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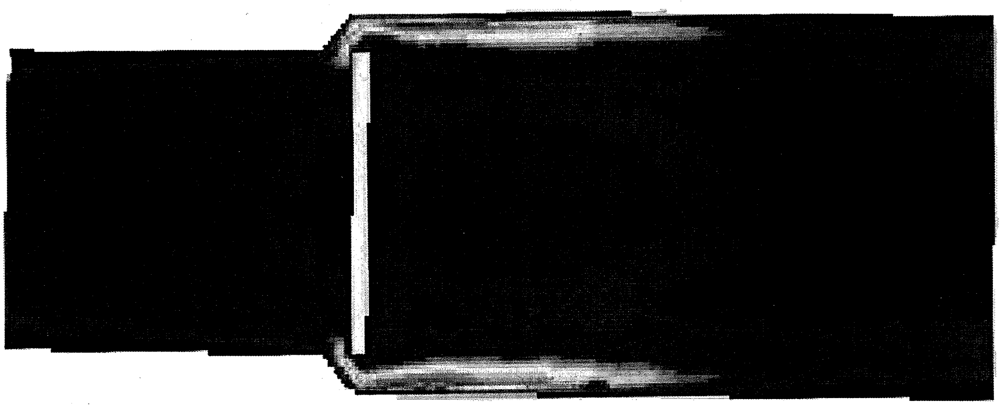

Overload Protection of a Wave Energy Converter

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List of Symbols

Roman Symbols

Symbol	Meaning	Unity
A_{flow}	The fluid cross sectional area around the piston	$[m^2]$
A_{piston}	The cross sectional area of the piston	$[m^2]$
C	Spring factor due to the power take-off system	$[kg/s^2]$
D	Damping factor due to the power take-off system	$[kg/s]$
F_{piston}	The force on the piston	$[N]$
F_{plate}	The force on a plate	$[N]$
c_w	Drag coefficient of a plate	[-]
d_{tube}	Diameter of a tube	$[m]$
f	Friction coefficient from the Moody-diagram	[-]
k	Pressure drop coefficients of butterfly valves	[-]
$k(x)$	Parameter to calculate the pressure drop depending on the position of the piston	[-]
l_{tube}	Length of a tube	$[m]$
m	Mass that is accelerated	$[kg]$
r_0	Radius in front of the diffusor	$[m]$
r_1	Radius behind the diffusor	$[m]$
r_p	Radius of the piston	$[m]$
r_y	Radius of the diffusor	$[m]$
v_0	Fluid velocity at the beginning	$[m/s]$
x	Position of the piston	$[m]$
$\dot{x}$	Velocity of the accelerated mass	$[m/s]$
$\ddot{x}$	Acceleration of the mass	$[m/s]$
y	Coordinate	[-]
z	Coordinate	[-]

Greek Symbol

Symbol	Meaning	Unity
α	Angle of the diffusor	[-]
β_2	Parameter to calculate the pressure drop in a conical valve	[-]
β_3	Parameter to calculate the pressure drop in a conical valve	[-]
$\delta p_{butterfly}$	Pressure drop in a butterfly valve	$[Pa]$
$\delta p_{conical}$	Pressure drop in a conical valve	$[Pa]$
$\delta p_{conti,diff}$	Pressure difference due to the continual equation	$[Pa]$
$\delta p_{drop,diff}$	Pressure drop due to the friction in a diffusor	$[Pa]$
$\delta p_{tot,diff}$	Pressure difference before and after the diffusor	$[Pa]$
δp_{tube}	Pressure drop in a tube	$[Pa]$
ρ	Density	$[kg/m^3]$
$\zeta_{conical}$	Parameter to calculate the pressure drop in a conical valve	[-]
ζ_{diff}	Parameter to calculate the pressure drop in a diffusor	[-]

Chapter 1

The Offshore Wave Energy Converter

1.1 Background

The need to combat global warming requires that a vast amount of new and sustainable energy must be found to replace the main polluting sources coming from the continued use of hydrocarbons as the main source of fuels. Renewable energy provides this and to date have concentrated largely on land based resources, such as wind, hydro and biomass. The amount of free land to exploit these resources is limited and mankind has chosen to find many other uses for the land which prevents it being used solely for the purpose of producing energy. Since approximately four fifths of the surface area of the earth is covered by ocean it seems strange that little significant progress has yet been made in Europe to harness ocean energy. Some research effort has been made but has generally been at a lower level compared to the funds made available for other renewable energy activity.

The annual electricity demand within the European Union is expected to rise by between 800 and 1500 TWh up to the year 2010 [sjoestroem]. The required growth could increase the dependence on imported fuels and this fact, together with environmental considerations, favours the development of indigenous and renewable energy resources.

One of the most promising sources which has wide availability is wave energy. Waves are created by the effect of wind blowing over the ocean surface and in the major oceans such as the Atlantic results in an enormous resource of wave energy arriving at the west coast of Europe. The total gross wave energy resource arriving at the coast of Europe is estimated to be about 1000 TWh annually [sjoestroem] , and could make a significant contribution to the energy budgets of these regions. Most renewable energy technologies have very few options for the principle of energy conversion. Wind energy requires a turbine which can be either horizontal or vertical axis, photovoltaics can utilize only limited materials and must be mounted in arrays, biomass requires chemical conversion or combustion for utilization and hydropower has limited options all based on turbines. Wave energy conversion by contrast has almost an infinite number of potential possibilities and still after a number of years of research the options are not clear for the optimum system. There are however a limited number of practical systems which are more mature and could be considered for further development.

1.2 Description of the Offshore Wave Energy Converter

One possibility to gain electric energy out of wave energy is the 'Offshore Wave Energy Converter' (OWEC). A wave energy converter of this type will utilize the wave movement only and is not influenced by tide or ocean currents. The water motion within a wave system is basically orbital. It will, however, give a buoy floating on the surface a nearly clean vertical motion. The 'Interproject Service' System (IPS) is based on this phenomenon and has a circular or oval buoy A. It is held in position by an elastic mooring system enabling it to move freely up and down against a damping water mass contained in a long vertical open tube - the acceleration tube - underneath the buoy. The relative movement between the buoy itself and the water mass is transferred by a working piston C into an energy conversion system D which in turn will drive a generator E (figure 1.1). When there is no vertical movement, the piston is held by an hydraulic system in the middle of the acceleration tube.

To protect the OWEC System against overloading in case of high waves the piston moves out of the narrow central part of the acceleration tube. Water can bypass the piston (area F) and damage is avoided (figure 1.2). The system can be damaged, if the piston does not stop its movement within a short distance to the central part of the acceleration tube (area C). The movement back into the area C can't cause any damage. Therefore just the movement out of the acceleration tube is considered in this study.

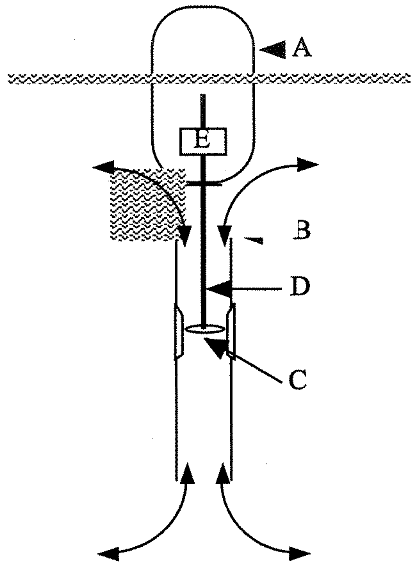

Figure 1.1: The IPS wave energy converter

The task is to find out the force on the piston while moving out of the acceleration tube depending on the position of the piston. In the beginning other technical instruments used for hydraulic systems with similar geometry were looked upon. Conclusions were drawn regarding the force on the piston as a function of the position of the piston (chapter 2.1 and 2.2). In order to consider the movement of the piston depending on the flow velocity in the acceleration tube an equation was formulated and solved (chapter 2.4). To verify the found solutions the fluid flow in the OWEC was simulated with FLUENT5. The force on the motionless piston in different positions could be calculated (chapter 3.5). Using the results of the FLUENT5 solution the equation describing the motion was solved again and the force on the moving piston was simulated (chapter 3.5.2).
Finally the solutions are compared in chapter 4.

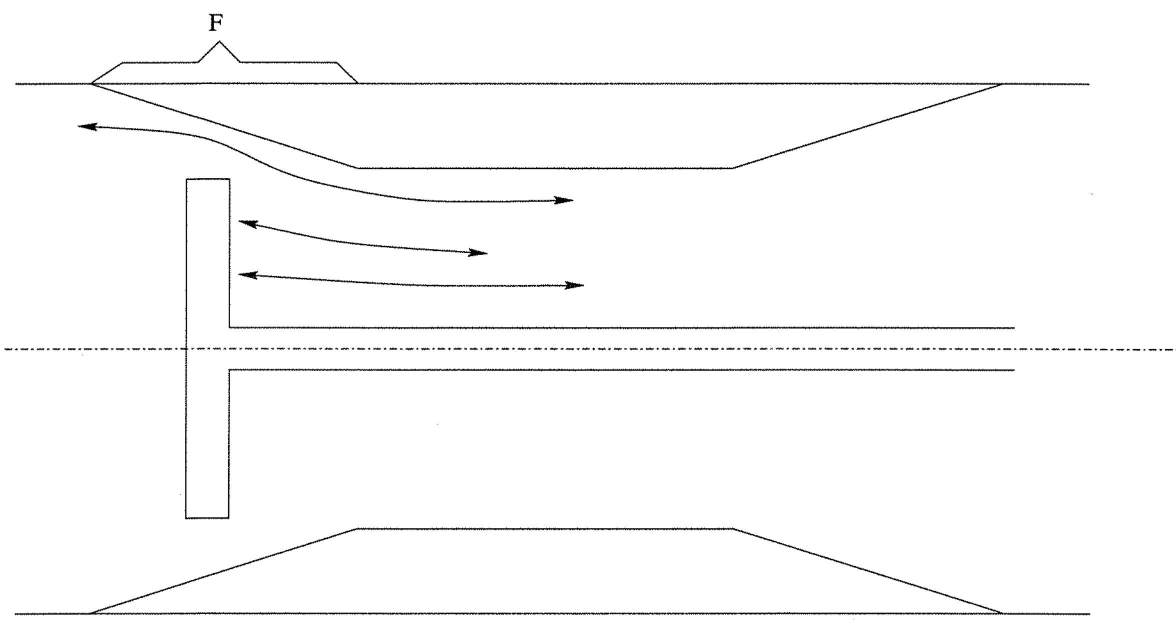

Figure 1.2: The fluid flow passing the piston

Chapter 2

The force on the piston

In order to calculate the force on the piston depending on the shape of the OWEC the pressure drop of the water passing the piston through an annulus are compared with pressure drop in different kind of valves. In the beginning the movement of the piston is not considered. If the shape of the geometry, especially of the annulus, is similar the fluid flow and therefore the pressure drop can be compared. As the flow area during the opening or closing process of a butterfly valve or conical valve are quiet similar to the area of the piston passing the diffusor, it can be assumed that the pressure drop behave similarly in these devices (chapter 2.1 and 2.2). For these valves previous research was done and parameters to calculate the pressure drop are known. The influence of the diffusor is considered in chapter 2.3. After this a differential equation is set up in order to consider the movement of the piston (chapter 2.4).

2.1 The butterfly valve

In order to compare the fluid flow through a valve with the fluid motion in the OWEC, the following assumption was made:
The buoy and the tube are fixed in relation to each other. The piston can move relative to the tube and the buoy. Surface waves force the buoy, and therefore also the tube, to oscillate in the vertical direction. The water mass in the tube is moved less by the waves due to its submerged position. Therefore the piston is forced more or less by that water mass not to oscillate with the buoy. Summing up, the piston and the tube nearly follow the wave motion, the water mass and the piston move less. When comparing the fluid flow with the flow through a valve, the used coordinate system is moving with the tube and the buoy (figure 2.4). Relative to this coordinate system the piston moves at the velocity of the oscillating OWEC.

A butterfly valve was found to exhibit similar flow as the piston leaving the acceleration-tube. A typical butterfly valve is shown in figure 2.1 as well as the area while opening the valve (figure 2.2).

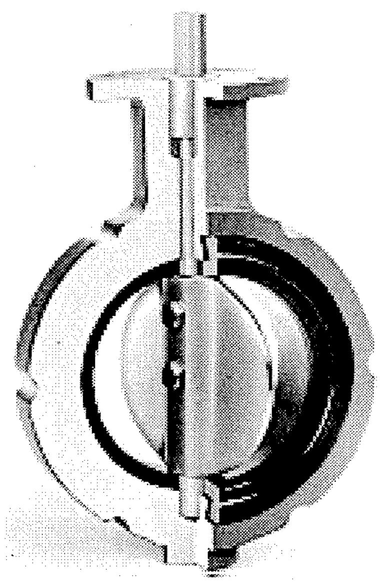

Figure 2.1: A butterfly valve

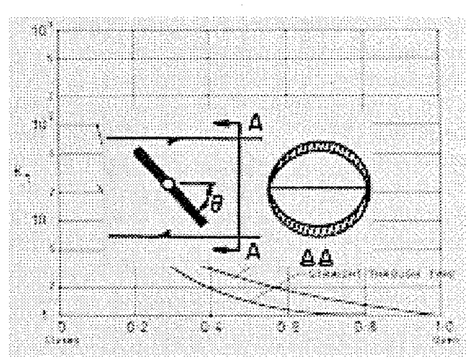

Figure 2.2: The flow-area of a butterfly valve while opening

The pressure drop in a butterfly valve can be expressed by a head drop coefficient k defined by equation 2.1. The effect of a partial opening on the pressure drop coefficient k of butterfly valves is shown in figure 2.3 [Zappe 1981].

$$\delta p_{butterfly} = k \frac{\rho v_0^2}{2} \tag{2.1}$$

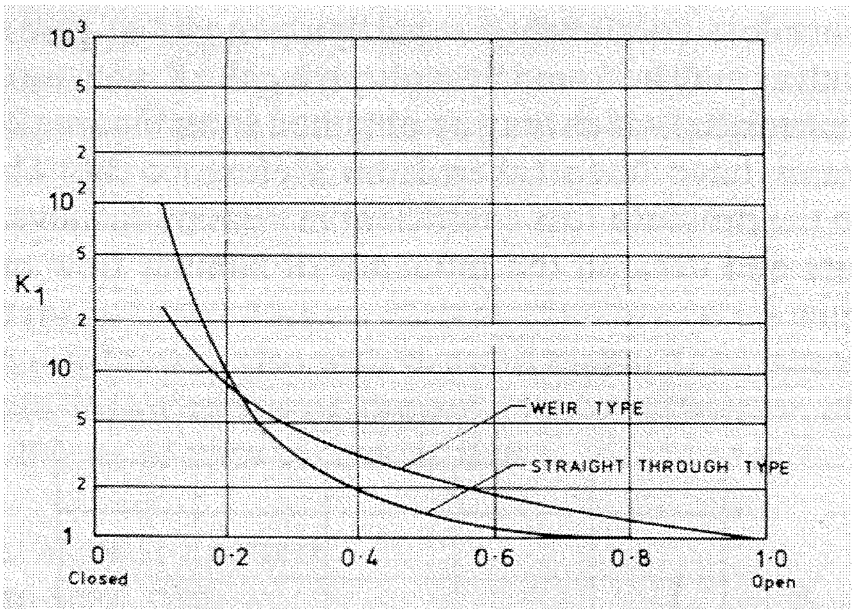

Figure 2.3: The k-value depending on the area opened

The coefficient k is now used in order to calculate the pressure drop of the fluid passing the piston in the diffusor. The area, through which the water passes the piston, the flow-area, depends on the position of the piston. Therefore the coordinates x and y are introduced (figure 2.4).

The flow-area of the fluid passing by the piston can be calculated using formula 2.2.

$$\begin{aligned} A_{flow} &= \int_{r_p}^{r_y} 2\,\pi\, z\, dz \\ &= \int_{r_p}^{r_y} 2\,\pi\, \cos\alpha\, y\, dy \\ &= 2\,\pi\, \cos\alpha \int_{r_p}^{r_y} y\, dy \end{aligned} \tag{2.2}$$

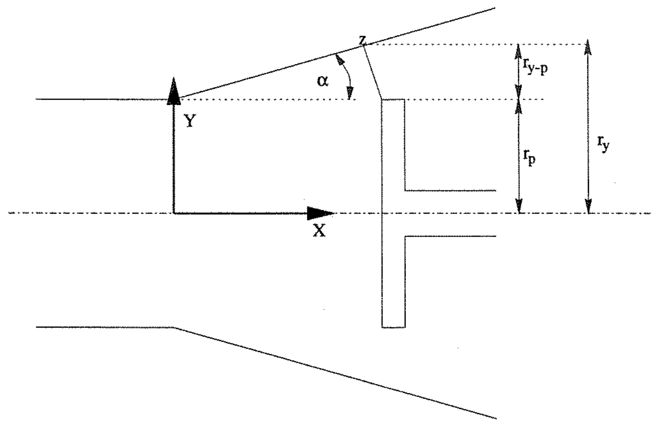

Figure 2.4: Coordinates to define the position of the piston

$$
\begin{aligned}
&= \pi\, \cos\alpha\, (r_y^2 - r_p^2) \\
&= \pi\, \cos\alpha\, (r_{y-p}^2 + 2\, r_p\, r_{y-p}) \\
&= \pi\, \cos\alpha\, (x^2\, \tan^2\alpha + 2\, r_p\, x\, \tan\alpha)
\end{aligned}
$$

As the valve coefficient k allows us to calculate the pressure drop in a butterfly valve, and the fluid flow is assumed to be similar in this energy converter, k-values for the OWEC are calculated with MATLAB, depending on the position of the piston (figure 2.5).

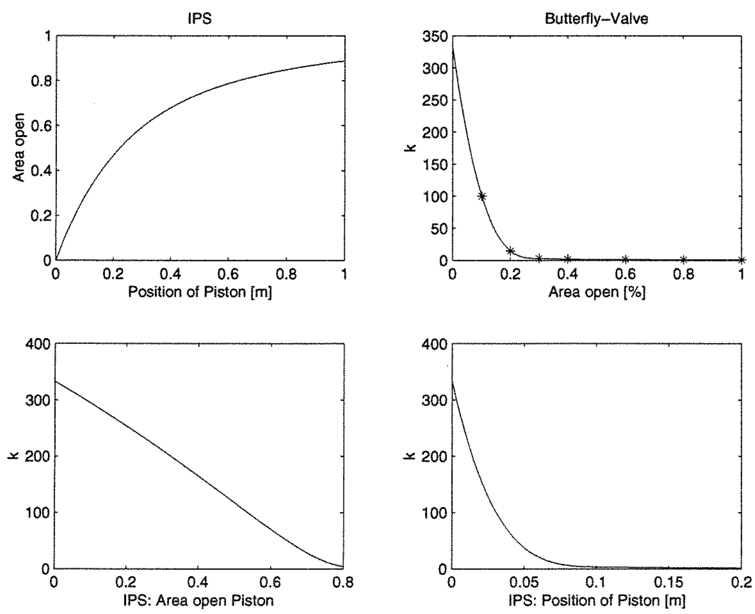

Figure 2.5: The k-value of the piston depending on the position of the piston with α=45^o

Knowing the pressure drop coefficient k for the piston in the diffusor the pressure drop over the piston can be calculated depending on the fluid velocity. With the equation 2.3 the force on the piston is known. This force depends besides of the fluid velocity on the size of the piston. Therefore figure 2.6 shows the results of equation 2.3 for the radius r_p=0.4 m and 0.5 m as well as the velocities v_0=0.5 m/s or 1 m/s.

$$\begin{aligned} F_{piston} &= A_{piston}\,\delta p_{butterfly} \\ &= \pi\, r_p^2\,\delta p_{butterfly} \end{aligned} \tag{2.3}$$

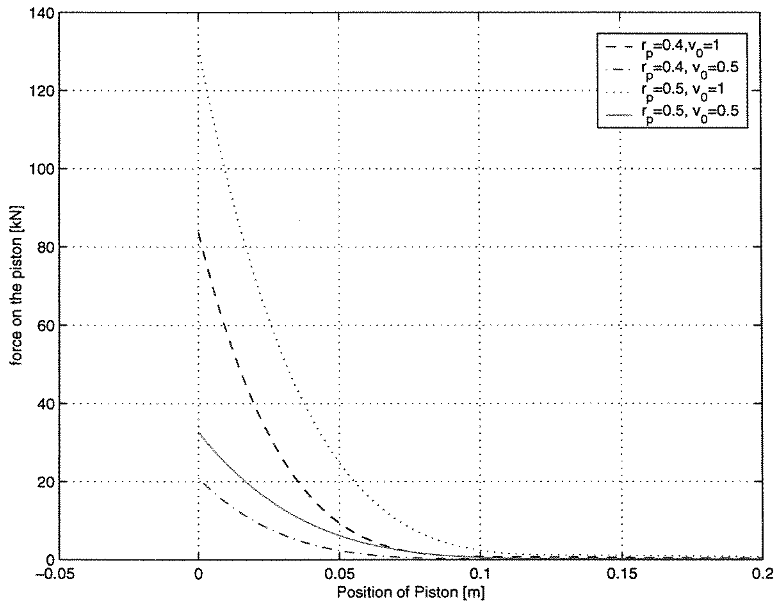

Figure 2.6: Force on the piston calculated with k values of a butterfly valve

2.2 The conical valve

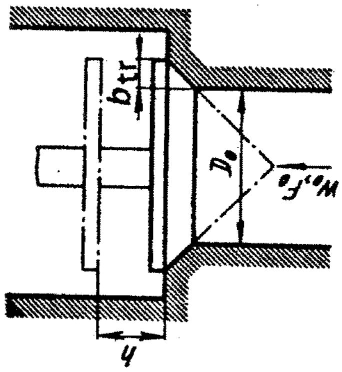

Figure 2.7: A conical valve

Figure 2.7 shows a conical valve. The pressure drop can be calculated with equation 2.4 depending on the position of the plate. The equation is valid within $0.1 \leq h/D \leq 0.25$.

$$\begin{aligned} \delta p_{conical} &= \zeta_{conical} \frac{\rho v_0^2}{2} \\ &= (2.7 - \beta_2 + \beta_3) \frac{\rho v_0^2}{2} \end{aligned} \tag{2.4}$$

h/D	0.1	0.12	0.14	0.16	0.18	0.2	0.22	0.24	0.25
β_2	8.00	6.66	5.71	5.00	4.44	4.00	3.63	3.33	3.20
β_3	14.0	9.73	7.15	5.46	4.32	3.50	2.90	2.43	2.24

Table 2.1: Parameters to calculate the pressure drop in a conical valve [Idelchik 1986]

The force on the piston is calculated with equation 2.5 and is shown in figure 2.8. The program for these calculations is shown in appendix B.1.

$$\begin{aligned} F_{Piston} &= A_{Piston}\, \delta p_{conical} \\ &= \pi\, r_p^2\, \delta p_{conical} \end{aligned} \tag{2.5}$$

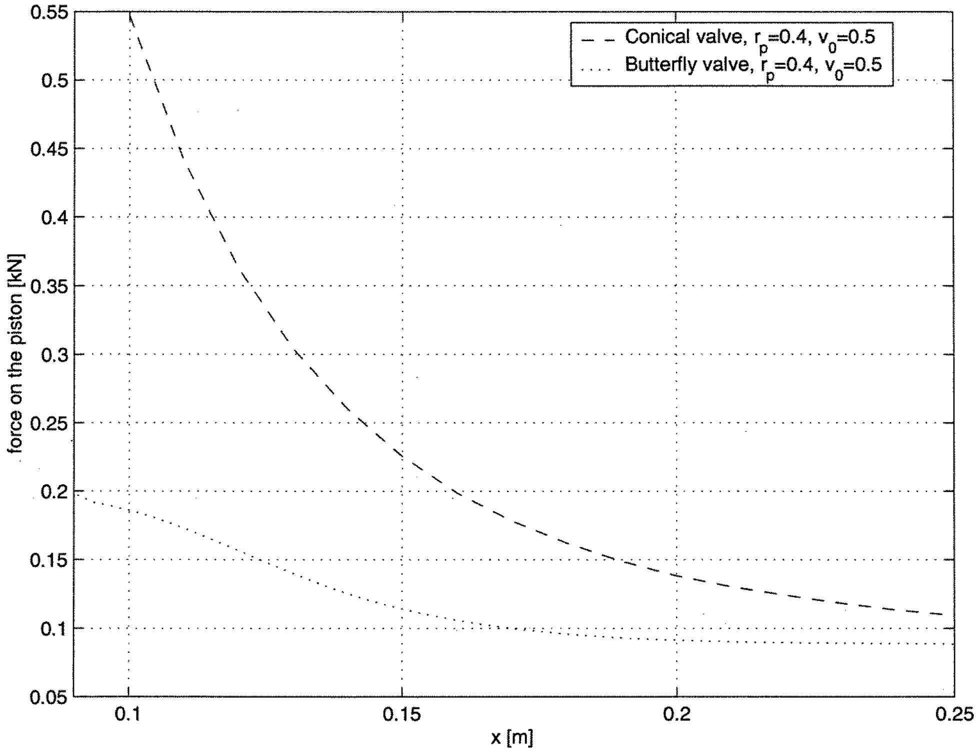

Figure 2.8: Force on the piston calculated with $\zeta_{conical}$

2.3 The pressure drop in a diffusor

There is also pressure drop in a diffusor, which is well known. Relating to literature like [Idelchik 1986] the pressure drop in a diffusor can be calculated with formula 2.6

$$\delta p_{drop,diff} = \zeta_{diff} \frac{\rho v_0^2}{2} \tag{2.6}$$

For a diffusor the values of ζ_{diff} are interpolated depending on the diffusor-angle as well as on the Reynolds number. This is shown in figure 2.9.

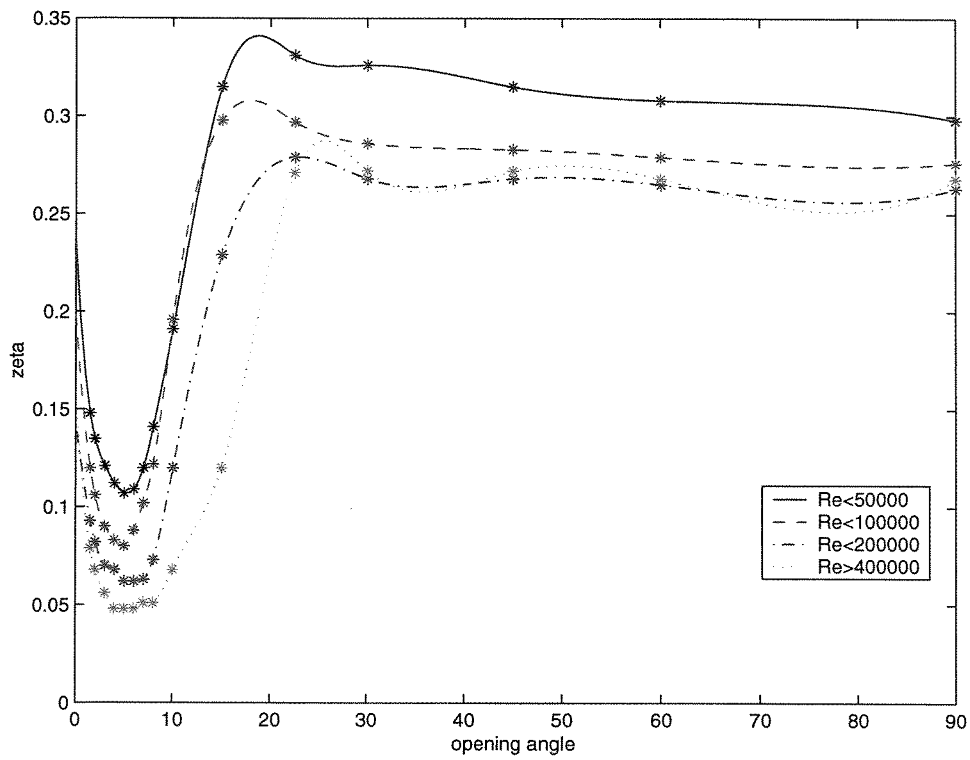

Figure 2.9: The parameter ζ_{diff} depending on the angle of the diffusor

The pressure drop depending on the angle of the diffusor is shown in figure 2.10.

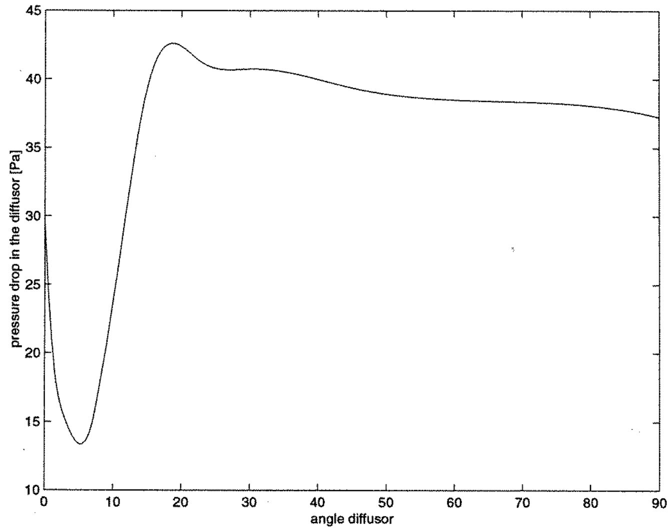

Figure 2.10: Pressure drop in a diffusor with v_0=0.5m/s and r_0=0.4m

As ζ_{diff} depends on Reynolds, therefore on the velocity v_0 as well as the radius r_0 in front of the diffusor, these sizes have to be known in order to find the right value of ζ_{diff}. To compare the size of the pressure drops the same values for v_0 as well as r_p are chosen again. The results are shown in table 2.2.

	r_p = 0.4m		r_p = 0.5	
-	v_0=0.4	v_0=0.5	v_0=0.4	v_0=0.5
Pressure drop [Pa]	15.28	23.875	15.28	23.875

Table 2.2: The pressure drop in a diffusor, $\alpha = 10°$

This pressure drop due to the diffusor is very small, compared with the pressure drop over the piston.
In order to show the influence of the angle of the diffusor three-dimensional graphics were calculated. In figure 2.11 the force on the piston depending on the position of the piston as well as the angle of the diffusor is shown. The pressure drop in the diffusor reduces the total force minimally. The program for these calculations is listed in appendix B.2.

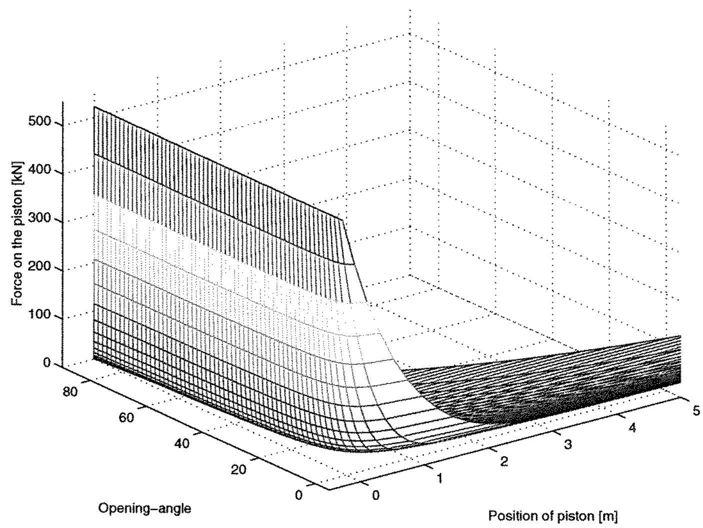

Figure 2.11: The force on the piston with r_p=0.4 and v_0=0.5

2.4 The movement of the piston

The working area of the piston is limited by the diffusor. This is to avoid damage to the power takeoff system in case of high waves. Actually the system can be damaged, if the piston does not stop after moving out of the diffusor. Therefore this movement is calculated, establishing the differential equation 2.7. The known coefficient for the pressure drop in a butterfly valve is then used to calculate the force on the piston.
To set up the differential equation some simplifications are made. The water is supposed to flow through the tube and to push the piston. When the piston enters the diffusor the water will start to flow through the annulus; the force on the piston will then decrease until the piston stops. In order to solve the differential equation the coefficient k of the butterfly valve is interpolated. The butterfly valve is chosen as the coefficient k is known over a wide range. This coefficient is not supposed to decrease below 1.11, as this is the drag coefficient of a round plate in a fluid flow. Just when the piston is leaving the working area, it has the same velocity as the water in the working area. Therefore, just in this moment, the relative velocity between the piston and the flowing water is zero, but it increases, as the piston begins to stop.

$$m\ddot{x} = k(x)\, A_{piston}\, \frac{\rho}{2}\, (v_0 - \dot{x})^2 - D\,\dot{x} - C\,(a + x) \tag{2.7}$$

$\mathrm{m} = 267.6\,\mathrm{kg}$

$\mathrm{D} = 3\,\frac{N\,s}{m}$

$\mathrm{C} = 9000\,\frac{N}{m}$

$\mathrm{a} = 1\,\mathrm{m}$

The accelerated mass m is the mass of the piston, of the piston rod, the part of the accelerated gear unit and the surrounding water of the piston that is accelerated. Even if the piston itself is a hollow body filled with air and the mass of the piston is nullified by its boost, it still has to be accelerated. If the piston is moving in the working area, the whole water mass in the cylinder has to be accelerated. But if the piston moves in the diffusor, the water can pass the piston through the annulus.

Therefore just the surrounding water of the piston is accelerated with the piston and considered in this calculation.
The damping factor D as well as the spring constant C is given by the power takeoff system. The value a is introduced in order to have a force coming from the spring constant when the piston leaves the acceleration area.

The solution of the differential equation with a fluid velocity of 1 m/s is shown in figure 2.12 and 2.13. The solution of the differential equation with a fluid velocity of 0.5 m/s is shown in figure 2.14 and 2.15.

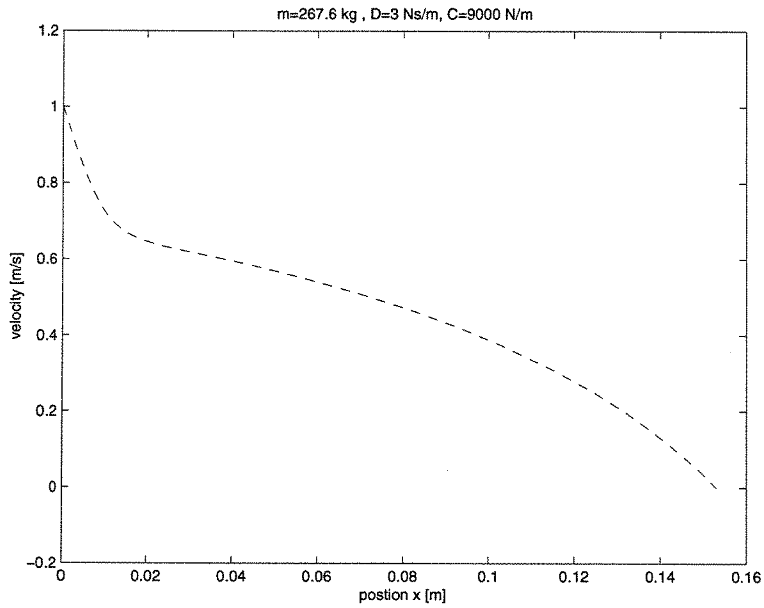

Figure 2.12: The velocity of the piston depending on the position of the piston with a fluid velocity of 1 m/s

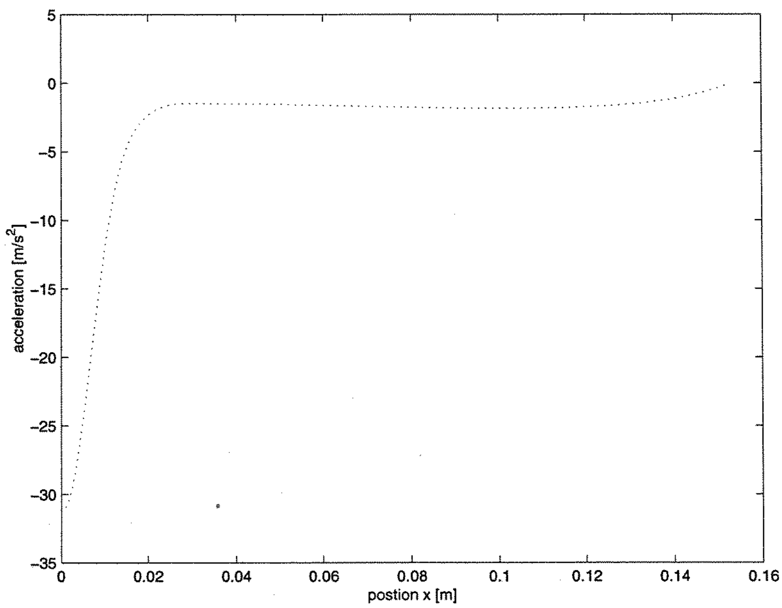

Figure 2.13: The acceleration of the piston depending on the position of the piston with a fluid velocity of 1 m/s

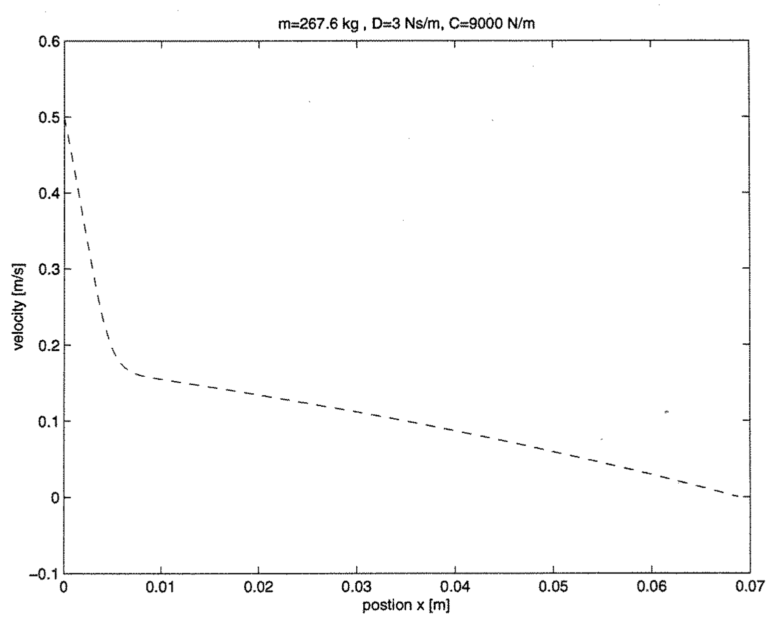

Figure 2.14: The velocity of the piston depending on the position of the piston with a fluid velocity of 0.5 m/s

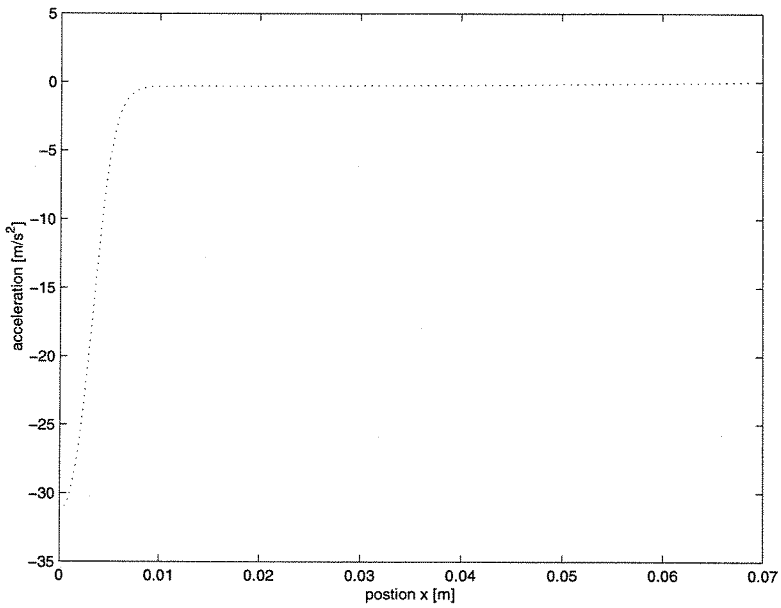

Figure 2.15: The acceleration of the piston depending on the position of the piston with a fluid velocity of 0.5 m/s

Chapter 3

Numerical Calculation

3.1 Description of FLUENT5

In order to verify calculations in chapter 2 the fluid flow in the OWEC is calculated with FLUENT5. FLUENT5 is a software package to simulate fluid dynamics. In order to do that, first of all the geometry has to be created as a model. FLUENT5 allows a large series of CAD-Packages to create the Geometry. In this case, the geometry and the mesh are made by GAMBIT (section 3.1.1). After that FLUENT5 can read the case. Before starting a simulation the grid has to be checked. In case of negative volumes the volume has to be meshed again. One can chose between the segregated and the coupled solver (section 3.1.2). There are different kind of models in order to simulate the fluid flow (section 3.1.3). The operating pressure has to be set. In order to set for example the velocity at the velocity inlet, the velocity of a moving wall or the pressure at a pressure outlet the boundary conditions have to be set accordingly. The discretisation equations have to be chosen (section 3.1.3) for the convection terms of each governing equation.
In order to prove the results calculated with FLUENT5, geometrically simple models were built (section 3.2, 3.3 and 3.4). The pressure drop in these models could be calculated due to known parameter and be compared with results calculated with FLUENT5. Finally the OWEC was built as a model and the force on the piston calculated with FLUENT5 (section 3.5 and section 3.5.2).

3.1.1 Gambit

With GAMBIT the geometry is made and has to be meshed. GAMBIT allows also to create the mesh. It is important to have a good mesh of the geometry, otherwise

FLUENT5 will not be able to solve the case properly. The number of cells has to be chosen well. It is a question of the space capacity of the PC or Workstation and of the time for solving, because more time is needed for more cells. The quality of the mesh has to be good, too. This means the volume or the shape of the meshes should not change too roughly and the mesh has to be fine enough. After meshing the Geometry the boundary-conditions have to be chosen. Finally FLUENT5 can read the case.

3.1.2 The different solvers

FLUENT5 offers two different kind of solvers:

- Segregated Solver
- Coupled Solver

The segregated and the coupled solver have different approaches for the resolution of the coupled continuity, momentum and energy equations. The segregated solver calculates the equations sequentially, while the coupled one solves them simultaneously. In this case the segregated solver was chosen.

3.1.3 The different simulation models

For the considered velocities the flow in the OWEC is turbulent. Therefore turbulent models are necessary in this work and the used ones are described in the following.

The k-ϵ Model

The simplest model of turbulence are two-equation models. The model transport equation for k is derived from the exact equation, while the model transport equation for ϵ is obtained using physical reasoning. It is a little different to its exact mathematical counterpart. In FLUENT5 there exist three different k-ϵ Models:

- Standard k-ϵ Model
- RNG k-ϵ Model
- Realizable k-ϵ Model

For the standard k-ϵ Model the turbulent kinetic energy, k, and its rate of dissipation, ϵ, are obtained from the following transport equations:

$$\rho\frac{Dk}{Dt} = \frac{\delta}{\delta x_i}[(\mu + \frac{\mu_t}{\sigma_k})\frac{\delta k}{\delta x_i}] + G_k + G_b - \rho\epsilon - Y_M \tag{3.1}$$

$$\rho\frac{D\epsilon}{Dt} = \frac{\delta}{\delta x_i}[(\mu + \frac{\mu_t}{\sigma_k})\frac{\delta \epsilon}{\delta x_i}] + C_{1\epsilon}\frac{\epsilon}{k}(G_k + C_{3\epsilon}G_b) - C_{2\epsilon}\rho\frac{\epsilon^2}{k} \tag{3.2}$$

The term G_k represents the production of turbulent kinetic energy due to the mean velocity gradients:

$$G_k = -\rho\,\overline{\mu_i\,\mu_j}\frac{\delta\,\mu_j}{\delta\,x_i} \tag{3.3}$$

G_b is the generation of turbulence due to the buoyancy. The buoyancy is not included in the models of this work. To account for the effect of high Mach-numbers the dilatation dissipation term, Y_M, is included in the k-equation; but is not of interest for the OWEC.

The Reynolds Stress Model

The Reynolds Stress Model (RSM) is the most elaborate turbulence model that FLUENT5 provides. The RSM closes the Reynolds-averaged Navier-Stokes equation by solving transport equations for the Reynolds stresses, together with an equation for the dissipation rate. Therefore seven additional transport equations are required in 3D flows.

$$LTD + I_{ij} = D^T_{ij} + D^L_{ij} - P_{ij} - G_{ij} + \phi_{ij} - \epsilon_{ij} - F_{ij} \tag{3.4}$$

LTD : Local Time Derivative

C_{ij} : Convection

D_{ij}^T : Turbulent Diffusion

D_{ij}^L : Molecular Diffusion

P_{ij} : Stress Production

G_{ij} : Buoyancy Production

ϕ_{ij} : Pressure Strain

ϵ_{ij} : Dissipation

F_{ij} : Production by System Rotation

For the exact Equations see the FLUENT5 Manual Pages [Fluent 1998].

Discretisation

FLUENT5 uses a control-volume-based technique to convert the governing equations to algebraic equations that can be solved numerically. This control volume technique consists of integrating the governing equations about each control volume, yielding discrete equations that conserve each quantity on a control-volume basis.
Discretisation of the governing equations can be illustrated most easily by considering the steady-state conservation for transport of a scalar quantity ϕ. This is demonstrated by the following equation written in integral form for a control volume V as follows:

$$\oint \rho \phi v \, dA = \oint \Gamma_\phi \Delta \phi \, dA + \int_V S_\phi \, dV \tag{3.5}$$

ρ : density

v : velocity vector

A : surface area vector

Γ_ϕ : diffusion coefficient for ϕ

$\Delta \phi$: gradient of ϕ

S_ϕ : source of ϕ per unit volume

Equation 3.5 is applied to each control volume, or cell, in the computational domain. FLUENT5 stores discrete values of the scalar ϕ at the cell centers. However, the face values ϕ are required for the convection terms, the equation 3.5 must be interpolated from the cell center values. This is accomplished using an upwind scheme. Upwind means that the face value ϕ is derived from quantities in the cell upstream, or "upwind", relative to the direction of the normal velocity v_n. FLUENT5 allows to choose from several upwind schemes: first order, second order, power law and QUICK.

3.2 The pressure drop in a tube

The pressure drop of a fluid flow in a tube can be calculated according to the Moody-diagram [Haeggstroem 1988].

$$\delta p_{tube} = f \, \frac{l_{tube}}{d_{tube}} \, \frac{\rho}{2} \, v_0^2 \tag{3.6}$$

The friction coefficient f depends on Reynolds number and the relative roughness of the pipe and can be taken from the Moody-diagram (figure 3.1).

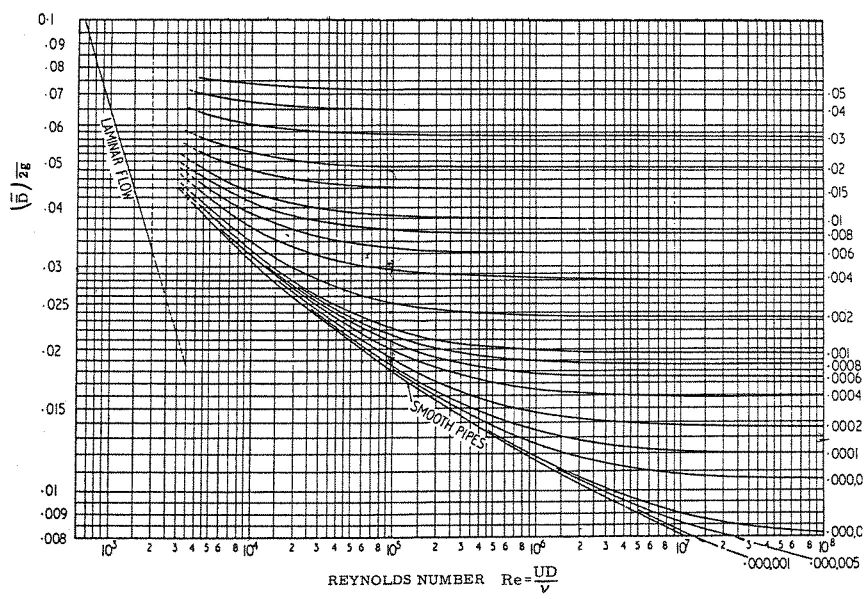

Figure 3.1: The Moody-diagram

For a horizontal pipe with a diameter of 0.8 m the pressure drop per meter depending on the Reynolds number was calculated. The results are shown in table 3.1. In order to simulate the pressure drop with FLUENT5, a 40m long tube was simulated. The length of 40m was taken in order to be sure, that the turbulence in case of turbulent flow is fully developed. The pressure drop was regarded at 35 meters over a length of one meter. Table 3.1 and diagram 3.2 show the results for the pressure drop calculated according to the Moody-diagram and simulated with FLUENT5. Changes in the simulation model were made in order to find out the influences they make on the simulated pressure drop. These changes are shown in appendix A.1. Mentionable is the pressure drop at a velocity of 0.005 m/s. It is not known, if the flow is turbulent or laminar. In this case a laminar model was used simulating with FLUENT5. However, to calculate the right pressure drop in this case is very complicated.

fluid velocity [m/s]	pressure drop calculated with moody [Pa/m]	pressure drop calculated with FLUENT5 [Pa/m]	difference [%]
0.001	0.0000561	0.000054	3.83
0.005	0.000468	0.00035	25.2
0.05	0.03431	0.034	0.912
0.5	2.18356	2.2	0.752
2	27.4505	27.2	0.9125

Table 3.1: The pressure drop per meter in a smooth pipe

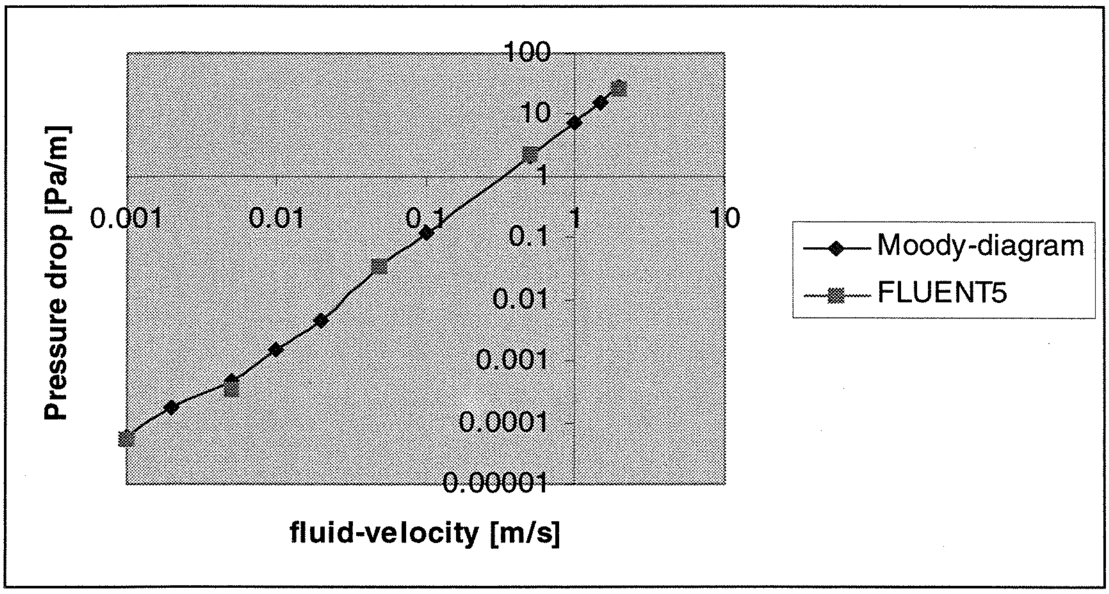

Figure 3.2: The pressure drop calculated according to the Moody-diagram and with FLUENT5

3.3 The pressure drop in a diffusor

About the pressure drop in a horizontal diffusor enough research has been done, so the pressure drop can be calculated with the known coefficient ζ_{diff} (equation 3.8). As the fluid flow decelerates the static pressure increases (equation 3.9).

$$\delta p_{tot,diff} = \delta p_{conti,diff} - \delta p_{drop,diff} \tag{3.7}$$

$$\delta p_{drop,diff} = \zeta_{diff} \, \frac{\rho}{2} \, v_0^2 \tag{3.8}$$

$$\delta p_{conti,diff} = \frac{\rho}{2} \, v_0^2 \, (1 - \frac{r_0^4}{r_1^4}) \tag{3.9}$$

In order to simulate the fluid flow in a diffusor with FLUENT5, the geometry and the mesh were built with Gambit and part of it is shown in picture 3.3. The velocity-field with a entrance velocity of 1 m/s is shown in figure 3.4.

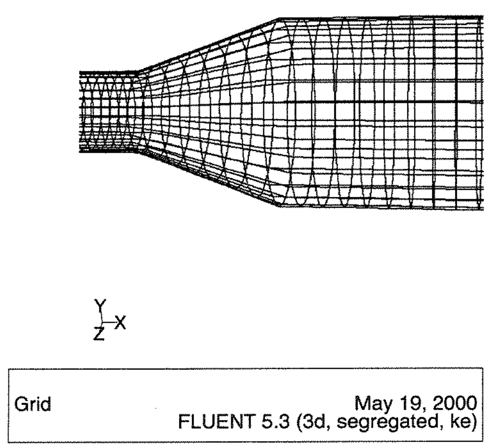

Figure 3.3: The geometry and the mesh of the diffusor

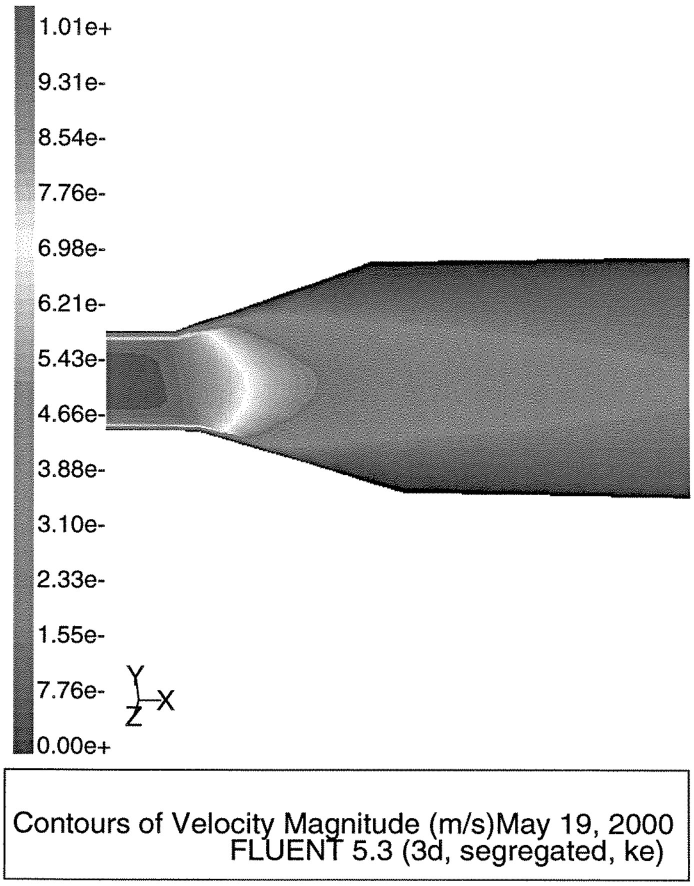

Figure 3.4: The velocity-field in the diffusor

The pressure difference calculated by equation 3.7 to 3.9 can be compared with the pressure difference simulated with FLUENT5 (table 3.2 and diagram 3.5).

In figure 3.4 the velocity-field is not symmetrical even if the geometry as well as the grid are. Probably this is caused by some unsteadiness in the three dimensional model.

fluid	pressure drop calculated		difference
velocity [m/s]	with ζ_{diff} [Pa]	with FLUENT5 [Pa]	[%]
0.1	3.345	3.2	4.546
0.5	80.49	83	3.021
1	339.5	360	6.529
2	1293.1	1450	10.823

Table 3.2: The pressure drop in a diffusor

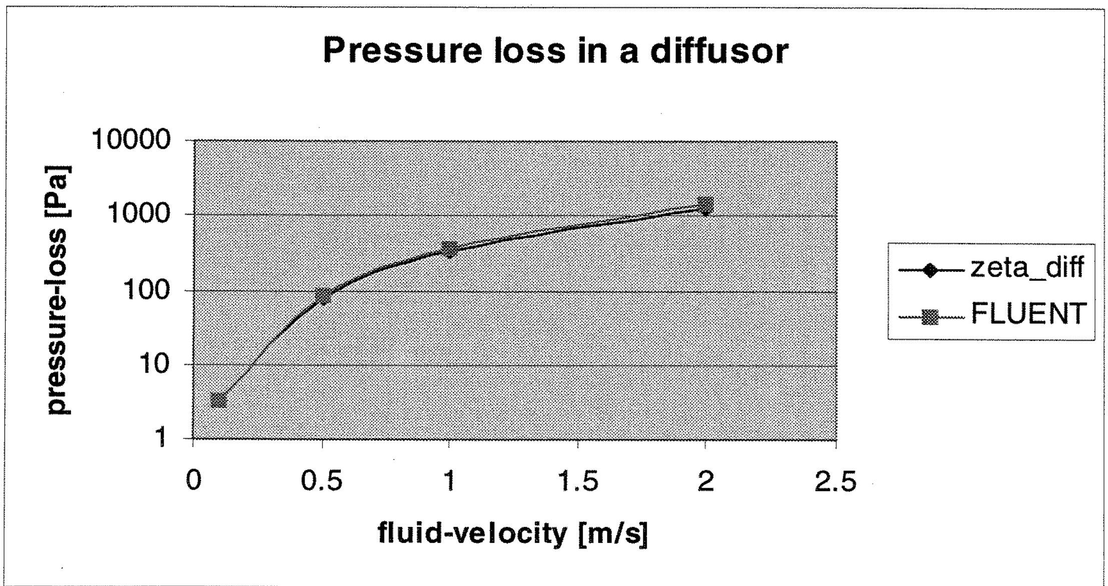

Figure 3.5: The pressure drop calculated according to ζ_{diff} and with FLUENT5

3.4 A plate in fluid flow

According to literature [Beitz 1995] the force on a plate in a fluid flow is nearly independent of the Reynolds number and can be calculated by formula 3.10.

$$\begin{aligned} F_{plate} &= c_w \frac{\rho}{2} v_0^2 \\ &= 1.1 \frac{\rho}{2} v_0^2 \end{aligned} \tag{3.10}$$

The force on a plate in a fluid flow was also simulated with FLUENT5. Quite a lot of efforts were made to get near the results calculated according to literature [Beitz 1995]. The influences of following calculations were checked in order to find out, in which case the best results are simulated.

- k-ϵ -model and RSM
- the distance y+ of the nodes to the wall
- the effect of surrounding walls
- the effect of the wall-functions
- the size of the grid
- the different kind of discretisations

The velocity-profile for that case, that the entrance velocity is 1 m/s, is shown in figure 3.6. Some of the results of the different simulations are shown in table 3.3. Changes made in the model were used for the next model again. The surface "face", where the value of y+ was refined, is the ringsurface of the plate. All results are found in appendix A.3.

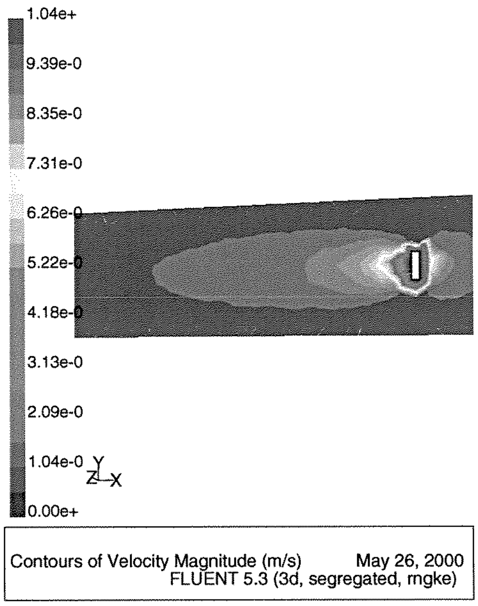

Figure 3.6: The value of the velocity around the plate, entrance velocity: 1m/s

radius piston in [m]	fluid velocity [m/s]	Force on the plate calculated with c_w [N]	FLUENT5 [N]	Models [%]
0.1	1.0	17.4	31.8	k-ϵ -model
0.1	1.0	17.4	30.8	k-ϵ -model, y+=610
0.1	1.0	17.4	23.1	k-ϵ -model, face y+=100
0.1	1.0	17.4	21.1	k-ϵ -model, RNG,
0.1	1.0	17.4	20.7	k-ϵ -model, RNG, 2. order discret.
0.1	1.0	17.4	18.6	RSM, 2.order discret. Y+=100

Table 3.3: Force on a plate

3.5 The force on the piston in the OWEC

This chapter is divided into two parts. First of all the force on the piston is calculated depending on the geometry, the fluid velocity and the position of the piston (chapter 3.5.1), but not considering the movement of the piston. A coefficient k(x) was calculated according to the butterfly valve. After that the differential equation was solved. The velocity of the piston depending on the position is then approximately known. The simulation was started again, considering the movement of the piston (chapter 3.5.2).

3.5.1 The force on the stillstanding piston

A three dimensional model of the OWEC was built and meshed with GAMBIT. The geometry as well as the sizes of the OWEC were chosen as follows:

- $r_1 = 0.4\,\mathrm{m}$
- $r_2 = 0.5\,\mathrm{m}$
- $\alpha = 45°$

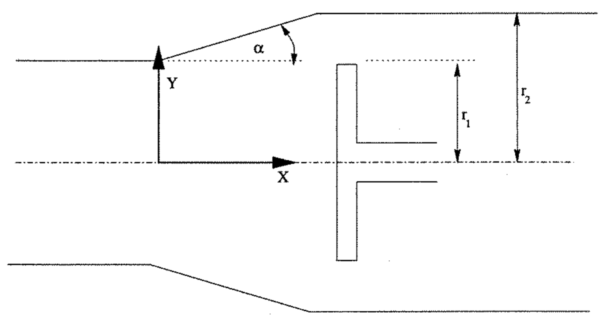

Figure 3.7: The model of the OWEC

In order to calculate the force on the piston depending on the position of the piston several different models were built. The mesh of the model with the piston situated 10 cm behind the beginning of the diffusor is shown in figure 3.8.

As the RSM calculated better solutions for the force in a fluid flow than the k-ϵ-model both models were used to calculate the force on the piston. The RSM did not converge every time. However, simulating in FLUENT5 the following settings were made every time:

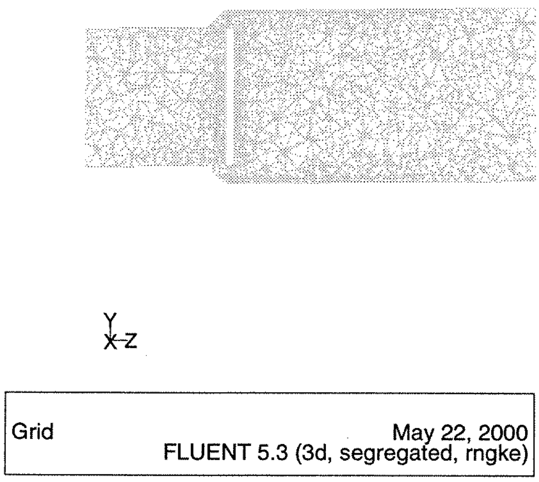

Figure 3.8: The mesh of the OWEC

- The distance y+ was chosen to be under 500.
- At the ring-surface of the piston y+ was refined to be between 50 and 200.
- A second order discretisation scheme was selected in all cases.
- Calculating with the k-ϵ-model the RNG model was selected.

The results of the simulations calculating with the k-ϵ-model are shown in table 3.4 and in figure 3.9 and 3.10. All the results are shown in the appendix A.4. The fluid field and the direction of the flow are shown in figure 3.11 and figure 3.12.

position piston in [m]	fluid velocity [m/s]	force on the piston [N]	parameter k(x) [-]
0.02	0.5	20130	321
0.04	0.5	4692	74.8
0.06	0.5	2173	34.7
0.08	0.5	1238	19.7
0.10	0.5	865	13.8
0.15	0.5	567	9.04
0.20	0.5	473	7.54
0.02	1.0	88075	351
0.04	1.0	20310	80.9
0.06	1.0	8528	34.0
0.08	1.0	4836	19.28
0.10	1.0	3365	13.4
0.15	1.0	2212	8.82
0.20	1.0	1867	7.44

Table 3.4: Force on the piston at 0.5 m/s and 1m/s (k-ϵ-model)

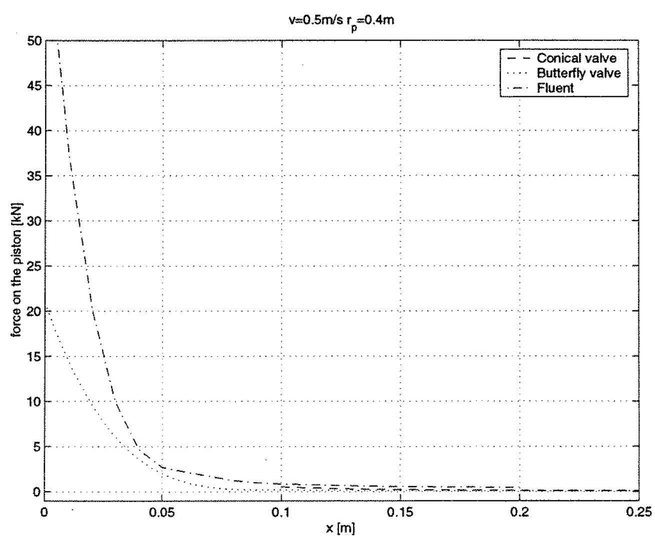

Figure 3.9: Force on the piston calculated with FLUENT5 (k-ϵ-model) or according to the valve-parameters, fluid velocity v=0.5 m/s, no movement of the piston

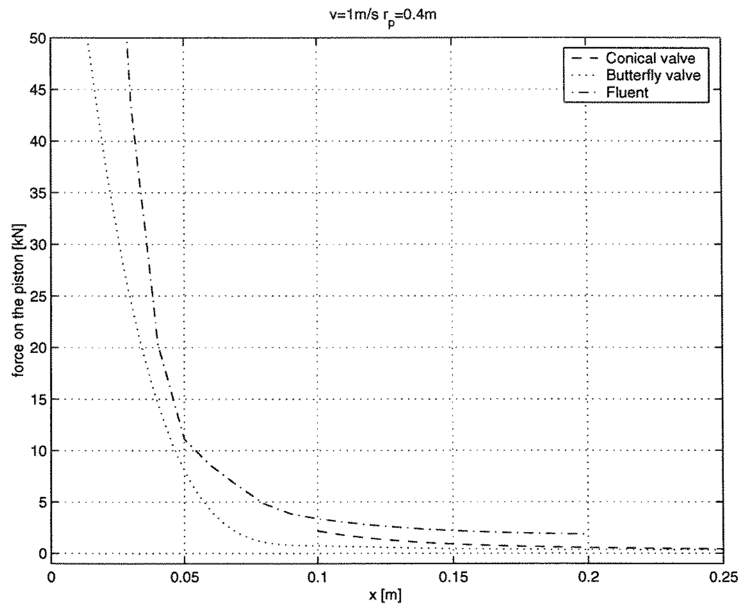

Figure 3.10: Force on the piston calculated with FLUENT5 (k-ϵ-model) or according to the valve-parameters, fluid velocity v=1 m/s, no movement of the piston

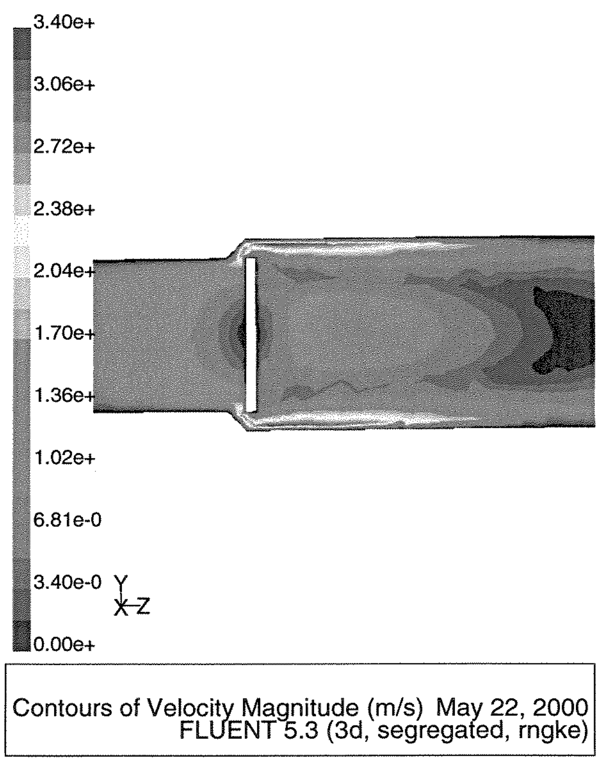

Figure 3.11: The fluid flow in the OWEC at a fluid velocity of 1 m/s (k-ϵ-model), no movement of the piston

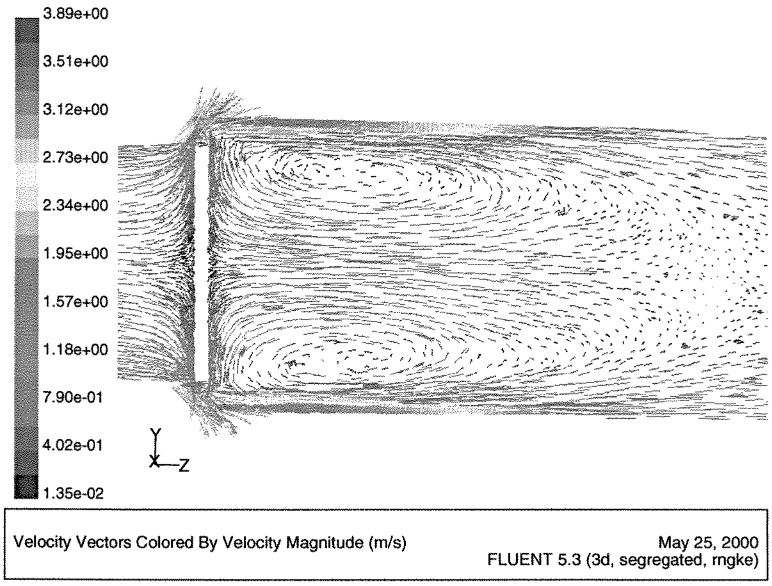

Figure 3.12: The fluid direction in the OWEC at a fluid velocity of 1 m/s (k-ϵ-model), no movement of the piston

3.5.2 The force on the piston moving in the diffusor

The solution of the differential equation is dependent on the parameter k(x). This parameter can be easily calculated knowing the force on the piston depending on the position of the piston. As the force is simulated (chapter 3.5.1) it can be interpolated in between these positions. The differential equation 2.7 can then be solved. The program to solve the differential equation is shown in appendix B.3. Now the force on the piston as well as the velocity of the piston depending on the position are known. FLUENT5 provides the possibility of moving walls. But the supported movement is in tangential direction to the fluid velocity. Therefore this possibility cannot be used to simulate the force on the moving wall. When the piston is moving out of the diffusor not the whole fluid flow has to pass the annulus. A part of the flow follows the piston. Behind the piston the fluid particles directly at the wall of the piston move with the same velocity and direction as the piston. In order to simulate the moving piston, the front area of the piston is set to be a "mass flow inlet", and the back side of the piston is set to be a "velocity outlet". It is possible to simulate the movement of the piston giving the mass inflow as well as the velocity outlet the values, calculated with help of the differential equation. The fluid field and the direction of the flow are shown in figure 3.13 and figure 3.14.

The simulated force can be compared with the solution of the differential equation. As FLUENT5 does not support the possibility to plot the force on a "mass flow inlet" or "velocity outlet", the forces on these surfaces were calculated with the surface intergral over the total pressure. The way FLUENT5 computes forces is just the same, but comparisons between the force plotted from FLUENT5 and the force calculated with the surface integral have shown a small difference. Because of the small difference a reduction of the force is considered. The results from the differential equation with the simulation are compared in figure 3.15.

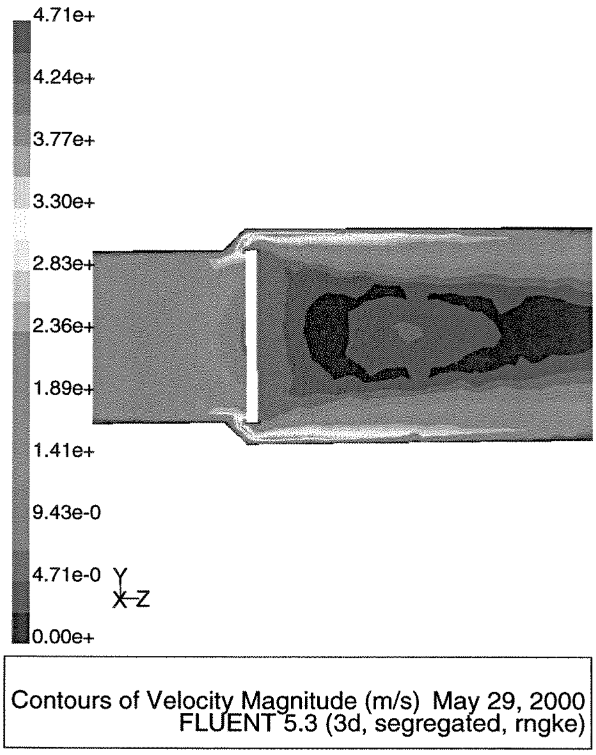

Figure 3.13: The fluid flow in the OWEC with a moving piston at a velocity of 2 m/s

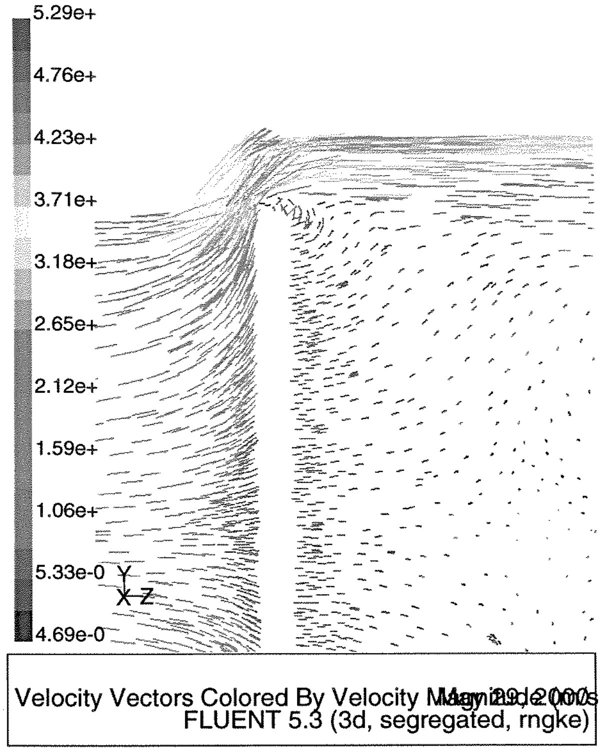

Figure 3.14: The fluid direction in the OWEC with a moving piston at a velocity of 2 m/s

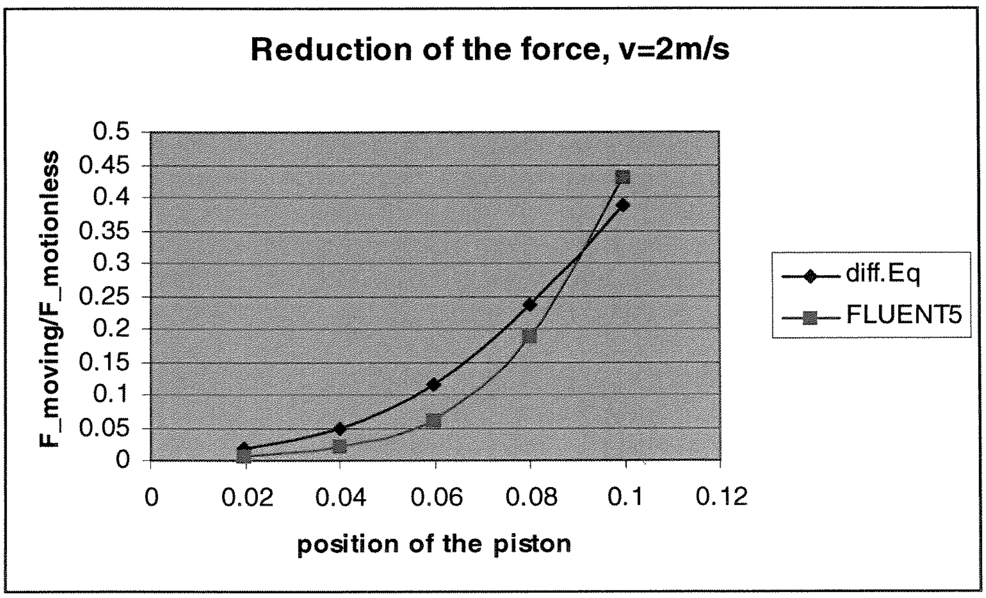

Figure 3.15: The reduction of the force on the moving piston to the force on the motionless piston

Chapter 4

Summary and comparison of the results

The aim of this work is to find out the force on the piston while moving out of the acceleration tube. First this force was calculated based on known coefficients from a butterfly and a conical valve. In order to prove these results, a simulation with FLUENT5 was made. The results are discussed in this chapter.
In order to be sure, that the results, calculated with FLUENT5, are realistic, simple geometries were modeled and simulated in the beginning.

4.1 The pressure drop in smooth tube

In chapter 3.2 the pressure drop per meter in a smooth tube are calculated with FLUENT5 and according to the Moody-diagram. The derivation between these results averages between 0.7% to 3.8% . Just at a fluid velocity of 0.005 m/s FLUENT5 calculates a 25% smaller pressure drop. Somewhere around this velocity the fluid flow changes from laminar to turbulent flow. Measurements have shown in the past, that the pressure drop coefficient in the Moody-diagram should have at a Reynolds number of 4000 a minimum (Nikuradses original experiments [Olson 1980]). Still, even considering this minimum, the pressure drop calculated with FLUENT5 is smaller than the pressure drop according to the Moody-diagram. In the OWEC the considered fluid flow will be turbulent with a high Reynolds number. That is why not more research was done to explain this divergence.

4.2 The pressure drop in a diffusor

As the fluid velocity decreases in a diffusor the static pressure increases. On the other hand there is an energy loss in a diffusor, that reduces the static pressure. In order to compare the results of the simulation, the static pressure before and after the diffusor are considered. This is shown in figure 3.5 and appendix A.2. The difference of the results range between 4% and 10%.

4.3 The force on a plate

In the OWEC the pressure drop over the piston is far higher than the pressure drop due to the friction in the tube or the drop of the diffusor. Therefore the pressure drop of a circular plate in a fluid flow was simulated. The influence of different models, discretisation schemes, the grid and the size of y+ were searched out, in order to get the right solutions. As shown in appendix A.3 the best results were simulated with the Reynolds-Stress-Model, a second order discretisation scheme, a fine grid and a small value of y+. The influence of y+ on the ringsurface of the plate as well as the choice of the best model (RSM) is mentionable. It is also important that the turbulence of the fluid flow in front of the plate is fully developed. Therefore the distance from the velocity inlet to the plate has to be large enough. More research could have be done like finding out the influence of the wake frequency in a time dependent simulation on the drag coefficient, but there was not enough available time within this project. However, the difference between the simulated solutions and the expected force range between 4.3% and 8.2%. This difference is acceptable.

4.4 The force on the fixed piston

As figure 3.9 and figure 3.10 show, the forces calculated with FLUENT5 match quite close to the solutions calculated with the valve parameters. Just when the piston is near to the working area, FLUENT5 simulates larger forces on the piston than those based on the butterfly valve. As the geometry of the two items are different, it is not surprising, that the pressure drop is different too. The geometry of the conical valve seems to bee more similar to the OWEC. The force on the piston, based on the conical valve, agree better with the simulation results in their range of validity.

4.5 The force on the moving piston

In chapter 3.5.1 the force, and according to equation 2.1 a coefficient k(x), for the non moving piston is calculated. After solving the differential equation 2.7 with this parameter the velocity as well as the acceleration of the piston depending on its position is approximately known. The force on the moving piston can then be simulated. The quotient of the remaining force calculated with FLUENT5 is compared with the results of the differential equation. The solutions simulated with FLUENT5 prove the results of the differential equation.

Chapter 5

Conclusions

The aim of this work was to find out the force on the piston while moving out of the acceleration tube. In the beginning comparisons to valve coefficients were made and a differential equation was developed to describe the movement of the piston. The results were proved, using the fluid simulation program FLUENT5.

If the piston is moving within the acceleration tube, the whole water mass in the tube has to be moved too. If the piston enters the diffusor and the annulus is still very small, the viscosity of the water limits the water mass passing the piston. In this case the accelerated mass is far higher as considered in this work. More research could be done here to find a solution describing the accelerated mass.

Simulating the fluid flow in the OWEC, the RSM did not converge in all cases. The results of a simulation calculating with the RSM would be interesting, to find out, how big the influence of the chosen model on the piston-force in the OWEC is.

If there is a possibility to include a motion of a wall in fluid-direction, a time dependent simulation with FLUENT5 could be simulated. This would show the movement of the piston. Of course the force coming from the power take-off system as well as the accelerated water mass would have to be included in this simulation.

Finally a laboratory test or measurements on an existing InterProject Service Offshore Wave Energy Converter could validate the calculations made in this work.

Appendix A

Comparison of the different solutions

A.1 Comparison of the pressure drop in a tube

Comparison of the Pressure loss in a smooth pipe calculated with fluent5 or coefficiants from the moody-diagramm

rho	diameter	length	kinem. viscosity	viscosity
998.2	0.8	1	1.00681E-06	0.001005

velocity v	dyn pressure =rho*v^2/2	Reynolds =v*d/nu	coefficiant f	**pelta p (moody)** =f*l/d*rho/2*v^2	**fluent5**	diff [%]
0.001	0.0004991	794.5870647	0.09	5.61488E-05	0.000054	-3.82689
0.002	0.0019964	1589.174129	0.07	0.000174685		
0.005	0.0124775	3972.935323	0.03	0.000467906	0.00035	-25.1987
0.01	0.04991	7945.870647	0.025	0.001559688		
0.02	0.19964	15891.74129	0.018	0.0044919		
0.05	1.24775	39729.35323	0.022	0.034313125	0.034	-0.91255
0.1	4.991	79458.70647	0.019	0.11853625		
0.5	124.775	397293.5323	0.014	2.1835625	2.2	0.752784
1	499.1	794587.0647	0.012	7.4865		
1.5	1122.975	1191880.597	0.0115	16.14276563		
2	1996.4	1589174.129	0.011	27.4505	27.2	-0.91255

modell variation	velocity	delta p moody	delta p after	
boundary condition: turbulence Intensity: 0%	2	27.4505	27.2	-0.91255168
solver : coupled	2	27.4505	aborted	
standard k-e-model	2	27.4505	27.5	0.180324584
realizable k-e-model		27.4505	27.5	0.180324584
standard k-e-model non equilibrium wall function	2	27.4505	27.6	0.544616674

A.2 Comparison of the pressure drop in a diffusor

Comparison of the pressure loss in a diffusor calculated with FLUENT and known parameters

rho	diameter	length	kinem. viscosity	viscosity
998.2	0.8	1	1.00681E-06	0.001005

velocity v	dyn pressure =rho*v^2/2	Reynolds =v*d/nu
0.001	0.0004991	794.5870647
0.1	4.991	79458.70647
0.5	124.775	397293.5323
1	499.1	794587.0647
1.5	1122.975	1191880.597
2	1996.4	1589174.129

Pressure loss calculated according to Idelchik

Rad.1 Diffusor r_0	Rad.2 Diffusor r_1	koefficiant n
0.4	0.9	5.0625

velocity v	zeta_d	dp Idelchik	dp (conti + Bernoull p1=rho/2*v0^2*(1-r0^4/r1^4)	total
0.1	0.314	1.6455327	4.991	3.3454673
0.5	0.273	44.2826475	124.775	80.4923525
1	0.2715	162.60678	499.1	336.49322
2	0.271	703.33172	1996.4	1293.06828

Pressure loss calculated with FLUENT

velocity m/s	before diff. (fluent)	after diff (fluent)	difference %
0.1	-3.2	~0	-4.545853125
0.5	-83	~0	3.021262048
1	-360	~0	6.529661111
2	-1450	~0	10.82287724

A.3 Comparison of the force on a plate in a fluid flow

Pressure loss of a plate calculated with FLUENT and according to c_w

Radius: 0.100

Force calculated witch c_w=1.11:

v=0.5m/s	4.351
v=1m/s	17.404
v=1.5m/s	39.160
v=2m/s	69.618

Force calculated with FLUENT5

velocity	fluid	F_piston	difference [%]	Model
1.000	h2o	31.980	83.746	y+ = 3000
1.000	h2o	30.810	77.024	y+ = 1200
1.000	h2o	30.810	77.024	y+ = 610
1.000	h2o	23.090	32.667	face y+=100
1.000	h2o	21.096	21.210	face y+=100, RNG
1.000	h2o	20.746	19.199	face y+=100, RNG, 2. Order
1.000	h2o	18.571	6.703	RSM,face y+=100, 2. Order
0.500	h2o	5.461	25.508	k-e-model, y+=200, 2.Order
0.500	h2o	4.708	8.202	RSM, y+=200, 2.Order
1.500	h2o	47.021	20.074	k-e-model, y+=200, 2.Order
1.500	h2o	41.050	4.826	RSM, y+=200, 2.Order
2.000	h2o	88.529	27.164	k-e-model, y+=200, 2.Order
2.000	h2o	72.645	4.348	RSM, y+=200, 2.Order

A.4 The force on the not moving piston

The force on the not moving piston calculated with Fluent and according to valve-parameters

rho	998.2	viscosity	0.001005
diameter_p	0.8m	alpha=45	
diameter_tube	1m	kinem. viscosity	0
alpha=45			

FLUENT

x(piston)	k-e-model, RNG F_p [N]	v=0.5 m/s RSM F_p [N]	k(x)
0.02	20130.00	-	320.96
0.04	4692.00	-	74.81
0.06	2173.00	-	34.65
0.08	1238.00	-	19.74
0.10	865.00	-	13.79
0.15	567.00	501.00	9.04
0.20	473.00	449.00	7.54

x(piston)	k-e-model,RNG F_p [N]	v=1 m/s RSM F_p [N]	k(x)
0.02	88075.00	-	351.07
0.04	20301.00	-	80.92
0.06	8528.00	-	33.99
0.08	4836.00	-	19.28
0.10	3365.00	-	13.41
0.15	2212.00	2008.00	8.82
0.20	1867.00	1700.00	7.44

	Butterfly Valve		Conical Valve	
	v=0.5	v=1	v=0.5	v=1
x(piston)	F_p [N]	F_p [N]	F_p [N]	F_p [N]
0.02	9482	37934	-	-
0.04	3601	14420	-	-
0.06	1063	4261	-	-
0.08	263	1050	-	-
0.1	186	740	550	2250
0.15	114	459	250	830

A.5 The force on the moving piston, v=0.5 m/s

Force on the piston calculated with t
and with fluent (mooving wall) at a

he diffential Equation:

position	velocity	acceleration	Force [kN]
0	0.5	-33.6379	0
0.0167	0.2051	-1.9204	8.6374
0.0194	0.178	-1.9217	8.6613
0.0218	0.1513	-1.8561	8.6996

position of piston	velocity of piston	mass-flow	a of piston	F(x)
0.02	0.171325	85.962254	-1.9053	8.670

lculated with Fluent:

position	no movement			
of piston	int p front [Pa]	int p back [Pa]	total	int p fro
0.02	84342.8	-3732.6	88075.4	7723

A.6 The force on the moving piston, v=1 m/s

Force on the piston calculated with the differntial equation and with fluent (mooving wall) at a velocity of 1 m/s

Solution of the diffential Equation:

position	velocity	acceleration	Force [kN]
0	1	-33.6435	0
0.0002	0.9934	-33.6101	0.0107
0.0198	0.6974	-6.4021	7.4672
0.0249	0.6451	-7.3203	7.2669
0.0295	0.5861	-8.2946	7.0477
0.0337	0.521	-9.0285	6.8887
0.0374	0.4518	-9.3417	6.8377
0.0398	0.3976	-9.225	6.8911
0.042	0.3449	-8.8122	7.0209
0.0439	0.2953	-8.15	7.2148

position of piston	velocity of piston	mass-flow	a of piston	F(x) [kN]	F(x) not moving [kN	**Reduction**
0.02	0.69534902	348.8911078	-6.438108	7.459345	88.057	0.082525
0.04	0.392809091	197.0918129	-9.187473	6.9029	20.301	0.340028

Solution calculated with Fluent:

position	no movement		
of piston	int p front [Pa]	int p back [Pa]	total
0.02	84342.8	-3732.6	88075.4
0.04	19798	-1098	20896

position	moving piston			
of piston	int p front [Pa]	int p back [Pa]	total	**Reduction**
0.02	8212.7	-106.44	8319.14	0.094455
0.04	6427.4	-330.33	6757.73	0.323398

The piston stops before 0.06m.

A.7 The force on the moving piston, v=2 m/s

Force on the piston calculated with the differntial equation and with fluent (mooving wall) at a velocity of 2m/s

he diffential Equation:

position	velocity	acceleration	Force [kN]
0	2	-33.6547	0
0.0128	1.82	-18.8308	4.0818
0.0169	1.7796	-16.412	4.7659
0.021	1.7429	-15.7016	4.9921
0.0303	1.6542	-17.2815	4.6528
0.0355	1.5966	-18.8773	4.2723
0.0405	1.534	-20.2559	3.9482
0.0498	1.4011	-20.7769	3.8927
0.0568	1.2984	-18.7203	4.5053
0.0632	1.2066	-16.5742	5.1373
0.0748	1.0419	-16.0475	5.3818
0.0799	0.9596	-16.2553	5.3723
0.0855	0.8612	-15.7979	5.5449
0.095	0.6808	-13.1048	6.3502
0.0989	0.6047	-11.5279	6.8075
0.1025	0.5381	-10.1159	7.2167

position of piston	velocity of piston	mass-flow	a of piston	F(x) [kN]	F(x) not moving [kN]	**Reduction**
0.02	1.75185122	878.9906873	-15.87487	4.9369293	264.0013	0.018909
0.04	1.54026	772.8248729	-20.11804	3.98061	80.0553	0.049318
0.06	1.2525	628.4414017	-17.64725	4.8213	33.4454	0.11639
0.08	0.957842857	480.5972916	-16.24713	5.3753821	18.9721	0.23747
0.1	0.58435	293.1973917	-11.09646	6.9325333	13.253	0.387633

lculated with Fluent:

position	no movement		
of piston	int p front [Pa]	int p back [Pa]	total
0.02	267739.9	-3627.3	271367.2
0.04	78185.4	-4261.6	82447
0.06	31934.1	-3011.6	34945.7
0.08	17679.8	-2276.5	19956.3
0.1	12074.9	-1869.9	13944.8

position	moving piston			
of piston	int p front [Pa]	int p back [Pa]	total	**Reduction**
0.02	2774.2	751.926	2022.274	0.0074522
0.04	2313.2	664.168	1649.032	0.0200011
0.06	2159.22	4.525	2154.695	0.0616584
0.08	3753.5	-23.75	3777.25	0.1892761
0.1	5273.7	-707.53	5981.23	0.4289219

he piston stops before 0.15m.

Appendix B

Calculation programs

B.1 The force on the piston calculated according to the valves

```
% The force on the piston depending on the parameter k
% (butterfly valve) and zeta (conical valve)will be calculated.
% The force simulated with Fluent is also shown.
% The influence of the diffusor is not regarded.
%
% A_prozent : opened area [%],at 2m =>0,9104
% A_p       : surface piston
% A         : surface piston
% F_p       : force on the piston [kN]
% H         : the opening height of the conical valve
% Beta2     : parameter for the pressure loss in a conical valve
% Beta3     : parameter for the pressure loss in a conical valve
%
% a         : area opened at a butterfly valve
% dp_...    : pressure loss over the piston
% k         : parameter for the pressure loss in a butterfly valve
% r_p       : radius of piston
% x         : position of the piston 0....0.2 [m]
% x1        : position of the piston calculated with a [m]
% y         : opening-angel here 10 degrees
% v_0       : flow velocity in the tube [m/s]
% rho       : density water [kg/m^3]
% y         : angel of the diffusor
% zeta      : parameter for the pressure loss in a conical valve
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear;
%Initializing
H = 0.1:0.01:0.25; %just guilty within: 0.1<H<0.25!!!
x = 0:0.01:0.2;
r_p = 0.4;
v_0 = 0.5;
rho = 1000;
a=0:0.01:1,
y=45;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%conical valve

 load ('h_d.dat.m');
 load ('beta2.dat.m');
 load ('beta3.dat.m');
 figure(1);
clf;
Beta2 = interp1(h_d,beta2,H,'spline');
plot(h_d,beta2,'*',H,Beta2,'--')
hold on;
Beta3 = interp1(h_d,beta3,H,'spline');
plot(h_d,beta3,'*',H,Beta3,'-.');
hold off;
     ylabel('Beta')
     title('Butterfly-Valve')
h = legend('beta2','beta2','beta3','beta3',0);

zeta = 2.7 -Beta2 + Beta3;
dp_conical = v_0^2*rho/2.*zeta
A = pi*r_p^2;
F_p_conical = A/1000.*dp_conical
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%5
%butterfly valve
%
load ('k_Werte_x.dat');
load ('k_Werte_y.dat');
     k = interp1(k_Werte_x,k_Werte_y,a,'spline');

x1= sqrt((r_p*sin(y*pi/180)*cos(y*pi/180)/(tan(y*pi/180)^2))^2 + r_p^2./((1./a)-
1)*cos(y*pi/180)/(tan(y*pi/180)^2))-
r_p*sin(y*pi/180)*cos(y*pi/180)/(tan(y*pi/180)^2);
dp_butterfly = v_0^2*rho/2.*k
F_p_butterfly = A/1000.*dp_butterfly

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%5
% Fluent-solutions
%
load ('fluent_x.dat.m');
load ('fluent_y_v05.dat.m');
     F_fluent = interp1(fluent_x,fluent_y_v05,x,'spline');
F_fluent_kN = F_fluent/1000;

figure(2)
clf;
plot(H,F_p_conical,'--');

hold on;
plot(x1,F_p_butterfly,':');
plot(x,F_fluent_kN,'-.');
grid
title('v=0.5m/s r_p=0.4m')
xlabel('x [m]')
     ylabel('force on the piston [kN]')
  xlim([0 0.25])
  ylim([-1 50])
h = legend('Conical valve','Butterfly valve','Fluent',0);
```

B.2 The force on the piston depending on the diffusor angel and the position

```
% The force on the piston is calculated depending on
% the k-value as well as the losses due to the opening.
%
% a          : area opened at a valve
% alpha      : diffusor-angel
% dp_k       : pressure loss (k)
% dp_diff    : pressure loss due to the diffusor
% k          : parameter k(a)
% nu         : 1/density water [m^3/kg]
% rho        : density water [kg/m^3]
% r_p        : radius of the piston
% v_0        : flow velocity in the tube[m/s]
% x          : position of the piston calculated with a [m]
% zeta       : value of zeta
% A_prozent  : opened area [%],at 2m =>0,9104
% A_p        : surface piston
% F_p        : force on the piston [kN]
% Re         : Reynolds
% X          : Position of the piston depending on a and alpha
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear;
%Initializing
a    = 0:0.02:1;
alpha    = 0:0.5:90;
r_p = 0.4;
v_0 = 0.5;
rho = 1000;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% interpolation of the parameter k(a)
 load ('k_Werte_x.dat');
 load ('k_Werte_y.dat');
    k = interp1(k_Werte_x,k_Werte_y,a,'spline');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
[A,Y] = meshgrid(a,alpha);
[K,Y] = meshgrid(k,alpha);
X = sqrt((r_p.*sin(Y.*pi/180)./cos(Y.*pi/180)./(tan(Y.*pi/180).^2)).^2
+ r_p^2./cos(Y.*pi/180)./(tan(Y.*pi/180).^2)./((1./A)-1)) -
r_p.*sin(Y.*pi/180)./cos(Y.*pi/180)./(tan(Y.*pi/180).^2);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%zeta-Wert intertpolation of the opening losses
%
%symetrical velocity field upstrem the diffusor
nu = 1/rho;
Re = v_0*2*r_p/nu
load ('alpha_wert.dat');
      load ('zeta50000.dat');
      load ('zeta100000.dat');
      load ('zeta200000.dat');
      load ('zeta400000.dat');

figure(1);
clf;
    Zeta50000 = interp1(alpha_wert,zeta50000,alpha,'spline');
    Zeta100000 = interp1(alpha_wert,zeta100000,alpha,'spline');
```

```
    Zeta200000 = interp1(alpha_wert,zeta200000,alpha,'spline');
    Zeta400000 = interp1(alpha_wert,zeta400000,alpha,'spline');
    plot(alpha,Zeta50000,'-',alpha,Zeta100000,'--',alpha,Zeta200000,'-
.',alpha,Zeta400000,':')
    hold on

plot(alpha_wert,zeta50000,'*',alpha_wert,zeta100000,'*',alpha_wert,zeta
200000,'*',alpha_wert,zeta400000,'*')
    hold off
    xlabel('opening angel')
    ylabel('zeta');
h = legend('Re<50000','Re<100000','Re<200000','Re>400000',0);

if Re < 100000
      zeta = Zeta50000;
elseif Re < 200000
      zeta = Zeta100000;
elseif Re < 400000
      zeta = Zeta200000;
else
      zeta = Zeta200000;
end
[A,Z] = meshgrid(a,zeta);
dp_diff = rho*v_0^2/2.*Z;
A_p = pi*r_p^2;
F_p_diff = A_p/1000.*dp_diff;
figure(2);
clf;
mesh(X,Y,F_p_diff)
rotate3d
    xlabel('Position of piston [m]')
    ylabel('0.5 * angel diffusor')
    zlabel('Force-loss diffusor [kN]');
figure(4);
clf;
plot(Y,dp_diff)
    xlabel('0.5 * angel diffusor')
    ylabel('pressure loss in the diffusor');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%5
figure(3)
clf;
dP = v_0^2*rho/2.*K;
A_p= pi*r_p^2;
%F_p = A_p/1000.*dP;
F_p = A_p/1000.*dP - F_p_diff;
surf(X,Y,F_p,'FaceColor','interp','EdgeColor','none')
%mesh(X,Y,F_p)
axis([-0.5 5 -5 90 0 22])
rotate3d
     xlabel('Position of piston [m]')
     ylabel('Opening-angle')
     zlabel('Force on the piston [kN]')
```

B.3 The differntial equation

```
%y1=x
%y2=xdot
%
function dy = diff_piston_fluent(t,y);
rho=998.2;
r_p=0.4;
v_0=2;
m_p=267.6;
D=3;
C=9000;
load ('k_fluent_x.dat.m');
load ('k_fluent_y.dat.m');
k = interp1(k_fluent_x,k_fluent_y,y(1),'spline');
%k=1.11+1./(600.*(y(1)+0.07).^5);
dy = zeros(3,1);    % a column vector
 y(1);
 dy(1) = y(2);
 dy(2) = 1/m_p*(k*rho/2*pi*r_p^2*(v_0-y(2))^2-D*y(2)-C*(1+y(1)));
```

```
%C      : Spring coefficiant
%D      : Damping coefficiant
%a      : acceleration
%k      : pressure loss parameter, interpolated
%m_p    : accelerated mass
%rho    : density water
%v_0    : fluid velocity before the piston
% 15 seconds to solve the differential equation
clear;
   [T,Y] = ode15s('diff_piston_fluent_v2',[0 15],[0 2 0]);
rho=998.2;
r_p=0.4;
v_0=2;
m_p=267.6;
D=3;
C=9000;
load ('k_fluent_x.dat.m');
load ('k_fluent_y.dat.m');
k = interp1(k_fluent_x,k_fluent_y,Y(:,1),'spline');
%k=1.11+1./(600.*(Y(:,1)+0.07).^5);
a=1/m_p.*(k*rho/2*pi*r_p^2.*(v_0-Y(:,2)).^2-D.*Y(:,2)-C.*(1+Y(:,1)));
figure(1)
     clf;
     hold on
     plot(T,Y(:,1),'-o')
     plot(T,Y(:,2),'--')
     hold off
     xlabel('time [s]')
     ylabel('whatever')
     h = legend('position ot the piston','velocity',0);
figure(2)
     clf;
     subplot (2,1,1);
     plot(Y(:,1),Y(:,2),'--')
     xlabel('postion [m]')
     ylabel('velocity [m/s]')
     title('v=0.4 m/s , m=268 kg , D=3 Ns/m, C=9000 N/m')
     subplot (2,1,2)
     plot(Y(:,1),a,':')
     xlabel('postion [m]')
     ylabel('acceleration [m/s^2]')
% Now the force is calculated
     F_piston2 = (k*rho/2*pi*r_p^2.*(v_0-Y(:,2)).^2)/1000;
     figure(3)
     clf;
     plot(Y(:,1),F_piston2,':');
     xlabel('postion [m]')
     ylabel('Fluid flow force [kN]')
     h = legend('force according to the fluid flow');
figure(4)
     clf;
     hold on
     plot(Y(:,1),k,':')
     plot(k_fluent_x,k_fluent_y,'*')
  hold off
```

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