Cooling in the ALICE detector

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Abstract

At CERN, the European Laboratory for Particle Physics in Geneva, Switzerland, a new modern particle accelerator called the LHC, Large Hadron Collider, is being projected. One of the four large detectors of the LHC, ALICE, consists of many sub-detectors. Temperature stability in ALICE is of great importance for the experiments performed here.

In the ALICE sub-detector TPC, Time Projection Chamber, there is a great risk for thermal instability. This will cause false data in the experiments, and therefore it is imperative to come to terms with the problem. One suggested solution is to install a water-cooled thermal screen around the TPC detector. The task of this thesis work was to design the new thermal screen and to evaluate its thermal abilities by computer simulations. Then, this chosen screen was to be simulated together with the TPC and its drift gas and the results studied. It was also desirable to see what would happen in case of parts of the thermal screen malfunctioning.

Several different designs of the thermal screen have been made and analysed, and the most efficient model has been selected. The chosen model succeeded in keeping a fairly homogenous temperature level and also had good cooling abilities. All simulations were made using the computer software STAR-CD. The next phase of the project involved modelling the thermal screen around the TPC field cage containing drift gas of a certain temperature.

The results of the simulations show that the performance of the cooling thermal screen is unsatisfactory. Although the screen itself seems to work efficiently, it does not succeed in keeping the TPC at an acceptable temperature level. The screen temperature rises more than the desired maximum of 0.5K. The scenario with parts of the thermal screen malfunctioning resulted in temperature peaks of +2K, which is unacceptable.

The conclusions drawn are therefore that the thermal screen must be allowed to be thicker or a new solution must be found. The idea of a thermal screen is a good one, but the limitations in the design of the thermal screen must be redefined if the cooling problem is to be solved.
Nomenclature

eV  Electron volt; 1 eV ≈ 1.602177×10^{-19} J
Ne  Neon
CO₂ Carbon dioxide
A   Ampere
J   Joule
kW  Kilowatts
MW  Megawatts
K   Degrees Kelvin
°C  Degrees Celsius; 0 K ≈ -273 °C
Pa  Pascal; 1 Pa = 1N/m²
bar 1 bar = 1.013×10⁵ Pa
Re  Reynold’s number
Δt  Temperature difference
Δp  Pressure drop
ρ   Water density [1 000 kg/m³]
Cₚ  Specific heat for water [4179 J/kg·°C]
ν   Kinematic viscosity of water [0.0011 N/s]
u   Water velocity [m/s]
dₑquiv  Equivalent diameter of a channel [m]
A   Cross-section area [m²]
P   Perimeter of the channel [m]
L   Channel length [m]
f₁  Friction coefficient of channel walls
ζ   Loss coefficient
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<tr>
<td>ALICE</td>
<td>A Large Ion Collider Experiment</td>
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<td>ATLAS</td>
<td>A Toroidal LHC Apparatus</td>
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<td>CERN</td>
<td>The European Laboratory for Particle Physics</td>
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<td>CMS</td>
<td>Compact Muon Solenoid</td>
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<td>ITS</td>
<td>Inner Tracking System</td>
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<tr>
<td>LEP</td>
<td>Large Electron-Positron Collider</td>
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<td>LHC</td>
<td>Large Hadron Collider</td>
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<tr>
<td>PHOS</td>
<td>Photon Spectrometer</td>
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<td>QGP</td>
<td>Quark Gluon Plasma</td>
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<td>RICH</td>
<td>Ring Imaging Cherenkov</td>
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1 Background

1.1 CERN

CERN is the European Laboratory for Particle Physics, the world’s largest particle physics research centre. It was officially formed in 1954 under the name Conseil Européen pour la Recherche Nucléaire, from which the abbreviation CERN is taken. From the original 12 signatories of the CERN convention (Sweden being one of these 12), membership has grown to the present 20 member states (2000): Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland and United Kingdom. Additional to that, there are seven observer states or organizations. States with Observer status are Israel, Japan, the Russian Federation, Turkey, the United States of America, the European Commission and Unesco.

The CERN main site is on the border between Switzerland and France, just outside Geneva. CERN exists primarily to provide European physicists with accelerators that meet research demands at the limits of human knowledge. There are about 3 000 employed at CERN and some 6 500 scientists, half of the world’s particle physicists, come here for their research. They represent 500 universities and over 80 nationalities.

![Figure 1-1: Satellite photo of the CERN site on the Franco-Swiss border (courtesy of CERN).](image)

The laboratory provides advanced scientific facilities for researchers to use. There are accelerators, which accelerate particles to a fraction under the speed of light, and detectors to make these particles visible. All this to explore what matter is made of, and what forces hold it together.

What is happening at CERN in the early 2000’s is that a new particle accelerator is under development and construction. It is a huge project and the result will be the largest and most advanced scientific instrumentation ever built by mankind – the Large Hadron Collider, LHC.
1.2 LHC

This new accelerator will be built in the existing 27 kilometre long circular tunnel that still hosts the old accelerator, LEP (the Large Electron-Positron collider). The LHC will bring protons into head-on collision at about ten times higher energies (14 TeV \(^1\)) than ever achieved before. The research, technical and educational potential of the LHC and its experiments is enormous. Besides proton-proton collisions, both proton-nucleus and nucleus-nucleus collisions are foreseen as part of the initial experimental program at the LHC. This will allow scientists to further investigate the structure of matter and to recreate the conditions in Universe only \(10^{-12}\) seconds after the Big Bang, when the temperature was \(10^{16}\) degrees. With heavy ions at a centre-of-mass energy of 5.5 TeV/nucleon, the LHC is the only machine that will reach (and even extend) the energy range probed by cosmic ray nucleus-nucleus collisions. One of the main improvements with the LHC compared to older experiments is the number of particles produced in the collisions. At the LEP energies, about 1 500 particles are produced in each collision. At the LHC, about 50 000 particles will be created in one such event.

Heavy-ion collisions at the LHC are expected to provide a very different, and significantly better, environment for the study of strongly interacting matter than existing accelerators. 8 000 superconducting magnets will keep the beams on track. The entire 27kilometre ring (with a weight of 30 000 tons) will be cooled by liquid helium to a temperature of 1.9K, making the LHC the world’s largest superconducting installation. The reason for this low operating temperature is that the magnets in the accelerator have to be superconductive in order to produce the magnetic field required to bend the beam of protons into a circle. There will be 1 500 power converters, some of which will provide an electric current of 12 500 A and a power of 2.5 MW.

To detect the particles created in the collisions, new detectors are needed. Right now four new detectors are being constructed for the LHC. These are called:

- ATLAS (A Toroidal LHC ApparatuS)
- CMS (Compact Muon Solenoid)
- ALICE (A Large Ion Collider Experiment)
- LHCb (Large Hadron Collider beauty experiment)

Each of the detectors is being projected for its own purpose, to explore different phenomena in the accelerator. In modern experiments, large multi-layered detectors surround the collision point. Each layer of the detector serves a separate function in recording tracks and identifying each of the many particles that may be produced in a collision. The focus of this thesis project is the detector ALICE and the challenge to obtain a stable temperature in its inner parts.

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\(^1\) 1 eV \(\approx 1.602177 \times 10^{-19}\) J
The LHC project was approved in 1994 and has a project budget of 2.5 billion Swiss francs, about 15 billion Swedish crowns in today’s value (2001). The accelerator should be ready to use in 2005.
2 Introduction

2.1 The ALICE detector and its components

The main aim of the LHC detector ALICE is to study the collisions of heavy nuclei, such as lead. In collisions between these particles, a new phase of matter, quark gluon plasma (QGP), is produced. It is believed that, in the moments after the Big Bang, the quarks and gluons which today are situated inside protons and neutrons, where free – deconfined – in a so-called plasma. The temperatures were so high that the protons and neutrons melted. By studying QGP, the aim is to increase the knowledge of what happened in the moments directly following the Big Bang. For this purpose, the intentions are to carry out a comprehensive study of the hadrons, electrons, muons and photons produced in the collision of heavy nuclei.

The reason for colliding these heavier particles at higher energies is to raise the energy density and temperature of the collision, increasing the chances of deconfinement and thereby the production of QGP. At the LHC, the collisions of lead ions will happen at energies 300 times higher than at CERN’s experiments today.

Figure 2-1: Overview of the ALICE detector (courtesy of CERN).

The overall layout of the ALICE detector is shown in figures 4.1 and 4.2. ALICE consists, from the inside out, of the following components:

- an inner tracking system (ITS) for determination of particle positions
- a time projection chamber (TPC) for reconstruction of the paths of the particles
- a transition radiation detector (TRD) for electron identification
- a time of flight array (TOF), used for measuring the momenta of the particles
- a photon spectrometer (PHOS) and an array of RICH counters for detecting photons produced by particles travelling faster than the speed of light
- all these tracking devices are surrounded by a huge magnet, which actually is the same magnet as has been used to surround the LEP detector L3 at this detector station. The purpose of the magnet is to stop hazardous radiation from escaping from the detector.
2.1.1 ITS

The inner tracking system is where the collision takes place. It is made of cylindrical layers of silicon wafers. They will surround the collision point and measure the properties of particles emerging, deciding their positions with great accuracy.

2.1.2 TPC

The time projection chamber is the component discussed in this thesis project. Its main objective is to record the tracks made by the particles. As mentioned before, a collision at the LHC will produce about 50 000 particles. The detecting devises must have an extremely good resolution to be able to separate the different particle tracks. The TPC is a large gas-filled chamber with an electric field applied across it.

The structure and use of the TPC is more thoroughly discussed in section 2.2 and chapter 4.

2.1.3 TRD

The transition radiation detector is dedicated to the comprehensive investigation of electron pair physics and studies of production of charm and beauty quarks.

2.1.4 PID, PHOS, RICH counters and the muon spectrometer

The next step is particle identification. A special task of the ALICE experiment is to identify the mass of the particles emitted. The low energy particles may be identified by the loss of energy, and the higher energy particles are detecting by measuring the time it takes for a particle to travel from the collision point to the detector barrel, which is 3.5 metres away. The particle identification detector (PID) has a sensor...
that records the arrival of the particles. It is made of 160 000 counters distributed over 150 m². By using the tracking information from the other detectors, every track recorded by a sensor is identified.

At energies higher than those covered by the other detectors, the yield of the particles is low. The mass of these particles is measured by a high-momentum particle identification detector (HMPID) of 14 m². This detector is based on the detection of so-called Cherenkov photons emitted by the particles in a dielectric medium.

The temperature of the collision is taken by the photon spectrometer (PHOS), by detecting photons emerging from it. It will be made of lead-tungsten crystals that will start to glow when they are struck by high-energy photons. The glow can be measured and the temperature calculated from the results. Lead-tungsten is extremely dense, which means that it stops most photons that reach it from travelling through it.

The array of RICH counters is optimised for high-momentum particle identification. RICH stands for Ring Imaging Cherenkov. This is because the pattern of the photons detected looks like a ring.

There is also a muon spectrometer for the detection of muons. This is done by recording the decay of certain particles at which muons are emitted.

### 2.2 The Time Projection Chamber

The task of the time projection chamber is track finding, momentum measurement and particle identification. The TPC is a large sub-detector full of gas with an electric field applied across it. When charged particles pass through, they will knock electrons out of atoms in the gas – a process called ionisation. The gas ions, now positively charged, will be drawn towards one end of the TPC chamber, and the loose electrons will drift in the other direction in the electric field. By measuring the arrival of electrons at the end of the chamber, the TPC will reconstruct the paths of the originally charged particles. This sub-detector is the main tracking system of the ALICE detector and it is central to the design of the experiment.

The TPC is supposed to work in rather extreme conditions, because of the very high particle multiplicity and the large drift length. It is of the uttermost importance that the temperature is stable within the chamber. If not, the velocity of the electrons will not be constant, and their arrival at the end plates of the chamber will not be accurately recorded. The result of this is that it would be impossible to say in which event certain electrons have been created, and, consequently, it will be impossible to recreate the path of the particles produced in the collision.

The drift gases to be used in the TPC are chosen to guarantee optimum performance of the TPC at a minimum risk of failure. Extensive investigations of different gas mixtures have been performed. Mixtures of cool gases that have a small diffusion constant are needed, so the preferred gas would be a neon mixture since it has a high radiation length, and therefore smaller effects of multiple scattering and space charge. The chosen drift gas in the TPC field cage is a mixture of 90 % Ne and 10 % CO₂.

### 2.3 The aim of the project

Almost all components in the ALICE detector emit heat. The accuracy of the results depends on a homogenous temperature distribution, and therefore it is important to reduce the heat flow between the components to a minimum. A control of the thermal situation in the TPC is necessary in order to secure a long-term reliability and duration of the system. The TPC itself as well as the surrounding sub-detector systems in the whole ALICE detector are depending on a well-governed thermal behaviour. Therefore, one of the principal design objectives for the TPC field cage is to protect the TPC drift volume from the influence of any heat sources that could cause local or time related temperature changes of the drift gas by more than 0.1 degrees. Despite the efforts to have the different sub detectors operating unaffected by
each other, previous studies have shown that small temperature differences in the surrounding components cause intolerable temperature differences in the drift gas of the TPC.

The main heat source is the surrounding transition radiation detector, TRD, which emits about 100 kW. Heat sources within the TPC are, apart from the inner tracking system, ITS, exposed power-transmitting components such as cables, the field cage resistor chain and nearby electronics. Some electronic components at the TPC ends also influence the temperature profile. The front-end electronics emit about 20 kW. The results of previous studies show that the warmest areas in the TPC detector is in the outer part of the detector, within the NeCO\(_2\) gas mixture. There, the temperature difference is about 2K. To lower these differences is imperative for the experiment.

A sketch of the TPC, axial cross section view, showing the heat sources which influence it is shown in figure 2-3.

Figure 2-3: Heat influence on the TPC.

Time-related influence on the temperature profile occurs when neighbouring detectors are subject to power and/or cooling failures that gradually change their bulk temperature until normal operation and thermal equilibrium are restored.

2.4 The task

One proposed solution to achieve thermal stability is by installing an actively cooled thermal screen around the TPC field cage, thus decreasing the net heat flow to and from the sub-detector. Since, as already mentioned, the warmest area in the TPC drift gas is in the outer part of the TPC field cage, a thermal screen seems like a suitable solution to the cooling problem. The tracking system should be as light as possible to minimize the number of secondary interactions produced by the primary particles in the tracker material. A thermal screen would mean additional material in the detector, which is not desirable, but as things stand today this option must be evaluated.

When a suitable thermal screen has been chosen, it must be analysed in its presumed environment. Simulations are to be made of the TPC detector and its immediate neighbours, and the thermal influence between the components is to be quantified.

The thermal screen must also be able to cope with sudden temperature fluctuations due to failure of other components, for example if one of the front electronics panels suddenly malfunctions. The effects of possible occurring component failure will be studied.

This thesis project comprises creating CFD models of different designs of one thermal panel and simulate water flowing through it in order to evaluate the different models’ ability to maintain a stable temperature. Further, it comprises modelling of the TPC to analyse the thermal screen behaviour. More details on the definition of the thesis project can be found in Appendix A1.

It is important to notice that since none of the components described in this report exist today, it is impossible to make any real measurements; this thesis will consist only of simulations and calculations concerning the thermal behaviour.
3 Modelling of the thermal screen

Some previous studies have been made of the suitability of a thermal screen around the TPC. The conclusions drawn so far are that a good material for such a screen is aluminium, due to its lightness combined with its heat transfer capabilities. The preferable cooling medium is water, since it is cheap, it is not toxic, and its specific heat is much higher than that of air, which otherwise would be a suitable fluid. The only drawback is that the tracking system is extremely vulnerable to leakage, and this must be avoided at all cost. The cooling system is therefore to be an under-pressure (in order to minimize the risks of leakage), closed-circuit system. The design of the thermal screen is 72 panels, installed in rows of 18 by 4, thus surrounding the TPC field cage. Each row of panels shields an angle of 20 degrees. Since each panel has its own cooling water supply, it can be regulated separately, a feature that gives the screen the ability to have different temperatures in certain parts, and therefore be a more efficient device.

Figure 3-1: Model of the TPC field cage with one of the 72 panels illustrated on its surface.

3.1 Design aspects

There are some important aspects concerning the design of the channels in the thermal screen. The maximum acceptable pressure drop in the channels is only a few hundred millibar, because it is an under-pressure system and a too large pressure drop may cause the channel walls to buckle. Maximum value of the pressure drop is set to 500 millibar (50 000 Pa). In order to find the thermally and hydraulically most suitable solution pressure drops, temperature maps and velocity profiles of the panels must be considered. Therefore, extensive analyses will be made on one of these 72 panels, assuming that the overall result will be in conformity with the result of that single panel.
The thickness of the screen is limited for reasons due to the material budget in the detector. Since the amount and position of material traversed by particles in the inner detectors have an impact on the performance of the outer detectors, it is very important to have as little material as possible in the thermal screen. Therefore, the maximum height of the channels in which the water will flow in the panel, is only one single millimetre. This fact, naturally, makes the conditions for the flowing water somewhat difficult. If the channel height is one millimetre, the width will have to be considerably larger if you need an efficient water flow. The quota between channel width and height will be very large, thus making the conditions in the channels more complicated compared to flow in, for example, a circular tube channel.

Some different proposals of the thermal screen design have been made. Since many bends in the channels lead to large pressure drops, it is necessary to keep that number as low as possible. On the other hand, a lot of bends and turns will make it easier to reach a large area of the screen with the cooling fluid. Consequently, the best solution is probably a combination of both criteria.

### 3.2 STAR-CD

To produce the different models of the thermal screen the computational fluid dynamics (CFD) code STAR-CD was used. STAR-CD is a powerful tool for thermo fluids analysis. The name ‘STAR’ stands for ‘Simulation of Turbulent flow in Arbitrary Regions’. It has built-in models of a range of flow phenomena, such as compressibility, turbulence, heat transfer, mass transfer, transients, and multiphase flow.

STAR-CD is prepared for receiving information from external sources. A whole mesh can be imported, as long as there is sufficient information about the cells and the nodes. Any additional information can be inserted during the process, such as information of areas with certain conditions. If the same information is valid for more than one calculation, it is possible to store all that information in a separate file and feeding STAR-CD with it when starting up a new analysis.

By using STAR-CD, it is possible to create the geometry of the model, as well as performing different kinds of thermal analysis, such as temperature and velocity maps and pressure drops. The analysis will involve inlet speed of the cooling fluid, gravitation and the thermal properties of aluminium channels and water. All the models have in common the overall length, 1 250 mm, plate height, 1.4 mm and channel height, 1 mm. All the models have a width of 883 millimetres except model 7, which is one metre wide. The water inlet of all models is placed in the lower left corner and the outlet in the upper right corner, except in model 5, where the two inlets are to the left and the two outlets are to the right.

### 3.3 Different designs and CFD-simulated thermal analysis of the thermal screen

The 7 different below described designs of the thermal screen have been calculated in the computational software STAR-CD. Additional to just varying the design of the screens, some different water velocities have been looked at. Charts have been made of velocity and pressure profiles, as well as temperature maps. These can be viewed in Appendix A3. The STAR-CD code is given in Appendix A6.
The simulations were done under the following boundary conditions.

Power input: 100 kW

**Water properties**

Thermal conductivity \( k = 0.604 \text{ W/m} \cdot \text{°C} \)

Density \( \rho = 1000 \text{ kg/m}^3 \)

Specific heat \( C_p = 4179 \text{ J/kg} \cdot \text{°C} \)

The inlet temperature of the water is set to 18°C for all models.

The inlet water velocity is given for all different cases.

All pressure drops have also been calculated by hand using suitable formulae and calculator, see section 3.4.2.

### 3.3.1 Thermal analysis of Model 1

Model 1 consists of 15 millimetre wide channels. Two channels run parallel along the horizontal direction of the panel, and 18 channels run perpendicular to these two. The channel cross section area is 15x1 square millimetres overall.

![Model 1](image)

*Figure 3-3: Model 1.*

Two different water inlet velocities have been tried: 1 m/s (Model 1a) and 1.5 m/s (Model 1b).

**Model 1a – water inlet velocity 1 m/s**

The inlet velocity yields a maximum speed of 1.7 m/s in the inlet and outlet areas. In the 14 middle vertical channels, the water velocity is very low, nearly zero.

The increase of the water temperature between inlet and outlet is from 18.00°C to 19.49°C. The maximum temperature difference, \( \Delta t \), of the whole plate is 1.56K. In both cases the warmest area is in the upper middle section of the plate.

The pressure drop is 6 400 Pa.

**Model 1b – water inlet velocity 1.5 m/s**

The maximum increase of the water temperature is from 18.00°C to 19.00°C, which is more efficient cooling than for Model 1a. The hottest area is in the middle upper parts of the channels. The maximum plate \( \Delta t \) is 1.31K. The warmest spot of the plate is in the upper right corner of the plate.
Maximum velocity of the water is 1.8 m/s, in the outlet section. In the 14 middle vertical channels the speed is nearly zero, 0.06 m/s.

The pressure drop is 9 900 Pa.

### 3.3.2 Thermal analysis of Model 2

Model 2 has the same character as Model 1; two main parallel channels joined by nine vertical channels. This model has rather wide channels – the cross section area is 80x1 square millimetres – in order to cover a larger area and hereby have more efficient cooling abilities.

![Model 2](image)

*Figure 3-4: Model 2.*

These cooling abilities make Model 2 very interesting. Three different water velocities have been analysed: 0.19, 1 and 1.5 m/s.

**Model 2a – water inlet velocity 1 m/s**

The maximum achieved speed in the channels is about 1.2 m/s, in the outlet area. In the middle vertical channels, the velocity of the water is almost zero.

The increase of the water temperature is from 18.00°C to 18.21°C, the hottest part of the channels being in the upper part of the middle vertical channel. Looking at the whole plate, the maximum Δt is 1.25K. The hottest area of the panel is in the upper left-hand corner. The pressure drop in the channels is 6 700 Pa.

**Model 2b – water inlet velocity 0.19 m/s**

The water velocity of 0.19 m/s corresponds to a flow of 0.015 kg/s in the 80 mm wide channels.

The increase of the water temperature is a little bigger because of the low water flow rate, from 18.00°C to 18.89°C. The hottest area still is in the middle upper part of the channels. The maximum Δt in the whole panel is 1.58K.

Maximum water velocity in the channels is 0.27 m/s close to the inlet and outlet sections. The velocity in the middle connecting channels is about 0 m/s.

Due to the small water flow, the pressure drop is small, 1 130 Pa.

**Model 2c – water inlet velocity 1.5 m/s**

The water flow is 1.5 m/s, which gives a mass flow of 0.12 kg/s.
The water temperature rises from 18.00°C to 18.16°C, thanks to the high water velocity. Again, the warmest water temperature is found in the upper part of the middle vertical channels. The maximum Δt of the whole panel is 1.21K. The hottest area is the upper left corner.

The velocity map shows that maximum velocity is found in the outlet section, 1.7 m/s. Once again, the velocity in the five middle vertical channels is close to zero. The pressure drop with this water velocity is 10 800 Pa.

### 3.3.3 Thermal analysis of Model 3

Model 3 consists of one single channel, width 51 millimetres, height 1 millimetre, with 18 bends of 90°.

![Figure 3-5: Model 3.](image)

The inlet water velocity analysed is 1 m/s. This corresponds to a mass flow of 0.05 kg/s. The water temperature is only increased from 18.00°C to 18.15°C. Looking at the whole panel, the maximum Δt is 1.72K. The hottest areas are the upper left and the lower right corners.

Since, in this case, there is only one single channel through which the water passes, the water velocity in the screen is nearly constant – it is only at small areas around the bends that the water flows somewhat faster than elsewhere. Maximum velocity achieved is 1.6 m/s. The pressure drop for this model is large compared to other models, 58 000 Pa. This is the reason why this model is not suitable as thermal screen.
3.3.4 Thermal analysis of Model 4

Model 4 is a copy of Model 2, only with slimmer channels, 51 millimetres.

Three different inlet speeds have been tried: 0.3, 1 and 1.5 m/s.

Model 4a – water inlet velocity 1 m/s

1 m/s gives a mass flow of 0.05 kg/s. The temperature increase of the water is from 18.00°C to 18.63°C, although this higher temperature is almost invisible in the plot. There is a visible hot spot of about 18.3°C in the upper parts of the three middle vertical channels. The maximum panel temperature increase is 1.81K, and, like in the case of model 2, the hottest area of the plate is in the upper left corner.

Highest velocity rate is found in the outlet section: 1.1 m/s. The velocity in the five middle connecting channels is nearly zero. The pressure drop in the channels is calculated to 6 600 Pa.

Model 4b – water inlet velocity 0.3 m/s

The velocity of 0.3 m/s corresponds to a mass flow of 0.015 kg/s in the channels. The temperature of the water rises from 18.00°C to 18.87°C, and the hottest area is in the upper part of the middle vertical channel of the screen.

The maximum Δt for the whole plate is 2.01K. Like in the other temperature maps for this model, the hottest area is in the upper left-hand corner of the panel. There is also a slight increase in temperature in the lower left corner.

The low velocity lessens the demands on the water circulation system. This is implied by the modest pressure drop, only 1 900 Pa. Maximum velocity in the channels is reached in the inlet and outlet parts, and maximum value is about 0.4 m/s. In the five middle connecting channels of this design, the velocity is roughly zero.

Model 4c – water inlet velocity 1.5 m/s

With 1.5 m/s the flow rate is 0.08 kg/s and the water temperature rises from 18.00°C to 18.59°C. Again, the water reaches its warmest temperature in the upper part of the middle vertical channel. The maximum Δt of the whole panel is 1.77K. Hottest area: the upper left corner of the plate.

Velocity profile: again, in the five middle connecting channels, the velocity is about zero. Maximum velocity, 1.8 m/s, is in the outlet area.

The higher velocity gives somewhat larger pressure drop in the channels, about 10 600 Pa.
3.3.5 Thermal analysis of Model 5

Model 5 is similar to Model 4, except that it has two inlets and two outlets. The channel width is 51 millimetres.

![Figure 3-7: Model 5.](image1)

The idea with this design is to get rid of the problem with the local hot spots in the upper left and lower right corners, which have been experienced in the previous models of the thermal screen. Unfortunately, the water velocity in the middle of the vertical channels is so near zero, that the cooling effect here is virtually non-existing. The temperature difference in that area is about 10 K. Therefore, this model is unsuitable.

This model clearly demonstrates what will happen if the water velocity is too low to transport the heat away from the channels.

3.3.6 Thermal analysis of Model 6

One method to get rid of the local hot spots in the corners of the panels is to move the channels closer to those areas. Model 6 has the same design as models 1, 2 and 4, but the channels are put closer to the ends of the plate. The minimum distance of the channels from the edge must not, for manufacturing reasons, exceed 5 centimetres. In this model, the distance between the channel and the edge is 4.25 cm.

![Figure 3-8: Model 6.](image2)

The water inlet velocity is set to 1 m/s, which corresponds to an inlet mass flow of 0.035 kg/s. The pressure drop is about 6 400 Pa.
3.3.7 Thermal analysis of Model 7

Model 7 is of the same character as Model 6 but the plate dimensions are 1 275x1 026 mm. The widening of the plate is made in order to make the thermal screen fit better around the TPC. With this width, 18 panels will fit very smoothly together around the TPC field cage. The channel cross section area is 35x1 square millimetres.

![Figure 3-9: Model 7.](image)

Model 7a: the inlet water velocity is 1 m/s, which corresponds to a mass flow of 0.035 kg/s and a pressure drop of 6 500 Pa. The temperature of the whole plate increases from 18.00 to 19.25°C. The water temperature rises from 18.00 to 18.53°C. This looks very promising.

An inlet velocity of 1.5 m/s was also tried, Model 7b, but this did not result in any significant changes of the temperature profiles. The pressure drop however, increased to 10 200 Pa. Therefore, model 7a is more suitable than model 7b.
3.4 Results for the thermal screen

3.4.1 Simulation results

All CFD-simulated results are presented in Table 3.1.

<table>
<thead>
<tr>
<th>Model</th>
<th>Channel cross section area [m²]</th>
<th>Inlet velocity [m/s]</th>
<th>Mass flow [kg/s]</th>
<th>Δtwater [K]</th>
<th>Δtplate [K]</th>
<th>Δp [Pa]</th>
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<td>1.5·10⁻⁵</td>
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<td>0.02</td>
<td>1.00</td>
<td>1.31</td>
<td>9 900</td>
</tr>
<tr>
<td>2b</td>
<td>8·10⁻⁵</td>
<td>0.19</td>
<td>0.015</td>
<td>0.89</td>
<td>1.58</td>
<td>1 130</td>
</tr>
<tr>
<td>2a</td>
<td>8·10⁻⁵</td>
<td>1</td>
<td>0.08</td>
<td>0.21</td>
<td>1.25</td>
<td>6 700</td>
</tr>
<tr>
<td>2c</td>
<td>8·10⁻⁵</td>
<td>1.5</td>
<td>0.12</td>
<td>0.16</td>
<td>1.21</td>
<td>10 800</td>
</tr>
<tr>
<td>3</td>
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<td>0.15</td>
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<tr>
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<td>1.77</td>
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<td>10.29</td>
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<td>0.05</td>
<td>0.48</td>
<td>1.22</td>
<td>10 200</td>
</tr>
</tbody>
</table>

Table 3.1: Data from STAR-CD calculations of the thermal screen.

The conclusions drawn are that, as expected, higher water velocities result in more efficient cooling. The drawback is that the pressure drop increases quickly with higher water speed, and from this follows that it puts greater demands on the cooling water circulation system. Model 3 yielded too large pressure drop. Model 5 with its two inlets and two outlets proved to be a not so efficient solution due to the circulation difficulties in the vertical channels of the plate. The best models are numbers 2, 4, 6 and 7, since they succeed in cooling the whole plates efficiently, they have minimised the hot spots and since they do not have too large pressure drops.

Model 2 has the most efficient cooling effect. There is, however, a risk of the channel walls buckling due to the pressure drop in the cooling system.

Model 7, with its channels moved towards the plate ends, succeeds in reducing the hot spots in the corners. It has also a modest pressure drop and the ability to cool the plate efficiently, and is probably the most suitable model.

3.4.2 Hand-made calculations

The simulated pressure drops were recalculated by hand (Models 3 and 5 were left out as they have been judged as not of interest). Detailed calculations are presented in Appendix A2. A summary of the results of the hand-made calculations is shown in Table 3.2.

To enable calculations, the models have been simplified: in order to calculate the Reynolds number it has been assumed that the water flow is evenly spread over the number of tube channels in each model. In the calculations, all flows turn out to be laminar.
Table 3-2: Results from hand-made calculations.

As can be seen, the hand-calculated pressure losses are much smaller than the simulated values. One explanation for the differences could be that the hand-made calculations have omitted losses due to bends and changes in cross section areas etc.

A comparison of the calculated pressure drops and the simulated values are shown in figure 3-10.

![Comparison of pressure drops](image)

**Figure 3-10**: Comparison of pressure drops from hand-made calculations.

Although there is a clear difference between the simulated and the calculated values of pressure drops, at least they follow the same trend.

The heat transfer $q$ has also been calculated based on the inlet mass flow and the simulated increase of the water temperature. Comment: Unfortunately, there is apparently a misprint in the figure texts of the CFD calculation figures in Appendix A3, which state ‘tot.power 27.8 Watt’. This seems to be a misprint, as the hand-made calculations show different values.
3.4.3 Discussion on differences between simulations and hand-made calculations

The total effect influencing the TPC is set to 100 kW. The number of panels are 72, i.e. the effect on each panel is $100 \times 10^3 / 72 = 1389$ W.

This value differs from the effect derived from calculating on mass flow and increase of water temperature $(\bar{m} \cdot C_p \cdot \Delta t) = 0.035 \times 4179 \times 2 = 293$ W.

The differences imply that there are some unknown factors which affect the simulated values. It is impossible to say what causes this without analysis of the original simulation models and codes. Unfortunately, these are no longer available to the author. It would be of interest to redo the CFD simulations to see if change of any parameters would yield new and different results. This would have to be done in a separate study.
4 Modelling of the TPC field cage and the thermal screen

To thoroughly analyse the behaviour of the TPC and the thermal screen and how they influence each other, those two components had to be simulated together. As in the case of the thermal screen alone, this was done using the program STAR-CD. The TPC field cage was modelled, and the thermal screen, which influences its thermal profile, was added around it. Then the whole installation was studied. This was a feasibility study for the chosen model of the thermal screen.

4.1 The TPC field cage

The task of the TPC detector is to register particle tracks. Important conditions for this task are thermal stability and low permeability to surrounding gases.

The TPC is built of six major components: the inner and outer containment vessels, the inner and outer field cage vessels, and the two end plates. The vessels are cylindrical and made of composite materials. The choice of composite materials is due to their high stability and relatively low mass. In the middle of the field cage, the central high voltage electrode is mounted. This device provides the field cage with its electrical field, in which the particles will be ionised in the drift gas.

<table>
<thead>
<tr>
<th>Component</th>
<th>Radius [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner containment vessel</td>
<td>0.61</td>
</tr>
<tr>
<td>Inner field cage vessel</td>
<td>0.78</td>
</tr>
<tr>
<td>Outer containment vessel</td>
<td>2.58</td>
</tr>
<tr>
<td>Outer field cage vessel</td>
<td>2.75</td>
</tr>
<tr>
<td>Thermal screen</td>
<td>2.94</td>
</tr>
</tbody>
</table>

*Table 4-1: The components of the TPC and their radii.*

The spaces between the inner containment vessel and the inner field cage vessel, and between the outer containment vessel and the inner field cage vessel, will be filled with CO$_2$ gas to provide further protection against leakage, and insulation against high voltage breakdowns in the central drum (which contains the inner tracking system).

The TPC field cage is built of support rods put together, forming a cylindrical drum with a volume of 95 m$^3$. The drift gas in the TPC is a mixture of 90% Ne and 10% CO$_2$. The gas enters the drift volume through the inner support rods at one end of the cage and exits through the outer ones in the cage’s other end.
Figure 4-1: TPC field cage. The arrows show the direction of the NeCO$_2$ flow in the support rods (courtesy of CERN).

Figure 4-2: Side view of the TPC field cage. The arrows show the NeCO$_2$ inlet into the drift volume.

On the end plates, the readout chambers are mounted on aluminium support wheels. The task of the readout chambers is to amplify and register the particle tracks.

One heat source in the TPC is the resistor chain, which is located in one of the steel rods forming the field cage. Since this rod affects the drift gas, some precautions must be made to isolate it from immediate contact with the drift gas. However, since there are plans made to deal with this problem, the emitted heat
will not affect the temperature profile of the TPC and the thermal screen. In this thesis project the
temperature gradient between the resistor chain and the drift gas is assumed to be zero.

4.2 Modelling of mesh

The modelling of the thermal screen and the TPC consisted mainly of defining a new and more
complicated mesh in STAR-CD. The new mesh formed the 72 panels. The TPC with one of these 72
panels can be seen in figure 3.1.

Since every panel has its own supply of cooling water (as was mentioned in the beginning of chapter 1),
the inlet temperature for each panel can be set individually. The idea is to achieve the best possible
performance of the thermal screen.

To be able to make a more detailed analysis, each of the 72 panels was divided into nine sections, so that
each of these sectors was possible to regulate individually in the simulation. By this method, it is easier to
simulate the hot spots occurring in the corners of the thermal screen and to study the effect of the cooling
water.

Figure 4-3: Division of screen panel into nine sections.

The resulting image of the thermal screen around the TPC is showed in figure 4.4 below. The corners of
each panel are showed in white. These are the cells which can be regulated individually, thus permitting a
more advanced simulation.

Figure 4-4: Thermal screen around the TPC, side view.
Once the mesh of the field cage was created, the drift gas supply was simulated by creating a gas flow from the cells where the inner support rods are situated. In similar fashion, the drift gas outlet was put in the cells where the outer support rods are situated (see figures 4-1 and 4-2). Now the TPC and the thermal screen are made in the same model. Everything is ready for simulation and thermal analysis. The simulation of water flowing through the thermal screen around the TPC field cage can now begin.

### 4.3 Simulation of TPC and thermal screen

All panels are set to 291K and the drift gas flows through the drift volume. In this simulation, it is assumed that the heat map of the thermal screen is stable at 291K, in order to make it easier to evaluate the results of this last simulation. This means that the temperature of the thermal screen panels is assumed to be 291K although the CFD simulation indicated that the water is heated up a bit during the flow through the panels.

#### 4.3.1 Thermal behaviour of the thermal screen and the TPC

The simulated temperature maps of the thermal screen and the TPC together can be viewed in Appendix A4. It can be seen how the drift gas is at 291K entering one end of the TPC but immediately heats up and slowly gets warmer during its journey towards the other end. The total increase of temperature is about 2 degrees and is mainly showing in the far end of the TPC field cage – that means, near the outlet of the drift gas.

#### 4.3.2 Disaster scenario

The idea is to simulate and study the results if one of the 72 panels forming the thermal screen suddenly fails. This could be due to the water system failing, or possibly due to buckling or clogging of the channels, thus preventing the water from flowing freely through the panel in question.

The results of this simulation are shown in Appendix A5. It is clear that the TPC depends on better performance of the thermal screen. The temperature in the area is increased to a temperature of over 300K, which is unacceptable.
5 Conclusions

A thermal screen around the Time Projection Chamber (TPC) consisting of 72 different panels has been designed and its performance has been simulated in order to investigate its abilities to create a suitable environment for the experiments in the ALICE detector.

Although the design of the thermal screen panels is successful in achieving a stable temperature profile, the interaction between the screen and the TPC results in unwanted temperature fluctuations. The overall temperature difference in the sub-detector is 2 degrees, which is too much. This implies that the performance of the thermal screen is not satisfactory.

The main challenges are:

- The demand that the thermal screen’s maximum thickness is limited makes the conditions in the channels very difficult. The limitations in the material budget diminish the screen’s abilities to work efficiently as a cooling device.
- The design of the channels makes the flowing conditions difficult. The ratio between width and height tends to induce turbulent flow and large pressure drops, which are not acceptable due to the weakness of the aluminium in the channel walls.
- Higher velocity in the channels would improve the cooling of the screen. However, that is not possible since it automatically increases the pressure drop in the channels.
- The “disaster scenario” with one panel in the screen turned off, shows the vulnerability of the device. The temperature immediately rises to unwanted levels. Data achieved from any experiments performed with this screen would not be trusted to be articulate.

With the delicate conditions in the detector, it is an extremely difficult environment for a heat exchanger of this kind. The goal to create a uniform temperature in the area demands further investigations and, perhaps, different solutions. One proposed step is to try a different channel design of the thermal screen panels. Perhaps tilted channels (i.e. no 90° elbows) will enable the water to flow at higher speed without causing large pressure drops. This would provide more efficient cooling. Another proposed step is to feed the screen panels near the far end of the TPC field cage with water at lower temperatures than 291K, thus creating a more uniform temperature profile.

Perhaps the design team must reconsider a larger thermal screen. Thicker panels would improve the cooling abilities, but on the other hand, more material in the detector increases the risk of false data in the experiments. These facts must be taken into serious consideration before deciding which course to follow in the future.

When carrying out hand-made calculations to check the simulated values of the flow through one thermal screen panel, some problems were encountered. It turned out that calculations using basic thermodynamic formulas for pipe and channel flow did not result in values anywhere near the simulated values for pressure drops. In addition, calculations of the power input do not add up with what is known about the heat sources affecting the TPC. It is difficult to draw any specific conclusions on the reason for the differences in the results since the author does no longer have access to the CFD software and code files used; it can only be speculated upon what causes these differences.
6 Bibliography


7 Appendices

Appendix A1: Thesis project specification
Appendix A2: Hand-made calculations of pressure drops in thermal screen channels
Appendix A3: Temperature, pressure and velocity maps, thermal screen models 1-7
Appendix A4: Temperature maps for TPC and thermal screen
Appendix A5: Temperature maps with one screen panel turned off
Appendix A6: STAR-CD code, thermal screen panel
Project Definition
The cooling system of the ALICE detector

Specification of Master of Science Thesis
Ylva Almén
2000-2001, KTH, Stockholm
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Project Definition
The cooling system of the ALICE detector

Specification of Master of Science Thesis
Ylva Almén, KTH, Stockholm

1. Introduction

1.1 Purpose
The purpose of this document is to specify the scope of this thesis project and to present a plan for the different project phases.

1.2 Reader’s Guide
The reader is assumed to be familiar with basic concepts used in thermodynamics. On the last page can be found a list of abbreviations.

1.3 People in the project
The following people are directly involved in the project:

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Switzerland
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Email: guillermo.peon@cern.ch

Examiner at KTH
Björn Palm
Department of Energy Technology
KTH(Royal Institute of Technology)
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Sweden
Tel: +46 8 790 7453
Email: bpalm@egi.kth.se
2. Project definition

2.1 Background

2.1.1 CERN

CERN is the European Laboratory for Particle Physics, the world’s largest particle physics research centre. There are accelerators, which are used to accelerate particles to a fraction under the speed of light, and detectors to make the particles visible. This to explore what matter is made of, and what forces hold it together. Some 7000 scientists from more than 80 nations work here.

2.1.2 The LHC Project

The LHC, Large Hadron Collider, is a particle accelerator, which will be taken into operation in 2005. It will be built on the premises of the old accelerator, LEP (Large Electron-Positron collider). The LHC will be able to collide beams of protons at an energy level higher than ever before. Along the LHC tunnel, there will be four large detectors. The mission of these detectors is to record the results of particles colliding.

2.1.3 The ALICE and TPC detectors

ALICE, A Large Ion Collider Experiment, is one of the four detectors in the LHC accelerator. Its aim is to study the results of the colliding of heavy nuclei, such as lead. The Time Projection Chamber, TPC, is a sub-detector in the inner parts of the ALICE detector. In the TPC, the path of the originally charged particles will be reconstructed by measuring the arrival of electrons at the end of the chamber.

2.2 Goals/achievements

The aim of the thesis project is to solve the cooling problem in the TPC. Previous studies have shown that small temperature differences from the surrounding sub-detectors cause intolerable temperature differences in the drift gas of the TPC. To protect the Inner Tracking System, ITS (which surrounds the collision point), from large temperature fluctuations, an actively cooled thermal screen around the TPC is suggested.

2.3 Phases in the project/methods of attack

This section suggests a division of the project into phases, to give an overview of the work.
• Design of thermal screen
• Modelling of the TPC
• Thermal and fluid dynamics analysis of the thermal screen

With three roughly equally sized phases, each phase would be about six or seven weeks.

2.3.1 Design of thermal screen

The design phase includes a requirements phase, in which the assignment will be defined on a more detailed level. This phase will also involve communication with the people working in the project.

The main aim of the design phase is however to develop two or three different alternative designs for the thermal screen in the TPC. Therefore, a thorough 3-dimensional model of the whole sub-detector is necessary to produce. This will be done using the commercially available Computational Fluid Dynamics code STAR-CD. Finally, temperature maps and head loss will be evaluated and one design of the screen will be chosen.

2.3.2 Modelling of the TPC

Using the designed model of the thermal screen, the thermal influence in the drift gas of the surrounding sub-detectors and of some electronic components in the TPC will be analysed. Therefore, a model of the TPC is needed. The modelling must take into account the influence of the chosen thermal screen, new supply and exit for the drift gas, front electronics which can have impact on the temperatures in the chamber, and the boundary conditions for the ITS which is in the centre of the TPC.

2.3.3 Thermal and fluid dynamics analysis of the thermal screen

In the last phase is required a thorough analysis of the influence of the thermal screen temperature on the drift gas temperature in the TPC. If the results of this analysis are unacceptable, another design of the screen must be considered.

Finally, some analysis will be made concerning the changing of temperature at the TPC ends. What if one sector (or more) of the front electronics is turned off? The effects will be studied.

2.4 Review meetings

Approximately two meetings (not including the final report meeting) will be held at KTH in Stockholm in order to keep the examiner informed of how the project is proceeding. This number may be increased or decreased, depending on the author’s number of visits to Stockholm.
2.5 Documentation

Documentation will be done continuously throughout the whole project, concurrently with the other phases. A report of the status and proceedings of the project is to be sent by email to Stockholm every two weeks.

2.6 Milestones

A few milestones will be of help keeping the project on schedule. They are approximate indications of what goals should be reached at certain dates.

- 27th of October, 2000: 1/3 report: two or three alternative designs of the thermal screen
- 21st of December, 2000: 2/3 report: model of the TPC produced
- 1st of March, 2001: Final report

2.7 Abbreviations

- **ALICE**: A Large Ion Collider Experiment. One of four detectors in the new particle accelerator, LHC, which will be built at CERN. In ALICE, the collisions between heavy nuclei will be studied.
- **CERN**: European Laboratory for Particle Physics "Conseil Européen pour la Recherche Nucléaire" (1951), later (1953) renamed to “Organisation européenne pour la recherche nucléaire” or “European Organization for Nuclear Research”. A laboratory for particle physics, situated close to Geneva on the border of Switzerland and France, and still often referred to by the first acronym.
- **ITS**: Inner Tracking System. Sub-detector in the inner parts of the ALICE detector.
- **LEP**: Large Electron-Positron collider. The presently largest accelerator at CERN.
- **LHC**: Large Hadron Collider. An accelerator under construction at CERN. It will replace LEP and is projected to be operational in 2005.
- **TPC**: Time Projection Chamber. A sub-detector in the ALICE detector.
Hand-made calculations of pressure drops in thermal screen channels

Calculation of Reynolds number

Formula used: (Ekroth and Granryd), formula 10.22: \( \text{Re} = \frac{u_{\text{mean}} d_{\text{eq}}}{\nu} \), where
- Mean velocity \( u_{\text{mean}} \) is calculated based on the assumption that the flow in the model is evenly spread over the number of channels
- Hydraulic diameter \( d_{\text{eq}} = \frac{4 A}{P} \) (\( A=\)channel cross section area, \( P=\)perimeter of the channel)
- Viscosity of water, \( \nu = 1 \times 10^{-6} \text{ m}^2/\text{s} \)

Calculation of friction coefficient \( f_1 \)

Formula used: (Ekroth and Granryd) formula 10.27: \( f_1 = \frac{C_1}{\text{Re}} \), where
\( C_1 = \{\text{channel width} < < \text{channel height}\} = 48 \)

Calculation of pressure drop \( \Delta p \)

It is assumed that the flow is evenly spread over all channels. The contribution of the pressure drop in the parallel channels will be insignificant compared to the total pressure drop. Assume that the length of the parallel channels is near zero \( \rightarrow \) the upper and lower horizontal channels are the so-called corresponding channel length, \( L \). This is equivalent of the plate length, 1.25 m.

Formula used: (Ekroth and Granryd) formula 10.18: \( \Delta p = f_1 \rho \frac{w^2}{d} L \), where
- \( f_1 = \) friction coefficient
- \( \rho = \) water density: 1000 kg/m\(^3\)
- \( w = \) velocity in the channels (evenly spread over the channels, i.e. \( u_{\text{mean}} \))
- \( L = L_c = \) corresponding channel length according to the above assumptions
- \( d = d_{\text{eq}} \)

Calculation of heat transfer coefficient \( \alpha \)

Assuming flow evenly spread over the channels

Formula: (Holman) 6-9: \( Nu = 3.66 + [0.0668(d/L)\text{RePr}]/[1+0.04(d/L)\text{RePr}]^{2/3} \), however this is valid for fully laminar flow in circular tubes. For flow in ducts of geometry width \( < < \) height, the constant to be used is 7.54 instead of 3.66 (according to (Ekroth and Granryd) 11.76).

(Holman) Table A-9 (water at 20°C): \( \text{Pr}=6.78 \); \( k =0.604 \text{ W/mK} \); \( \text{Cp} = 4.179 \text{ kJ/kgK} \)

Formula used: (Ekroth and Granryd) 11.50:

Heat transfer coefficient \( \alpha = Nu \times \lambda / L \), where
- Thermal conductivity \( \lambda = k = 0.604 \text{ W/mK} \)

Assuming that the majority of the heat transfer occurs in the vertical, parallel channels (thus assuming that heat transfer in the horizontal parts of the channels is close to zero). The corresponding channel length \( L = L_c \) is, according to the above assumptions, equal to the horizontal channel length = 0.8 m.
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<tr>
<th>Model</th>
<th>Channel cross sect. area A (m²)</th>
<th>Inlet velocity (m/s)</th>
<th>Mean velocity (m/s)</th>
<th>Mass flow ṁ</th>
<th>Reynolds number Re</th>
<th>Friction factor f₁</th>
<th>Hand-made calc.Δp [Pa]</th>
<th>CFD simulation Δp [Pa]</th>
<th>Calculated Heat transfer q = ṁ·Cₚ·ΔT</th>
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Comparison of pressure drops

![Comparison of pressure drops](image)
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<td><strong>Storheter</strong></td>
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<td>massflöde $\dot{m}$ (kg/s)</td>
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<td><strong>III Tryckförlust $\Delta p$</strong></td>
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<td>$\Delta p = f1 \cdot \rho \cdot u^2 \cdot Lk / d$ där korr.längden Lk</td>
<td>1,25</td>
<td>$\Delta p = f1 \cdot \rho \cdot u^2 \cdot Lk / d$ där korr.längden Lk</td>
</tr>
<tr>
<td><strong>IV Värmeövergångstal $\alpha$</strong></td>
<td><em><em>Nu=7,54+[0,0668</em>(dekv/L)<em>Re</em>Pr]/(1+0,04(dekv</em>Re*Pr/L)^0,67)]**</td>
<td><em><em>Nu=7,54+[0,0668</em>(dekv/L)<em>Re</em>Pr]/(1+0,04(dekv</em>Re*Pr/L)^0,67)]**</td>
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<td>Pr (tab A9, ca 20gr)</td>
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<td>Pr (tab A9, ca 20gr)</td>
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<td>Värmeledn.tal k</td>
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<tr>
<td>Nu=</td>
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<td>u inlopp (m/s)</td>
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<td>d-ekv: 4A/P (m)</td>
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<td>där korr.längden Lk</td>
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**IV Värmeövergångstal α**

Nu=7,54+[(0,0668*(dekv/L)*Re*Pr/[(1+0,04)(dekv*Re*Pr/L)*0,67])
Pr (tab A9, ca 20gr) 3,6
Värmeledn.tal k 0,604
Nu= 7,764011
α= Nu * k / dekv 2374,04
Lk= 0,8

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<td>u inlopp (m/s)</td>
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<td>d-ekv: 4A/P (m)</td>
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<td>Viskositet v (m²/s)</td>
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<td></td>
<td>u medel (m/s)</td>
<td>0,0211111</td>
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<td>I Reynolds tal Re</td>
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**IV Värmeövergångstal α**

Nu=7,54+[(0,0668*(dekv/L)*Re*Pr/[(1+0,04)(dekv*Re*Pr/L)*0,67])
Pr (tab A9, ca 20gr) 3,6
Värmeledn.tal k 0,604
Nu= 7,5852119
α= Nu * k / dekv 2319,3682
Lk= 0,8

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<td>Viskositet v (m²/s)</td>
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<tr>
<td></td>
<td>u medel (m/s)</td>
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**IV Värmeövergångstal α**

Nu=7,54+[(0,0668*(dekv/L)*Re*Pr/[(1+0,04)(dekv*Re*Pr/L)*0,67])
Pr (tab A9, ca 20gr) 3,6
Värmeledn.tal k 0,604
Nu= 7,755558
α= Nu * k / dekv 2371,456
Lk= 0,8
Tabel 1: Modelldata för tre olika modeller

<table>
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<tr>
<th>Modell</th>
<th>Bredd (m)</th>
<th>Höjd (m)</th>
<th>Antal kanaler</th>
<th>Storheter</th>
<th>Massflöde ( \dot{m} ) (kg/s)</th>
<th>U inlopp (m/s)</th>
<th>( d )-ekv: ( 4A/P ) (m)</th>
<th>Densitet ( \rho ) (kg/m(^3))</th>
<th>Viskositet ( \nu ) (m(^2)/s)</th>
<th>( u ) medel (m/s)</th>
<th>( \Delta p / f_1^* \rho u(\dot{\nu})^2L_k / d ) korr.längd (m)</th>
<th>( \Delta p = f_1^* \rho u(\dot{\nu})^2L_k / d ) korr.längd (m)</th>
<th>Värmeövergångstal (Nu)</th>
<th>( \alpha = \frac{Nu \cdot k \cdot dekv}{\dot{m}} ) (W/m(^2)/K)</th>
<th>( L_k = \frac{Nu}{\alpha} ) (m)</th>
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<td>0,3</td>
<td>0,001962</td>
<td>1000</td>
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<td>0,033333</td>
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<td>1000</td>
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<td>0,0765</td>
<td></td>
<td>1,25</td>
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<td>32,69231</td>
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</table>

I. Reynolds tal \( Re \) = \( \frac{\dot{m} \cdot u}{\rho \cdot d} \)

II. Friktionsfaktor \( f_1 \) = \( 0,16667 \cdot \frac{Re \cdot \nu}{d} \)

III. Tryckförlust \( \Delta p \) = \( f_1^* \frac{\rho \cdot u(\dot{\nu})^2 \cdot L_k}{d} \)

IV. Värmeövergångstal (Nu) = \( 7,54 + \left[ \frac{0,0668 \cdot (dekv) / L \cdot Re \cdot Pr}{1 + 0,04 \cdot (dekv \cdot Re \cdot Pr / L)^{0,67}} \right] \)

\( Pr \) (tab A9, ca 20gr) = 6,74

Värmeledn. tal \( k \) = 0,604

Nu = 7,609662

\( \alpha = \frac{Nu \cdot k \cdot dekv}{\dot{m}} \) = 2343,179

Lk = 0,8

Appendix A2
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<td>A=</td>
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<tr>
<td><strong>Storheter</strong></td>
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<td>d-ekv: 4A/P (m)</td>
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<td>Densitet ρ (kg/m³)</td>
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</tr>
<tr>
<td>Viskositet ν (m²/s)</td>
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<tr>
<td>u medel (m/s)</td>
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<tr>
<td>Massflöde medel, ṁ m</td>
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<tr>
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</tr>
<tr>
<td><strong>II Friktionsfaktor f1</strong></td>
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<td><strong>III Tryckförlust Δp</strong></td>
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<td>Δp=f1<em>ρ</em>u(²)*Lk / d</td>
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<td>där korr.längden Lk</td>
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<tr>
<td><strong>IV Värmeövergångstal α</strong></td>
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</tr>
<tr>
<td>Nu=7,54+[(0,0668*(dekvl/L)<em>Re</em>Pr)/(1+0,04*(dekvl<em>Re</em>Pr/L)⁰,⁶⁷)]</td>
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<tr>
<td>Pr (tab A9, ca 20gr)</td>
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### Modell 7a

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**Antal kanaler**
12

**Storheter**

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<td>( d )-ekv: ( 4A/P ) (m)</td>
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<table>
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<th>Densitet ( \rho ) (kg/m³)</th>
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</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>( u ) medel (m/s)</td>
<td>0,083333</td>
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</tbody>
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**Massflöde medel, \( \dot{m} \) m**

**I Reynolds tal \( Re \)**
162,037

**II Friktionsfaktor \( f_1 \)**
0,296229

**III Tryckförlust \( \Delta p \)**
1322,449

\( \Delta p = f_1 \cdot \rho \cdot u^2 \cdot Lk / d \)

**där korr. längden \( Lk \)**
1,25

**IV Värmeövergångstal \( \alpha \)**

\[ \text{Nu} = 7,54 + [0,0668 \cdot (\text{dekv}/L) \cdot \text{Re} \cdot \text{Pr}] / (1 + 0,04 \cdot (\text{dekv} \cdot \text{Re} \cdot \text{Pr}/L)^{0,67}) \]

**Pr (tab A9, ca 20gr)**
6,78

**Värmeledn.tal \( k \)**
0,604

**Nu =**
7,673798

**\( \alpha = \text{Nu} \cdot k / \text{dekv} \)**
2383,701

**Lk =**
1

---

### Modell 7b

<table>
<thead>
<tr>
<th>Bredd</th>
<th>0,035</th>
<th>Höjd h</th>
<th>0,001</th>
<th>P</th>
<th>0,072</th>
<th>A</th>
<th>0,000035</th>
</tr>
</thead>
</table>

**Antal kanaler**
12

**Storheter**

<table>
<thead>
<tr>
<th>Massflöde ( \dot{m} ) (kg/s)</th>
<th>0,0525</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u ) inlopp (m/s)</td>
<td>1,5</td>
</tr>
<tr>
<td>( d )-ekv: ( 4A/P ) (m)</td>
<td>0,001944</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Densitet ( \rho ) (kg/m³)</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viskositet ( \nu ) (m²/s)</td>
<td>0,000001</td>
</tr>
<tr>
<td>( u ) medel (m/s)</td>
<td>0,125</td>
</tr>
</tbody>
</table>

**Massflöde medel, \( \dot{m} \) m**

**I Reynolds tal \( Re \)**
243,056

**II Friktionsfaktor \( f_1 \)**
0,197486

**III Tryckförlust \( \Delta p \)**
1983,673

\( \Delta p = f_1 \cdot \rho \cdot u^2 \cdot Lk / d \)

**där korr. längden \( Lk \)**
1,25

**IV Värmeövergångstal \( \alpha \)**

\[ \text{Nu} = 7,54 + [0,0668 \cdot (\text{dekv}/L) \cdot \text{Re} \cdot \text{Pr}] / (1 + 0,04 \cdot (\text{dekv} \cdot \text{Re} \cdot \text{Pr}/L)^{0,67}) \]

**Pr (tab A9, ca 20gr)**
6,78

**Värmeledn.tal \( k \)**
0,604

**Nu =**
7,736864

**\( \alpha = \text{Nu} \cdot k / \text{dekv} \)**
2403,291

**Lk =**
1
MODEL 1a: Water velocity 1 m/s

Above: Velocity map:

Pressure map:
Temperature map:

Thermal screen between TPC and TRD. Temperature map. Model1
Dim=1250x583, channel dim=15x1, Tot. power=27.85Watt, v(water)=1 m/s
Y. Almen (ST/CV)

Overall temperature map:

Thermal screen between TPC and TRD. Velocity map. Model1
Dim=1250x583, channel dim=15x1, Tot. power=27.85Watt, v(water)=1 m/s
Y. Almen (ST/CV)
MODEL 1c: Water velocity 1.5 m/s

Velocity map:

13-NOV-**
VELOCITY MAGNITUDE
M/S
ITER = 200
LOCAL MX = 1.802
LOCAL MN = 0.7598E-1

1.802
1.873
1.545
1.417
1.289
1.161
1.033
0.9045
0.7764
0.6482
0.5201
0.3919
0.2638
0.1357
0.7598E-02

Thermal screen between TPC and TRD. Velocity map, Model1
Dim = 1250x983, channel dim = 15x1, Ttot. power = 27.8 watt, v(water) = 1.5 m/s
V. Almen (STC/CV)

Pressure map:

13-NOV-**
PRESSURE
RELATIVE
REL
ITER = 200
LOCAL MX = 0.0000
LOCAL MN = 9932

0.0000
-709.4
-358.7
-4357
-4966
-5076
-6385
-7094
-9932
-9352
-9233
-9513

Thermal screen between TPC and TRD. Pressure map, Model1
Dim = 1250x983, channel dim = 15x1, Ttot. power = 27.8 watt, v(water) = 1.5 m/s
V. Almen (STC/CV)
MODEL 1c: Water velocity 1.5 m/s

Temperature map:

Overall temperature map:
MODEL 2b: Water velocity 0.19 m/s

Velocity map:

Pressure map:

Thermal screen between TPC and TRD. Velocity map, Model2
Dim=1250x883, channel dim=15x1, Tot. power=27.8kWatt; v(water)=0.19m/s
V. Ahmenn (ST/CY)

Thermal screen between TPC and TRD. Pressure map, Model2
Dim=1250x883, channel dim=15x1, Tot. power=27.8kWatt; v(water)=0.19m/s
V. Ahmenn (ST/CY)
MODEL 2b: Water velocity 0.19 m/s

Temperature map:

Overall temperature map:

Thermal screen between TPC and TRD. Temperature map, Model2
Dim = 1250x988, channel dim = 15x1, Ttot_power = 27.8 watt, v(water) = 0.19 m/s
Y. Almen (ST/CV)
MODEL 2a: Water velocity 1 m/s

Velocity map:

Thermal screen between TPC and TRD. Velocity map. Model 1
Dim=1250x80x4, channel dim=60x1, Tot. power=27.8 watt, v(water)=1 m/s
Y. Almen (STiC) 

Pressure map:

Thermal screen between TPC and TRD. Pressure map. Model 2
Dim=1250x80x4, channel dim=60x1, Tot. power=27.8 watt, v(water)=1 m/s
Y. Almen (STiC)
MODEL 2a: Water velocity 1 m/s

Temperature map:

Overall temperature map:
MODEL 2c: Water velocity 1.5 m/s

Velocity map:

Pressure map:

Thermal screen between TPC and TRD. Velocity map, Model2
Dim=1250x2653, channel dim=80x1, Tot. power=27.9kwatt, v(water)=1.5m/s
Y. Almen (ST/CV)

Thermal screen between TPC and TRD. Pressure map, Model2
Dim=1250x2653, channel dim=80x1, Tot. power=27.9kwatt, v(water)=1.5m/s
Y. Almen (ST/CV)
MODEL 2c: Water velocity 1.5 m/s

Temperature map:

Thermal screen between TPC and TRD. Temperature map, Model2
Dim=1250x853, channel dim=80x1, Tot. power=27.8watt, v(water)=1.5m/s
Y. Almen (ST/CV)

Overall temperature map:

Thermal screen between TPC and TRD. Temperature map, Model2
Dim=1250x853, channel dim=80x1, Tot. power=27.8watt, v(water)=1.5m/s
Y. Almen (ST/CV)
MODEL 3 Water velocity 1 m/s

Velocity map:

Pressure map:

Thermal screen between TPC and TRD: Velocity map, Model3
Dim=1560x853, channel dim=51x1, Tot. power=27.6 watt, v(water)=1 m/s
Y. Almen (STFCV)

Thermal screen between TPC and TRD: Pressure map, Model3
Dim=1250x853, channel dim=51x1, Tot. power=27.6 watt, v(water)=1 m/s
Y. Almen (STFCV)
MODEL 3: Water velocity 1 m/s

Temperature map:

Overall temperature map:

Thermal screen between TPC and TRD. Temperature map, Model3
Dim=1250x693, channel dim=51x1, Tct. power=27.8watt, v(water)=1 m/s
Y. Almen (ST/CC)
MODEL 4a: Water velocity 1 m/s

Velocity map:

Pressure map:

Thermal screen between TPC and TRD. Velocity map, Model4
Dim=1250x853, channel dim=51x1, Tot. power=27.8watt, v(water)=1m/s
Y. Almen (ST/CV)

Thermal screen between TPC and TRD. Pressure map, Model4
Dim=1250x853, channel dim=51x1, Tot. power=27.8watt, v(water)=1m/s
Y. Almen (ST/CV)
MODEL 4a: Water velocity 1 m/s

Temperature map:

Overall temperature map:

Thermal screen between TPC and TRD. Temperature map, Model4
Dim=1250x283, channel dim=51x1, Tot. power=27.8watt, v(water)=1m/s
Y. Almen IST/CV
MODEL 4b: Water velocity 0.3 m/s

Velocity map:

Pressure map:
MODEL 4b: Water velocity 0.3 m/s

Temperature map:

Overall temperature map:
MODEL 4c: Water temperature 1.5 m/s

Velocity map:

Temperature screen between TPC and TRD. Velocity map. Model4
Dim = 1250x853, channel dim = 51x1, Tot. power = 27.8kWatt, v(water) = 1.5m/s
Y. Almen (ST/CV)

Pressure map:

Temperature screen between TPC and TRD. Pressure map. Model4
Dim = 1250x853, channel dim = 51x1, Tot. power = 27.8kWatt, v(water) = 1.5m/s
Y. Almen (ST/CV)
MODEL 4c: Water velocity 1.5 m/s

Temperature map:

Overall temperature map:

Thermal screen between TPC and TRD. Temperature map, Model 4
Dim = 1250x993 channel dim = 51x1, Tot. power = 27.9Watt, v(water) = 1.5m/s
V. Almen (ST/CV)
Model 7

12-Dec-00
VELOCITY MAGNITUDE
M/S
ITER = 68
LOCAL MX = 1.140
LOCAL MN = 0.8545E-02

1.140
1.059
0.9760
0.6972
0.6164
0.7356
0.6548
0.5741
0.4933
0.4125
0.3317
0.2509
0.1701
0.8933E-01
0.8545E-02

Thermal screen between TPC and TRD. Velocity map, Model7
Dim = 1250x1000, channel dim = 35x1, Tot. power = 27.8 Watt, v(water) = 1 m/s
Y. Almen (ST/CV)

12-Dec-00
PRESSURE
RELATIVE
PA
ITER = 68
LOCAL MX = 0.0000E+00
LOCAL MN = -6530.

0.0000E+00
-4564
-328.6
-1339
-1986
-2332
-2799
-3265
-3731
-4198
-4664
-5130
-5597
-6063
-6530.

Thermal screen between TPC and TRD. Pressure map, Model7
Dim = 1250x1000, channel dim = 35x1, Tot. power = 27.8 Watt, v(water) = 1 m/s
Y. Almen (ST/CV)
Resultat
"Katastrofscenario" – en panel ur funktion

6/12/2001

"Katastrofscenario"

6/12/2001

Appendix A5 to Report EG1-2015-052MSC
Disaster scenario - 1 panel malfunctioning
"Katastrofscenario"

Resultat, sammanfattning

- Maximal temperaturskillnad i TPC:n med skärm är 2 K, vilket överskrider önskade värden.
- Vid extremfallet då en av panelerna i skärmens är avstängd, blir maxdifferensen 11.3 K
DEFINITION OF BOUNDARY

INLET OF WATER
rdef,1,inlet,standard set add grange evav(y-0.0001) evav(x-0.0001) evav(x+0.0001) evav(y+0.0001) evav(z-0.0001) evav(z+0.0001) 1.0.0.1.0.291.998

OUTLET OF WATER
rdef,2,outlet
split 1

EXTerior TEMPERATURE
rdef,3,wall,standard

flux 25.16
iter,200.0.001
con,0.01
pows,0.01

#define cset

!CHANGE TO THE ALUMINIUM CELLS

cset,news grange -1e6 1e6 -1e6 1e6 -1e6 1e6 0.0005
type 2

cmod cset

cset news type 1

gm 1
�get non1 mncset
moni moni
pres,1.e-05,moni1

cset news type 2

gm 2
�get mon2 mncset
moni moni

BOUNDARIES

water inlet
cset news grange evav(x-0.0001) evav(x+0.0001) evav(y-0.0001) evav(y+0.0001) evav(z-0.0001) evav(z+0.0001) zoom off
view -1 0 0
plty children
cplot
brcme 1 all

water outlet
cset news grange evav(x-0.0001) evav(x+0.0001) evav(y-0.0001) evav(y+0.0001) evav(z-0.0001) evav(z+0.0001) zoom off
view 1 0 0
cplot
brcme 2 all

texterior heat flux
cset all
view 0 0 1
cplot
brcme 3 all

tvset news grange 0 evav(x-0.0001) -1e6 1e6 -1e6 1e6 2
!bset news region 7
!bset subs vset any
!rdef1,bset