enthalpy in a different way for different components. In this chapter the models we use for the components in which there are some special losses or sources will be discussed.

6.1 MHD-generator-model

The main goal of the MHD-generator-model is to calculate the additional pressure and enthalpy extraction in the MHD-generator, in relation with the Lorentz force and the electrical power output.

The typical time constant of the gasdynamic phenomena inside of the EBDF flow train is of order \( \tau = L/u \), in which \( L \) - is the length of the flow train, \( u \) - is the velocity of the working fluid. At different moments of the run the velocity varies considerably, but we can estimate \( \tau \) in the range from \( 10^{-2} \) - 1 sec.

On the other side the electrical phenomena which occur in the MHD-channel of the EBDF are very non-uniform in space with a frequency of about \( 10^4 \) Hz. This means that there is a big difference between the frequencies of the phenomena of the whole flow train (\( 1/\tau = 1 - 10^2 \) Hz) and the frequencies of the electrical phenomena in the MHD-channel. This allows us to use the steady approach for calculating the righthand terms in the MHD-channel.

To solve the set of equations in the MHD-channel we have to calculate the space and time averaged Lorentz force and electrical power extraction in every subvolume of the MHD-channel. For the averaged values of momentum and enthalpy losses we can write the following formulas:

\[
\langle B_{ui} \rangle = \frac{1}{V_i \tau} \int \int \left( \mathbf{j} \cdot \mathbf{B} + \mathbf{v} \cdot \mathbf{f}_{\text{fric}} + p \frac{\partial F}{\partial x} \right) \, dt \, dV
\]

\[
\langle E_{wi} \rangle = \frac{1}{V_i \tau} \int \int \left( \mathbf{j} \cdot \mathbf{E} + \mathbf{v} \cdot \mathbf{q}_w \right) \, dt \, dV
\]
The following identifiers are used:

- $i$: number of subvolume
- $V_i$: subvolume
- $\tau$: time step
- $\dot{J}$: current density
- $\dot{E}$: electrical field
- $\dot{B}$: magnetic field
- $\dot{f}_{\text{fric}}$: friction force
- $p \frac{\partial F}{\partial x}$: force connected with the diverging of the channel
- $q_w$: heat transfer
- $\varphi$: voltage difference between opposite electrodes

All of these terms are calculated except for the Lorentz force and the electrical power extraction. The magnetohydrodynamic terms which have to be calculated are in our approach:

$$<B_{ui}>_{\text{MHD}} = <\dot{J}><\dot{B}>$$

$$<B_{ei}>_{\text{MHD}} = <\dot{J}x\dot{E}> = <\dot{J}><\nabla \varphi>$$

In order to calculate these terms we have to calculate $<\dot{J}>$. For this we make use of a model developed for an Ar-Cs closed cycle MHD-generator [3]. This model is not a three dimensional time dependent model. It's a model based on empirical expressions developed with the help of data produced by experiments with the EBDF. As we know discharges in Ar-Cs MHD-generators occur in narrow channels called streamers. In this model a relationship between the total streamer current $I_s$, the streamer conductivity $\sigma_s$ and the streamer cross section $O_s$ is assumed (see Fig 6). This relationship has the following form:

$$\sigma_s O_s = (I_s) \frac{x_1 e^{-I_s / I_s 0}}{(\rho)^{x_2}} (1 + x_3 B^2)^{-1} x_4$$

$\rho$ is used here for the density of the gas. $I_s$ and the product $\sigma_s O_s$ can be expressed and calculated with the help of next expressions:
Following parameters are used:

- $u$: velocity of the streamer
- $s$: segment pitch
- $f$: streamer ignition frequency
- $I_L$: load current
- $R_L$: load resistance
- $R_i$: internal resistance of a generator segment
- $h$: height of the MHD-channel
- $\Delta V_a$: voltage drop at anode
- $\Delta V_c$: voltage drop at cathode

The expression for $f$ is also an empirical one. All of these parameters can be measured or calculated and therefore we can calculate $I_s$ and $\sigma_s$. With these calculations and the data of several experiments of the EBDF the values of $x_1$, $x_2$, $x_3$, $x_4$ and $I_{s0}$ are found to be:

- $x_1 = 1.57 \pm 0.04$
- $x_2 = -0.8 \pm 0.1$
- $x_3 = -3.1 \times 10^{-3} \pm 0.9 \times 10^{-3}$
- $x_4 = 9 \times 10^{-6} \pm 2 \times 10^{-6}$
- $I_{s0} = 600$ A

It should be stated here that the empirical equation is derived for the fully developed streamer region in the MHD-channel. This means that there is a region in the beginning of the MHD-channel in which the streamers are not completely developed. To take into account also this phenomena in this model a special formula is used. $\sigma_s$ will further be denoted as $\Sigma_s$:
\[ \Sigma_s = (1 - e^{-x/L})\hat{\Sigma}_s \]

\(\hat{\Sigma}_s\) is the asymptotic value of \(\Sigma_s\) in the fully developed region, \(x\) is the axial distance along the channel, \(L\) is used to denote the relaxation length for which the following expression is used:

\[ L_r = 440 B^{-6.14} + 0.110 \text{ m} \]

To find this expression again data of the same experiments of the EBDF are used.

We have added something to this model. In the formula which takes into account the effect of the relaxation area we multiplied the right hand term with the ratio of two quantities, \(\rho_{cs}\) and \(\rho_{cs0}\). \(\rho_{cs0}\) is the density of the cesium in the MHD-channel in steady mode, so when a constant supply of Cs-mass is added to the system. \(\rho_{cs}\) is the density of cesium in the specific subvolume at this time moment. This gives the following formula for the conductance of the streamer:

\[ \Sigma_s = \frac{\rho_{cs}}{\rho_{cs0}} (1 - e^{-x/L})\hat{\Sigma}_s \]

This extension is quite logical. When there will be more cesium in the MHD-channel the conductivity will of course be higher. This assumption can of course reduce our calculation time because when there is no cesium in the MHD-channel the conductivity is equal to zero and then it's of course unnecessary to calculate \(<j>\). In addition to the gasdynamic terms \((p, \rho, u)\) we will also calculate the density of cesium, especially in the MHD-channel.

The question now is how to calculate \(<j>\) with the help of this model. We can develop two expressions for \(\Sigma_s\). The first expression is the empirical one. The second expression can be derived with the help of Kirchhoff’s law and a few other expressions which are already shown in the calculation of the constants \(x_1, x_2, x_3, x_4\) and \(I_{s0}\). This means
we have the following expressions:

\[ \Sigma_s = (I_s)^x_1 e^{-I_s/I_0} (\rho)^x_2 (1 + x_3 B^2)^{-1} x_4 \]

\[ \Sigma_s = I_s h(uBh - \Delta V_a - \Delta V_c - I_s R_1 s f_j) \]

In our calculations all values are known except for \( I_s \) and \( \Sigma_s \), so these equations can be solved. For solving these equations an iteration process is used which will be discussed later. Once we have found the value of \( \Sigma_s \) (let's denote this value as \( \Sigma_{s1} \)) we can take into account the influence of the relaxation area and our assumption about the density of cesium by using this value in the formula already shown which takes into account these phenomena. Once we know \( I_s \) we can calculate \( I_1 \) with which we can calculate \( \langle j \rangle \):

\[ \langle j \rangle = \frac{I_1}{dS} \]

\[ \langle \varphi \rangle = R_1 I_1 \]

d is the width of the channel.

Important is that the calculated values for \( \langle j \rangle \) is not only averaged in time, but also in space. Only in the middle just between the electrodes of the MHD-channel a streamer looks like a thin thread. Near the electrodes this thread is splitted and is connected to one or more electrodes (see Fig. 7). When we take some position in the middle then at some time moment there will and at another there won't be a streamer. This means that the streamer current and also current density will change through time. Because we calculate current density with the data of measurements averaged in time, we also calculate \( \langle j \rangle \) and \( \langle \varphi \rangle \) averaged in time. The averaged values for \( \langle j \rangle \) can be right in the middle of the channel. Near the electrodes the current density will be higher and just between two electrodes it will be lower. We assume now that current density in every point of a subvolume in the MHD-channel is the same as the current density in the middle part of this subvolume.
Because of the fact that we use empirical formulas some expressions can only be used for some values of parameters. The expression for the streamer frequency e.g. gives a negative value for a magnetic field below 1.85T. This limits our range of calculation, because for a $B$ with a value lower than 1.85T we don't calculate additional terms for $B_{ui}$ and $B_{ei}$ in the MHD-channel. Further it's impossible to calculate when the velocity is below 212m/s. A run time error occurs in that case and therefore we only calculate for velocities which are higher than this value. The empirical expression for $\Sigma_{S}$ is only valid for values of $B$ between 3.23T and 5.24T. However we also use it for lower values. The mentioned limitations in calculations or applicability of formulas will give rise to some differences between experimental and calculated results.

The MHD-channel itself is a segmented Faraday-type (see Fig. 8). Especially in our model we wanted to use the features and dimensions of the MHD-generator which is used in run S03. First of all because this run was one with a high enthalpy extraction; Second because the previous mentioned empirical formulas were mainly based on this run. Some information about this run and about the MHD-generator is given in Table 2.

Table 2: Conditions of the MHD-generator in run S03

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>generator height</td>
<td>0.15m</td>
</tr>
<tr>
<td>generator width</td>
<td>0.05m - 0.18m</td>
</tr>
<tr>
<td>generator length</td>
<td>0.70m</td>
</tr>
<tr>
<td>segment pitch</td>
<td>0.028m</td>
</tr>
<tr>
<td>stagnation temperature</td>
<td>1980K</td>
</tr>
<tr>
<td>stagnation pressure</td>
<td>7.1 bar</td>
</tr>
<tr>
<td>inlet Mach number</td>
<td>1.66</td>
</tr>
<tr>
<td>mass flow</td>
<td>4.8 kg/s</td>
</tr>
<tr>
<td>seed concentration</td>
<td>0.07 %</td>
</tr>
<tr>
<td>magnetic induction</td>
<td>3.23T - 5.24T</td>
</tr>
<tr>
<td>load resistance</td>
<td>3.6Ω</td>
</tr>
</tbody>
</table>

In our numerical model the MHD-channel is divided into 12
subvolumes (nr 30 to 41), each with a length of 0.056m. The segment pitch is 0.028m and we have 25 electrodes. In each cross section in the middle of every subvolume we have an electrode pair. The entry cross section of the first subvolume in the generator is at the place of the first electrode pair. The last electrode pair is situated at the exit cross section of the last subvolume in the generator.

The computer program is working in the following way. After the timestep has been calculated the magnetic field $B$ [4], the streamer frequency $f$ and the relaxation length $L_r$ are calculated. The iteration process calculates the value of the streamer current. For this a function $F_{IS}$ is introduced which is the difference between the two expressions for the streamer conductance. So we can use the next expression for $F_{IS}$:

$$F_{IS} = I_s(h(uB - \Delta V_a - \Delta V_c - I_s R \frac{s f}{u})^{-1} - (I_s)^x_1 e^{-t_s/Is0} (\rho)^x_2 (1 + x_3 B^2)^{-1} x_4$$

In general $F_{IS}$ has the form shown in Fig 9. The problem now is to find the zero points of this function. The wanted zero point is also indicated in Fig. 11. In order to find this point we first calculate the place of the asymptotic axis. The expression for this is:

$$I_s \text{ axis} = \frac{1}{R_l} \frac{u}{sf} (uB - \Delta V_a - \Delta V_c)$$

From this point we take our first approximation point by just going some step to the left of the axis. The second point is chosen in a similar way and with these two points we can calculate another point which is more to the left etc. (see Fig. 11). The used iteration formula is:

$$x_k(i+1) = \frac{y_0 x_k(i) - y_k(i)x_0}{y_0 - y_k}$$

We can choose a reliable iteration process by choosing the first point not far from the asymptotic axis. Unfortunately this takes more
iteration steps and as a result a longer calculation time. In order to reduce our calculation time we take as a first approximation the value of \( I_s \) which was found by the previous time step in the same subvolume. In this way the wanted value of \( I_s \) can be found in two or three iterations, because the time step is too short to let \( I_s \) change very much. A disadvantage is that the value of \( I_s \) in the previous time moment can be at the right part of the asymptotic axis and in this case a wrong value of \( I_s \) is calculated. For excluding this case we follow the next procedure. If the value of \( I_s \) in the previous time moment is on the left part of the asymptotic axis this will be the first approximation; Otherwise we use a value which is at some step left from the asymptotic axis. In this way no mistakes will be made and calculation with the iteration formula is done until the absolute value of FIS is below 0.01.

Once the value of \( I_s \) is found it is easy to calculate the additional terms \( <B_{ul}> \) and \( <B_{ei}> \).

6.2 Heat exchanger model

In the heat exchanger heat is added to the argon gas. This model is developed to take into account the influence of these heat sources on the flow train. This means that \( B_{ei} \) has the meaning of heat sources in this component.

As we know the bed of the heat exchanger consists of a lot of holes in ceramic bricks. Let us assume that \( S_w \) is the total heating surface between the argon gas and the ceramic bricks. When we take \( q_w \) to be the heat transfer per unit area per second we can write the following expression for \( B_{ei} \):

\[
B_{ei} = \int \frac{q_w dS}{S_w}
\]

For \( q_w \) we can use in this case an expression which is valid for heat carrying media flowing through a pipe:

\[
q_w = \alpha (\overline{T} - T_w)
\]
in which:

\[ \bar{T} : \text{averaged value of temperature in the cross section of the pipe} \]
\[ T_w : \text{wall temperature} \]
\[ \alpha : \text{heat transfer coefficient} \]

The problems now is to find \( \bar{T} \) (averaged gas temperature), \( T_w \) and \( \alpha \). In order to do so we may look at Fig. 11. Here some part of the axial section is drawn. The shaded part is the ceramic brick and the unshaded part has the meaning of holes. For the heat exchange of the ceramic we can use the following formula:

\[ C \rho \frac{\delta T}{\delta t} = \lambda \frac{\delta^2 T}{\delta y^2} \]

in which:

\[ C : \text{specific heat of ceramic} \]
\[ \lambda : \text{coefficient of thermal conductivity} \]

Further we will indicate the characteristic length of the ceramic to be 1. This is the distance from the surface of a hole to the place exactly between two holes or the distance between the border of a hole and the isolation boundary. We take the ceramic temperature to be constant over the whole length 1 so we average this temperature in space. When we integrate our formula for heat exchange we obtain:

\[ \int_1^2 C \rho \, dy \frac{\delta T}{\delta t} \bigg|_2 = \lambda \left( \frac{\delta T}{\delta y} \bigg|_2 - \frac{\delta T}{\delta y} \bigg|_1 \right) \]

Because there is no heat exchanging at the places indicated in the figure by 2, we can make the following assumption:

\[ \lambda \frac{\delta T}{\delta y} \bigg|_2 = 0 \]

The remaining right hand term in the formula has the same meaning as \( q_w \), so we can write this formula in the following way:
\[
\int_0^1 C \rho \, dy \left( \frac{\partial T_w}{\partial t} \right) = q_w \quad \text{or}
\]
\[
C \rho \, \frac{\partial T_w}{\partial t} = \alpha(T_g - T_w)
\]

Our formula for heat exchange now is:
\[
C \rho \, \frac{\partial T_w}{\partial t} = \alpha(T_g - T_w)
\]

\(T_g\): the averaged gas temperature in the hole

\(T_w\): the averaged temperature inside of the ceramic brick

\(T_{w1}\): the wall temperature on the boundary between ceramic and argon gas

It should be stated here that now both temperatures are only dependent on time. Also with our assumptions we are able to state \(T_{w1} = T_w\), so:
\[
C \rho \, \frac{\partial T_w}{\partial t} = \alpha(T_g - T_w)
\]

With the help of this formula we can find \(T_w\) once we know \(T_g\) and \(\alpha\).

\(T_g\) can be calculated with the values of pressure \(p\) and density \(\rho\) of the gas in the following way:
\[
T_g = \frac{pp}{R_a}
\]

in which \(R_a\) is the gas constant of argon.

\(\alpha\) is a constant which can be calculated with the help of the Nusselt number \(N_u\) which is a number for indicating similarity of heat
transfer phenomena.

\[ N_u = \frac{\alpha d}{\lambda} \]

For heat exchangers this number can be written as:

\[ N_u = C R_e^{0.8} \]

in which:

- \( R_e \): Reynolds' number
- \( C \): constant equal to 0.018
- \( R \): Reynolds' number can be written as:

\[ R_e = \frac{\rho u d}{\mu} \]

in which:

- \( u \): velocity of the gas
- \( \mu \): viscosity of the gas

Because of the fact that we know \( \rho \) and \( u \) from our calculations of gasdynamic parameters we can calculate \( R_e \) and so also \( N_u \). Once we have \( N_u \) it's easy to find \( \alpha \).

The only problem left is the calculation of \( \bar{T}_w \). For this we first rewrite our formula for heat exchanging:

\[ \frac{\partial \bar{T}_w}{\partial t} = a(\bar{T}_g - \bar{T}_w) \]

\[ a = \frac{\alpha}{1 C \rho} \]

When we take \( \tau \) to be the time step we can write:

\[ \frac{\bar{T}_w^n - \bar{T}_w}{\tau} = a(\bar{T}_g - \bar{T}_w^n) \]

in which:

- \( \bar{T}_w^n \): the space averaged temperature in the next moment
T_w: the space averaged temperature in the previous moment

With this formula we can make the following expression for \( \overline{T_w}^n \):

\[
\frac{\overline{T_w}^n}{\overline{T_w}} = \frac{\overline{T_w} + \alpha \overline{T_g}}{1 + \alpha}
\]

In this way we can calculate the new value \( \overline{T_w}^n \) with the use of the previous value \( \overline{T_w} \).

As stated before now we know \( \overline{T_g}, \overline{T_w} \) and \( \alpha \) so we can calculate \( B_{ei} \) in the following way:

\[
B_{ei} = \alpha (\overline{T_g} - \overline{T_w}) S_w
\]

6.3 Scrubber model

In the scrubber-tank argon is cooled with water. Also cesium is seperated from the argon and bound to cesiumhydroxide. This addition of water of course influences the mass-, momentum- and enthalpy-losses in the scrubber. Suppose we have the following situation as shown in Fig. 12. The temperature at the entrance is indicated as \( T \) and at the exit as \( T_{out} \). The water flow is also shown. The enthalpy-losses per second can be calculated with the following formula:

\[
B_{ei} = -C_p (T - T_{out}) G
\]

in which:

- \( C_p \): specific heat of argon
- \( G \): mass flow rate of argon

The minus sign is used to indicate heat losses. We suppose these enthalpy-losses to be equal to the enthalpy needed to evaporate the amount of water which evaporates in 1 second. In this way we can calculate the mass difference per second:

\[
\Delta m = \frac{B_{ei}}{A}
\]

\( A \) is the enthalpy needed to evaporate 1 kg of water. In this way we
neglect the enthalpy needed to increase the temperature of water from room temperature to $T_{out}$. $T_{out}$ is taken to be 400K (which of course is higher than the boiling temperature of water). But this enthalpy can be neglected when we compare it to the enthalpy needed for evaporation. For the calculation of $\Delta m$ we also neglect the amount of cesium which is substracted in the scrubber.

The friction losses are calculated with the following formula:

$$B_{ui} = \xi \frac{G^2}{2F^2 \rho}$$

in which:

$\xi$: friction coefficient

$G$: mass flow rate of argon

$F$: cross section

$\rho$: density

The value of $\xi$ is taken to be equal to 1000 which is a normal value for this kind of scrubber. Because the calculated friction losses are those per unit area per second, we must multiply them with $F$. In this way the formula for friction losses in the scrubber is the following:

$$B_{ui} = \xi \frac{G^2}{2F \rho}$$

6.4 cesium system model

Cesium is injected in the cesium module between the 25th and the 60th second of the run. We presumed that during this time interval the mass flow of the cesium injection is equal to 0.07\% of the total mass flow rate. This means a value of $3.36 \times 10^{-3}$ kg/s for a total mass flow rate of 4.8 kg/s. As a result the right hand term in the equation of conservation of mass is equal to $3.36 \times 10^{-3}$ for this subvolume. Also here the right hand term in the equation of cesium mass is equal to this value.

We have made a wrong assumption here because with the percentage of 0.07\% actually the quotient of the density of injected cesium and
the total density is mean.

6.5 Operation of valves

Very important for the gasdynamic response of the total flow train of the EBDF is the time dependent behaviour of the valves which are placed in this flow train. Unfortunately we didn't have much information about the operation of the valves. Cross sections, exact opening and closing time moments and the time needed for opening and closing were unknown for us at that moment. Therefore we had to make some assumptions about the operation of the valves.

Our assumptions concerning the places of valves can be seen in Fig 13. It is assumed that there are 5 valves. The time-dependent behaviour assumed can be seen in Fig 14. Opening of valve V1 is supposed to be the start-up of the run. The name of this valve is a mix-up with a valve used for the vacuumpomp. The high temperature valve and the ball valve are taken to open at the same time while in reality the ball valve is opened shortly after the opening of the high temperature valve. Another assumption was that these valves open before valve V1 opens; Actually valve V1 opens after the high temperature valve and the ball valve are opened.

The maximum cross sections of the valves are taken to be the same as the cross sections of the components between which they are placed. Only the tank valve has a cross section which is much smaller because of the high pressure in the Ar-tank. The cross section of this tank valve is also taken to be constant. This cross section is calculated in such a way that the mass flow rate calculated with the initial conditions for the Ar-tank is equal to 4.8 kg/s.
7 Calculation results

The results for the calculation of the start-up of the flow train of the EBDF from \( t = 0 \) s to \( t = 15 \) s are shown in Fig 15 to 25. In Fig 15 to 22 the space distribution for different gasdynamic parameters are drawn. The time distribution for different gasdynamic parameters from \( t = 2 \) s to \( t = 15 \) s is shown in Fig 23 to 25.

In Fig 15 we can see the slow raise of mass flow rate along the flow train in 3 different moments between 0 and 2 sec. In Fig 19 we can see this process continuing for the time from 3 to 15 sec. it may be clear that it takes some time to fill the facility with Ar-gas. In our case this effect is probably stronger than in reality because we assumed a pipeline with a diameter too large.

Because we didn't know the cross-section of the tank valve we calculated a cross-section which would give a mass flow rate of 4.8 kg/s. Because of the decrease in pressure in the Ar-tank the mass flow rate through this valve slowly decreases in time.

Fig 16 and Fig 20 show the pressure along the flow train in the same moments as those for mass flow rate. These figures also show that it takes some time to build up pressure in the facility. Pressure drops strongly between subvolume 26 and 29. First cause for this is the nozzle placed between subvolume 28 and 29. However in the first moments pressure also drops because of our assumption that the high temperature valve (placed between 26 and 27) opens slowly. Because the valve is fully opened after 10 sec. after this moment pressure only decreases because of the nozzle (see Fig 20). Also we can see the occurrence of shock waves in the MHD-channel in this figure.

Fig 17 and Fig 21 clearly show the transition from subsonic to supersonic flow just downstream of the nozzle. Velocity rises rapidly and pressure and temperature (see Fig 22) decrease (thermal energy converting into kinetic energy). In the MHD-channel velocity increases and we can see the arise of shock waves.

The small rise in velocity just upstream of the nozzle is caused by the high temperature valve which is opening slowly while Ar-gas is already flowing in the facility. This means in the beginning of the run the cross-section of the valve is quite small which causes a pressure
drop and a rise of velocity at that place.

Fig 18 shows the density along the flow train. The distribution of density looks quite strange just after the beginning of the run (0 sec.). This is caused by our choice of the initial conditions of pressure and temperature. In the first and second sec. the highest density is of course near the Ar-tank. Again it is evident that because of the large volume of the pipeline it takes some time to fill the flow train of the facility.

The temperature distribution in Fig 22 clearly shows the heating of the gas in the heat-exchanger. Also we can notice some thermal shock waves in the MHD-channel. The temperatur downstream of the MHD-channel is obvious still quite high.

The slow increase of mass flow rate can be seen in Fig 23. In this figure the dynamic behaviour of mass flow rate in 4 different subvolumes is shown. Only in subvolume 2 (first subvolume of the pipeline) mass flow rate decreases. The cause for this is already explained before.

Fig 24 and Fig 25 show the behaviour of pressure and temperature in time for 4 different subvolumes. Interesting is the shape of pressure and temperature in subvolume 35 (MHD-channel); They have the same shape and also change on the same moments. Pressure in subvolume 57 (scrubber) is the pressure of the atmosphere. Temperature is still very high in this component and therefore the cooling with water in this component is quite understandable.
8 Conclusions

A numerical model for the simulation of the time dependent phenomena in the flow train of the Eindhoven Blow Down Facility is developed. This model is based on the calculation of the main gasdynamic parameters such as pressure, velocity, density, mass-, enthalpy- and momentum flow rates and enthalpy- and momentum losses in the different components of the EBDF. An empirical model for the description of the electrical parameters in the MHD-channel is used [3]. An improvement of this model was suggested which takes into account the influence of the unsteady propagation of cesium seed through the MHD-channel.

The numerical codes for a model which describes the gasdynamic behaviour in the flow train of an MHD-facility were developed in the Institute for High Temperatures USSR and used here. A lot of improvements to fit these codes to the problem of the calculation of the time dependent phenomena in the flow train of the EBDF were made. One of the main items was the simulation of the MHD-channel.

There has to be stated here that the resulted simulation is not a complete simulation of the Eindhoven Blow Down Facility. First of all we only simulated the first 15 sec. of the run. Second we can say now that some assumptions and therefore also some entry data appeared to be wrong. This is mainly caused by lack of information about the EBDF at that place at that moment.

However some interesting gasdynamic phenomena of the start-up of the facility can be seen e.g. filling with Ar-gas, transition from subsonic to supersonic flow near the nozzle and the shock waves in the MHD-channel.

As explained before the EBDF is a highly time-dependent installation with time constants in different time ranges caused by different gasdynamic phenomena. Further calculations with exact data can be more clear concerning the validity of the model. Also it can be interesting to compare the results with gasdynamic measurements of one or more runs of the facility.
References


### Table I: Parameters of Various Runs

<table>
<thead>
<tr>
<th>Run</th>
<th>T_0 (K)</th>
<th>P_a (bar)</th>
<th>mass flow (kg/s)</th>
<th>B (T)</th>
<th>R_L (ohm)</th>
<th>Cs (%)</th>
<th>(P_{th} ) (kW)</th>
<th>(P_{max} ) (kW)</th>
<th>(\eta_{ent} ) (%)</th>
<th>(N_2) (ppm)</th>
<th>(N_2) (ppm)</th>
<th>(CO_2) (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>303</td>
<td>1900</td>
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<td>5.1</td>
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<td>0.14</td>
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<td>0.11 - 0.20</td>
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a) estimated value
b) measurement strongly influences by impurities in the detection system
Fig 2 Subvolume with direction of flow rates
Fig 3 Division of the EBDF in subvolumes
Fig 5 Explanation of different cross sections
Fig 6 Schematic model of a streamer in a generator segment
Fig 7 Drawing of streamer schematically
Fig 9  $F_{is}$ as a function of streamer current $I_{s}$
Fig 10 Fis as a function of streamer current Is
Fig 11 Schematic side view of heat exchanger

Fig 12 Media flows in scrubber
Fig 13 Operation of valves
Fig 14 Assumptions about the places of valves
Fig. 15: Distribution of mass flow rate along flow train:  
1 - t = 0 s, 2 - t = 1 s, 3 - t = 2 s.
Fig. 16 Distribution of pressure along flow train:
1 - $t = 0$ s, 2 - $t = 1$ s, 3 - $t = 2$ s.
Fig. 17 Distribution of velocity along flow train:
1 - t = 0 s, 2 - t = 1 s, 3 - t = 2 s.
Fig. 18 Distribution of density along flow train: 
1 - $t = 0$ s, 2 - $t = 1$ s, 3 - $t = 2$ s.
Fig. 19 Distribution of mass flow rate along flow train:
1 - \( t = 3 \) s, 2 - \( t = 7 \) s, 3 - \( t = 11 \) s,
4 - \( t = 15 \) s.
Fig. 20 Distribution of pressure along flow train:
1 - $t = 3$ s, 2 - $t = 7$ s, 3 - $t = 11$ s, 4 - $t = 15$ s.
Fig. 21 Distribution of velocity along flow train: 
1 - t = 3 s, 2 - t = 7 s, 3 - t = 10 s, 
4 - t = 15 s.
Fig. 22 Distribution of temperature along flow train
1 - t = 3 s, 2 - t = 7 s, 3 - t = 11 s,
4 - t = 15 s.
Fig. 23 Time behaviour of mass flow rate:
1 – subv nr 2, 2 – subv nr 13
3 – subv nr 35, 4 – subv nr 57
Fig. 24 Time behaviour of pressure
1 – subv nr 2, 2 – subv nr 13
3 – subv nr 35, 4 – subv nr 57
Fig. 25 Time behaviour of temperature
1 – subv nr 13, 2 – subv nr 24,
3 – subv nr 35, 4 – subv nr 57.