Resum

CERN és el Consell Europeu de la Investigació Nuclear. És el laboratori més gran de física de partícules, on científics de tot el món estudien l’estructura de la matèria i les forces que la mantenien unida per aconseguir així entendre millor el comportament i l’origen de l’univers. Actualment s’ha començat a posar en marxa el més gran i potent accelerador de partícules del món, l’anomenat Large Hadron Collider (LHC); situat a la frontera franco-suïssa, ocupant una superfície de 27km i a una profunditat de 100m.

El LHC és un tunnel d’uns 2 metres de diàmetre, dividit en vuit parts o sectors, per on circularan les partícules transferides amb certa acceleració; aquestes partícules es mouen a través d’uns tubs més petits envoltats d’imants que s’encarreguen de mantenir-les en el seu camí. La línia d’imants i altres components del LHC desprenen calor i per això cal mantenir un correcte sistema de ventilació. El departament TS/CV (Technical Support/Cooling Ventilation) s’encarrega del dimensionament i creació de les línies de ventilació. Dins del departament existeix el grup CFD (Computational Fluid Dynamics) on es desenvolupa aquest projecte.

El projecte consisteix en crear un model complet, real però simplificat, en 3 dimensions del sector 5-6 del LHC per tal de realitzar diferents simulacions utilitzant les tècniques CFD. La finalitat és demostrar que el model creat funciona correctament i pot reflectir situacions reals que permetran un millor coneixement de la ventilació del tunel, tant en situació nominal com en situacions d’acciò, i l’obtenció d’informació molt útil per al sistema de seguretat i pel manteniment i millora de les instalacions.

Al llarg del projecte es descriuen els passos seguits per la creació del model, el mallat i el càlcul de les condicions de contorn. També es descriu la simulació en estat nominal i una simulació de risc que consisteix en incloure un focus de fum dins el tunel. Després s’analitzen els resultats i s’estreuen les conclusions pertinents.
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1 Glossary

Explanation of the terms used in this document:

**CERN**: CERN is the European Organization for Nuclear Research. It is the world’s largest particle physics laboratory.

**LHC**: the term LHC stands for Large Hadron Collider, the new particle accelerator at CERN.

**IP (Interaction Points, Experimental Points)**: points of the LHC where the particles bunch travelling in opposite senses collide against each other.

**CMS**: CMS is one of the CERN experiments situated in point 5, the term CMS stands for Compact Muon Solenoid.

**ATLAS**: ATLAS is also another experiment situated in point 1; the term ATLAS stands for A Toroidal LHC AparatuS.

**ALICE**: ALICE is the third experiment situated in point 2, the term ALICE stands for A Large Ion Collider Experiment.

**TS**: Technical Support Department.

**CV**: Cooling Ventilation Group.

**DC**: Detector Cooling Section.

**CFD**: Computational Fluid Dynamics.

**Cv**: Cell Volume.

**CDD**: CERN Drawing Directory.

**PS**: Proton Synchrotron

**LEP**: Large Electron Positron
2 **Introduction**

2.1 **Origin of the project**

This project was raised to solve some possible future problems of ventilation, in case of emergency or failure of the installation, of the Large Hadron Collider (LHC) at CERN using simulation software to recreate the real conditions inside the tunnel during the time of functioning. To achieve this goal a 3Dimension model must be created and used to simulate these conditions. The results of these simulations and studies can then be used to solve existing problems, to improve the ventilation system or to propose changes in the design of the air extraction and cooling maintenance system.

2.2 **Motivation**

The most important motivation was the possibility to develop this project working in an international organization like CERN, the European Organization for Nuclear Research. CERN currently employs engineers, physicists and many other people to conduct research using modern technology and it gives the possibility to improve the engineering knowledge and language skills.

Another important motivation was the opportunity to design a 3D model to give potential results for posterior studies and collaborate in a real engineering project.

After working at CERN for one year I have discovered the huge amount of possibilities for increasing my scientific and technical skills giving me the opportunity to work in this multicultural environment that allows me to know different mentalities and ways of life and work.
2.3 Aim and scope of the project

The aim of the project is to create a 3-dimensional model of the LHC sector 5-6, study and simulate the ventilation system in different boundary conditions, analyse the results and raise some improvements. To accomplish this objective, a software to create the model and another software to import it and perform the simulations; the project describes the different steps followed to create, mesh and simulate the model and to apply the correct different situations inside the tunnel. The tunnel is divided into eight similar parts, but only one of these parts is considered to develop the study, the tunnel between CMS - point 5 and point 6, sector 5-6, the other sectors can be assimilated to this one.

The scope of the project involves determining the best way to keep the tunnel’s safety even in case of abnormal conditions and to make the ventilation system as effective as possible. A series of simulations are foreseen in order to answer these questions. Once the results are obtained specific conclusions can be drawn with the aid of programs like Catia and StarCD+.

The tunnel has been closed on September 2008, but every improvement to proposed which involves a technical operation inside the tunnel can be considered after this date if it means an improvement of the LHC function conditions.
3 Introduction to CERN

CERN is a European Organization for Nuclear Research, founded in 1954. It is a laboratory where scientists unite to study the building blocks of matter and the forces that hold them together and to reach a better understanding of the behavior of the universe. The idea to combine the national science laboratories of Europe into one big science organization was born in 1949 and was first proposed by the French physicist and noble-prize winner Louis de Broglie [Ref. 1].

CERN is located on both sides of the France-Swiss border in the north of Geneva. (Fig. 3.1). Nowadays CERN is composed of 20 member States: Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland and the United Kingdom (Fig. 3.2)

Figure 3.1: CERN's location
But CERN is also composed of other countries that can collaborate but they can not take any decision, they are called Observer States and Non-Member States. Observer States and Organizations currently involved in CERN programmes are: the European Commission, India, Israel, Japan, the Russian Federation, Turkey, UNESCO and the USA. Non-Member States currently involved in CERN programmes are: Algeria, Argentina, Armenia, Australia, Azerbaijan, Belarus, Brazil, Canada, Chile, China, Colombia, Croatia, Cuba, Cyprus, Estonia, Georgia, Iceland, Iran, Ireland, Lithuania, Mexico, Montenegro, Morocco, New Zealand, Pakistan, Peru, Romania, Serbia, Slovenia, South Africa, South Korea, Taiwan, Thailand, Ukraine and Vietnam.

CERN builds and operates the particle accelerators needed for particle physics research in a unique centre which allows physicists around Europe to collaborate more fruitfully than if each country maintained an independent program.

CERN employs just around 2500 people. The Laboratory’s scientific and technical staff designs and builds the particle accelerators and ensures their smooth operation. They also help prepare, run, analyse and interpret the data from complex scientific experiments.
Some 8000 visiting scientists, half of the world’s particle physicists, come to CERN for their research. They represent 580 universities and 85 nationalities.

In the first three years after its opening, CERN worked on the construction of its first particle accelerator. In 1957, the proton Synchro-Cyclotron (SC) was switched on and after a short time, recorded the first results of pions decaying into an electron and a neutrino, as predicted by the weak interaction theory. The machine worked at a total collision power of a 600MeV. This power was multiplied by almost 50 when only two years later, CERN’s first major machine, the Proton Synchrotron (PS), came into operation. With its 24GeV power with which the protons collide, it was the biggest accelerator in the world.

In 1981, the CERN council approved the construction of a 27km circumference Large Electron-Positron collider (LEP) ring, the largest scientific instrument ever created, for an initial operating energy of 50GeV per beam. This new instrument lead to very accurate measurements of the Z-boson decay and confirmed the Standard Model of particle physics.

At present, CERN has just built the Large Hadron Collider (LHC) in the old tunnel of the LEP experiment. Two large detector experiments, ATLAS (A Toroidal LHC Aparatus) and CMS (Compact Muon Solenoid), will look for the Higgs boson, a particle predicted by the latest theories of modern physics. After the estimated start of these detector experiments, the LHC will collide protons with an energy of 14TeV. Besides the acceleration of protons, the LHC will accelerate lead nuclides up to a total collision power of 1150TeV which is almost equal to the power density in the universe short after the Big Bang. Together with ATLAS and CMS, two other experiments will be fed by the LHC: a dedicated heavy ion detector, ALICE, which will be built to exploit the unique physics potential of nucleus-nucleus interactions at LHC energies, and LHC-B, which will carry out precision measurements of CP-violation and rare decays of B mesons (Fig. 3.3). Because of the huge amount of events produced during operation, 800 million collisions per second, the detectors and the computer facilities have to handle as much information as the whole European telecommunication networks
investigation of the ventilation system of the LHC tunnel using CFD techniques

combined.

Not only high energy physics are practiced at CERN. The desire to discover new physical laws led to many new inventions in the fields of informatics and engineering. Tim Berners-Lee proposed in 1990 a distributed information system, based on 'hypertext'. By hiding network addresses behind highlighted items on the screen, information can be linked between several computers. The chosen name for this new invention was the "World-Wide Web".

![Diagram of the CERN network of interlinked accelerators and colliders](image)

Figure 3.3: the CERN network of interlinked accelerators and colliders

3.1 CERN's structure

The CERN Council is the highest authority of the Organization and has responsibility for all important decisions. It controls CERN's activities in
scientific, technical and administrative matters. The Council approves programmes of activity, adopts the budgets and reviews expenditure.

The Council is assisted by the Scientific Policy Committee and the Finance Committee.

The Director-General, appointed by the Council, manages the CERN Laboratory. He is assisted by a Directorate and runs the Laboratory through a structure of Departments.

CERN is run by 20 European Member States, each of which has two official delegates to the CERN Council. One represents his or her government’s administration; the other represents national scientific interests. Each Member State has a single vote and most decisions require a simple majority, although in practice the Council aims for a consensus as close as possible to unanimity.

The Scientific Policy Committee evaluates the scientific merit of activities proposed by physicists and makes recommendations on CERN’s scientific programme. Its members are scientists elected by their colleagues on the Committee and appointed by Council on the basis of scientific eminence without reference to nationality. Some members are also elected from non-Member States.

The Finance Committee is composed of representatives from national administrations and deals with all issues relating to financial contributions by the Member States and to the Organization’s budget and expenditure.

Appointed by Council, usually for five years, the Director-General manages CERN. The Director-General is assisted by a Directorate, whose members he proposes to Council. The Director-General reports directly to the Council. He can also propose to Council any adjustment he deems necessary to meet the evolving needs of the research programme.
3.1.1 Departments

CERN is divided in seven departments: Accelerators and Beams (AB), Accelerator Technology (AT), Finance (FI), Human Resources (HR), Information Technology (IT), Physics (PH) and Technical Support (TS); which include and carry all the studies, managements and organizations into the CERN.
4 The Large Hadron Collider (LHC)

4.1 The LHC project

The LHC, the world’s largest and most powerful particle accelerator, is the latest addition to CERN’s accelerator complex. It mainly consists of a 27 km ring of superconducting magnets with a number of accelerating structures to boost the energy of the particles along the way. It is situated near Geneva, where it spans the border between Switzerland and France about 100 m underground [Ref. 2].

Inside the accelerator, two beams of subatomic particles called ‘hadrons’ – either protons or lead ions – of particles travel at close to the speed of light with very high energies before colliding with one another. The beams travel in opposite directions inside the circular accelerator, gaining energy with every lap, in separate beam pipes – two tubes kept at ultrahigh vacuum. They are guided around the accelerator ring by a strong magnetic field, achieved using superconducting electromagnets.

These are built from coils of special electric cable that operates in a superconducting state, efficiently conducting electricity without resistance or loss of energy. This requires chilling the magnets to about -271°C – a temperature colder than outer space. For this reason, much of the accelerator is connected to a distribution system of liquid helium, which cools the magnets, as well as other supply services. Physicists will use the LHC to recreate the conditions just after the Big Bang, by colliding the two beams head-on at very high energy. Teams of physicists from around the world will analyse the particles created in the collisions using special detectors in a number of experiments dedicated to the LHC.

Thousands of magnets of different varieties and sizes are used to direct the beams around the accelerator. These include 1232 dipole magnets of 15 m length, which are used to bend the beams, and 392 quadrupole magnets, each 5–
7 m long, to focus the beams. Just prior to collision, another type of magnet is used to 'squeeze' the particles closer together to increase the chances of collisions. The particles are so tiny that the task of making them collide is akin to firing needles from two positions 10 km apart with such precision that they meet halfway.

All the controls for the accelerator, its services and technical infrastructure are housed under one roof at the CERN Control Centre. From there, the beams inside the LHC will be made to collide at four locations around the accelerator ring, corresponding to the positions of the particle detectors.

Some of the technical databases of the LHC are quite interesting. The Large Hadron Collider will collide two counter rotating proton beams at a centre of mass energy of 14TeV. This energy is seven times higher than the beam energy of any other proton accelerator to date. In order to achieve an unprecedented luminosity of 10^{34} \text{cm}^{-2}\text{s}^{-1}, it must operate with more than 2800 bunches per beam and a very high intensity. The machine can also be filled by lead ions up to 5.5TeV/nucleon and therefore allow heavy-ion experiments at energies about thirty times higher than at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory in New York. Some of the parameters of the new accelerator are listed below (Table 4.1):
### Constants of the LHC

<table>
<thead>
<tr>
<th>Constants of the LHC</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>7 TeV</td>
</tr>
<tr>
<td>Injection Energy</td>
<td>0.45 TeV</td>
</tr>
<tr>
<td>Dipole Field</td>
<td>8.36 Tesla</td>
</tr>
<tr>
<td>Number of dipole magnets</td>
<td>1232</td>
</tr>
<tr>
<td>Number of quadruple magnets</td>
<td>430</td>
</tr>
<tr>
<td>Number of corrector magnets</td>
<td>8000</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$1034 \text{ cm}^2\text{s}^{-1}$</td>
</tr>
<tr>
<td>Coil aperture in arcs</td>
<td>56 mm</td>
</tr>
<tr>
<td>Distance between apertures</td>
<td>194 mm</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>1011</td>
</tr>
<tr>
<td>Number of Bunches</td>
<td>2835</td>
</tr>
</tbody>
</table>

Table 4.1: LHC constants

The six experiments at the LHC are all run by international collaborations, bringing together scientists from institutes all over the world. Each
experiment is distinct, characterized by its unique particle detector.

The two large experiments, ATLAS (A Toroidal LHC AparatuS) and CMS (Compact Muon Solenoid), are based on general-purpose detectors to analyse the myriad of particles produced by the collisions in the accelerator. They are designed to investigate the largest range of physics possible. Having two independently designed detectors is vital for cross-confirmation of any new discoveries made. The primary task of the LHC is to make an initial exploration of the 1TeV range. The major LHC detectors, ATLAS and CMS should be able to accomplish this for any Higgs mass in the expected range. To get into the 1TeV scale the needed beam energy is 7TeV.

Two medium-size experiments, ALICE and LHCb, have specialized detectors for analyzing the LHC collisions in relation to specific phenomena.

Two experiments, TOTEM and LHCf, are much smaller in size. They are designed to focus on ‘forward particles’ (protons or heavy ions). These are particles that just brush past each other as the beams collide, rather than meeting head-on.

The ATLAS, CMS, ALICE and LHCb detectors are installed in four huge underground caverns located around the ring of the LHC (Fig. 4.1). The detectors used by the TOTEM experiment are positioned near the CMS detector, whereas those used by LHCf are near the ATLAS detector.

The LHC has an eight-fold symmetry with eight arc sections and eight long straight sections. Two counter-rotating proton beams will circulate in separate beam pipes installed in the same magnet (twin-aperture) (Fig. 4.1).

At the beginning and the end of the straight sections a dispersion suppressor cell, consisting of four quadrupole interleaved with four strings of two dipoles each, is in charge of correcting the orbital deviation due to the drift in the energy of the particles. The four long straight sections where the experiments are located are formed by the dispersion suppressors and the insertion magnets. These insertion magnets guide the separated beams to a common pipe where they are focused by
the so-called inner triplet magnets in order to get even tighter beams before the collisions take place inside the detectors.

Other insertions are to be used by systems for the machine operation: beam dump, beam cleaning (collimation), RF-cavities (accelerator units) and injection from pre-accelerators.

The injector complex includes many accelerators at CERN: linacs, booster, LEAR as an ion accumulator, PS and the SPS. The beams will be injected into the LHC from the SPS at energy of 450GeV and accelerated to 7TeV in about 30 min. They can then be used to collide for many hours.

Figure 4.1: LHC layout
4.2 LHC on the world

4.2.1 The largest machine in the world.

The precise circumference of the LHC accelerator is 26 659 m, with a total of 9300 magnets inside. Not only is the LHC the world’s largest particle accelerator, just one-eighth of its cryogenic distribution system would qualify as the world’s largest fridge. All the magnets will be pre-cooled to -193.2°C (80 K) using 10 080 tonnes of liquid nitrogen, before they are filled with nearly 60 tonnes of liquid helium to bring them down to -271.3°C (1.9 K) [Ref. 2].

4.2.2 The fastest racetrack on the planet.

At full power, trillions of protons will race around the LHC accelerator ring 11 245 times a second, travelling at 99.99% the speed of light. Two beams of protons will each travel at a maximum energy of 7 TeV (tera-electronvolt), corresponding to head-to-head collisions of 14 TeV. Altogether some 600 million collisions will take place every second [Ref. 2].

4.2.3 The emptiest space in the Solar System.

To avoid colliding with gas molecules inside the accelerator, the beams of particles travel in an ultra-high vacuum – a cavity as empty as interplanetary space. The internal pressure of the LHC is 10^{-13} atm, ten times less than the pressure on the Moon [Ref. 2].
4.2.4  The hottest spots in the galaxy, but even colder than outer space.

The LHC is a machine of extreme hot and cold. When two beams of protons collide, they will generate temperatures more than 100,000 times hotter than the heart of the Sun, concentrated within a minuscule space. By contrast, the 'cryogenic distribution system', which circulates super fluid helium around the accelerator ring, keeps the LHC at a super cool temperature of -271.3°C (1.9 K) – even colder than outer space [Ref. 2].

4.2.5  The biggest and most sophisticated detectors ever built.

To sample and record the results of up to 600 million proton collisions per second, physicists and engineers have built gargantuan devices that measure particles with micron precision. The LHC’s detectors have sophisticated electronic trigger systems that precisely measure the passage time of a particle to accuracies in the region of a few billionths of a second. The trigger system also registers the location of the particles to millionths of a metre. This incredibly quick and precise response is essential for ensuring that the particle recorded in successive layers of a detector is one and the same [Ref. 2].

4.2.6  The most powerful supercomputer system in the world.

The data recorded by each of the big experiments at the LHC will fill around 100,000 DVDs every year. To allow the thousands of scientists scattered around the globe to collaborate on the analysis over the next 15 years (the estimated lifetime of the LHC), tens of thousands of computers located around the world are being harnessed in a distributed computing network called the Grid [Ref. 2].
5 TS department/ CV group/ DC section, CFD team

The mandate of the Technical Support Department (TS) is to provide support for the technical infrastructure of CERN, accelerators and experiments. In addition, it manages the maintenance of sites and buildings, cleaning, gardening and access surveillance to sites and provides general services as transport, mail and housing. The technical support is provided, partly by using outsourced contracts, in the field of different groups, one of them is the Cooling Ventilation group (CV).

The mandate of the Cooling Ventilation group is to provide operation, maintenance and improvement of the existing cooling systems, pumping stations, air conditioning installations and fluid distribution systems for the PS, SPS and LHC machines as well as experimental areas and the Computer Centre; completion of the design and construction work of cooling, ventilation and fluid distribution systems of the LHC project, including new experimental areas (ATLAS, CMS, ALICE etc.); adaptation of the cooling and ventilation systems of the PS, SPS, BOOSTER and LHC; provide thermal calculations and cooling studies for physics detectors; studies with a view to reduce the cooling water consumption and to modernize the water distribution system at CERN.

The Detector Cooling Section (DC) is responsible of the cooling systems for ATLAS, CMS, ALICE and LHCb experiments sub-detectors. The mandate of the section is the completion of the design, construction and commissioning of the cooling systems for these experiments. For Atlas and Alice, after the development and prototype phase, the section is now in charge of the construction of the cooling units at CERN premises. For CMS and LHCb the Market Survey and Invitation to Tender strategy has been used.

The Section has an internal Team dedicated to CFD (Computational Fluid Dynamic) studies. The team develops 3D models to find numerical solution of thermal and fluid flow problems in confined spaces (as sub-detectors or cavern environments). The mandate of this team is to provide assistance to the LHC
experiments in the design and prototype phase and support all other CERN units too.

The team has considerable experience in solving fluid flow and heat transfer problems in high-energy particle detectors. The bulk of studies performed are mainly convection related, which is particularly relevant to the cooling of detector components. The main solutions sought are the flow field, heat transfer distribution and temperature map for a given configuration. However, a number of studies were also developed in areas such as operational safety and room ventilation.

The analysis are carried out using three commercial CFD software: STAR-CD, STAR-CCM+ and FLUENT commercial, general-purpose CFD codes by CD Adapco Group. STAR-CD and STAR-CCM+ studies run on a high-performance computing cluster (Openlab) allowing to solve large, memory intensive problems.

Their range of services include:

- Problem analysis
- Simulation strategy definition
- Choice of best CFD methodology to apply to a specific process
- Geometry and mesh generation
- Parametric studies
- Post processing and reporting

The CFD activity started in TS/CV group around 1993 when a technical student was appointed to work 100% on these studies. From that time on a number of young engineers (technical students, fellows, project associates, UPAS, trainee programmes) took over this activity, spending short to medium periods at CERN.

In 2004 when the TS department was created, the CV group decided to structure this activity into a formal team. At that moment about six young engineers were working on CFD so a team was created in the Detector Cooling section. Nowadays, the team counts with an average of five members spending between
one to two years in the team.

Most part of CFD applications at CERN are concerned with thermal-convection problems: natural, forced or mixed convection effects in and around the experiment detectors and sub-detectors. However, the team offers its services to all CERN units requiring solutions within the range of the CFD applications. Example studies include room ventilation, fire and operational safety.
6 Modelization

6.1 Computational Methodology

6.1.1 Numerical code: Star-CD

The studies were performed using a commercial software called Star-CD (Simulation of Turbulent flow in Arbitrary Regions – Computational Dynamics limited) used by CFD team of TS-CV (Technical Support-Cooling and Ventilation) group at CERN.

STAR-CD is a comprehensive CFD software tool from CD Adapco Group that comes with both pre and post-processing tools and is now enhanced with a choice of CAD integrated options. The solver provides a rich source of models for turbulence, combustion, radiation and multiphase physics. Geometries and meshes can be created using STAR-CD pre-processor or by employing STAR Design solid modeller and the automatic generation module Pro*Am. STAR-CD has also post-processing capabilities for organising and displaying output data.

STAR-CCM+ is the latest CFD software that has been developed by the group using state-of-the-art modelling and software technology. The result is a code that above all offers outstanding ease of use.

Available versions and platforms at CERN are:

- STAR-CD V3.24 on Linux Red Hat
- STAR-CD V4 on Linux Red Hat
- STAR-CCM+ V2.04 on Linux Red Hat

The code is based on finite volumes and solves the governing equation of fluid flow all over. The code solves for conservation equations, radiation and
conjugate heat transfer equation. The discretization methods and numerical solvers will be discussed briefly in the following (chapters 6.1.3 and 6.1.5).

The team uses basically STAR-CD V4 and STAR-CCM+ V2.04. STAR-CD software used comes fully integrated with pro-STAR, a Graphical User Interface (GUI) driven pre/post-processing environment that delivers a useful set of tools to set up, automatically mesh, run the analysis and post-process the results. STAR is the associated unstructured grid, finite volume solver. A total of 88 licenses are available to the team.

To run the codes a high performance, Itanium 64bits, InfiniBand cluster of 20 double cpu machines from CERN openlab cluster is used.

Another thermal simulation software, FLOTHERM from FLOMERICS, is also available to the team for thermal analysis of electronics components and systems.

For post-processing the results, the team has now access to ENSIGHT, a leading software for analysing and visualising the data generated in the CFD codes.

The future of the team depends on the next evolution of CERN projects and on the efficiency enhancement of the simulation studies.

### 6.1.2 Conservation equations

#### 6.1.2.1 Mass conservation

The integral form of the mass conservation equation is:

\[
\frac{d}{dt}\int_{\Omega} \rho \, d\Omega + \int_{S} \rho \bar{v} \cdot \bar{n} \, dS = 0
\]

(Eq. 6.1)

where \( \bar{v} \) is the velocity vector and \( \rho \) the mass density into the surface integral.
By applying the Gauss’ divergence theorem the surface integral can be transformed into a volume integral and by making the control volume infinitesimal a differential coordinate free form can be obtained for the continuity equation:

\[
\frac{\partial \rho}{\partial t} + \text{div}(\rho \vec{v}) = 0
\]  
(Eq. 6.2)

That in cartesian coordinates will become:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0
\]  
(Eq. 6.3)

where \(x_i(i = 1,2,3)\) are the cartesian coordinates and \(u_i\) are the components of velocity vector, \(\vec{v}\).

### 6.1.2.2 Momentum conservation

The momentum conservation equation is:

\[
\frac{\partial}{\partial t} \int_{\Omega} \rho \vec{v} d\Omega + \int_{S} \rho \vec{v} \cdot \vec{n} dS = \sum \vec{f}
\]  
(Eq. 6.4)

where \(\sum \vec{f}\) considers the forces acting on the Cv (Cell volum): surface forces (pressure, normal and shear stress, etc.) and body forces (gravity, centrifugal forces, etc.).

For a Newtonian fluid the surface stress tensor \(T\) (in tensor form or in index notation in cartesian coordinates) is given by:

\[
T = -\left(p + \frac{2}{3} \mu \text{div} \vec{v}\right) I + 2\mu \mathcal{D}
\]  
(Eq. 6.5)

or
Investigation of the Ventilation System of the LHC Tunnel using CFD Techniques

\[ T_{\gamma} = - \left( p + \frac{2}{3} \mu \delta_{\gamma} \text{div}\vec{v} \right) \]  

(Eq. 6.6)

where \( T \) is the unit tensor, \( \mu \) the dynamic viscosity, \( p \) the static pressure, \( \delta_{\gamma} \) is Kronecker symbol and \( D \) is the rate of strain tensor \( (D_{\gamma} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) ) \). From equations 6.4 and 6.5 applying the Gauss’ divergence theorem the surface integral can be transformed into a volume integral and by making the control volume infinitesimal a differential equation can be obtained here in cartesian coordinates with gravity \( (\mathbf{g}) \) as only the body force:

\[ \frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = \frac{\partial \tau_{\gamma}}{\partial x_j} - \frac{\partial p}{\partial x_j} + \rho g_i \]  

(Eq. 6.7)

The term \( \tau_{\gamma} \) describes the viscous part of the stress tensor:

\[ \tau_{\gamma} = 2\mu D_{\gamma} - \frac{2}{3} \mu \frac{\partial u_k}{\partial x_k} \delta_{\gamma} \]  

for laminar flow, \( \tau_{\gamma} = 2\mu D_{\gamma} - \frac{2}{3} \mu \frac{\partial u_k}{\partial x_k} \delta_{\gamma} - \overline{\rho u_i u_j} \) \( \) for turbulent flow \( (\overline{u_i u_j}) \) represents Reynolds’ stresses and \( u' \) are fluctuation about the ensemble average velocity). In the last equation a term can be found also which is significant in the studies performed, \( \rho g_i \), which expresses the only “momentum source” for a buoyancy driven flow. It could be split into two parts:

\[ \rho g_i = \rho_0 g_i + (\rho - \rho_0) \rho_i \]  

(Eq. 6.8)

where \( \rho_0 \) is the reference density and the other term is calculated in accordance to a law that relates \( \rho \) to \( T \) and \( p \) (usually for gas the effect of atmospheric pressure can be neglected and density becomes \( \rho = \frac{\rho_0}{1 + \beta_T (T - T_0)} \) where \( \beta_T \) is the thermal volumetric expansion coefficient).
6.1.2.3   Energy conservation

The energy conservation equation is:

\[ h = \bar{c}_p T - c_v^0 T_0 \]  

(Eq. 6.9)

where \( h \) is the enthalpy. The differential equation governing heat transfer for a fluid in differential form becomes:

\[
\frac{\partial \rho h}{\partial t} + \frac{\partial}{\partial x_j} \left( \rho h u_j + F_{h,j} \right) = \frac{\partial P}{\partial t} + u_j \frac{\partial P}{\partial x_j} + \tau_{ij} \frac{\partial u_i}{\partial x_j} + s_h
\]

(Eq. 6.10)

where \( \bar{c}_p \) is the mean constant-pressure specific heat at temperature \( T \), \( c_v^0 \) is the reference specific heat at temperature, \( s_h \) is the energy source, \( F_{h,j} \) is the diffusional energy flux in direction \( x_j \) that could be expressed by the Fourier’s law: \( F_{h,j} = -\lambda \frac{\partial T}{\partial x_j} \).

For solid (and incompressible fluids) the transport equation is solved for the specific internal energy, \( e = \bar{c}_v T - c_v^0 T_0 \) (\( \bar{c}_v \) is the mean constant-volume specific heat); for isotropic conductive materials, the energy equation becomes:

\[
\frac{\partial (\rho e)}{\partial t} = \frac{\partial}{\partial x_j} \left( \lambda \frac{\partial T}{\partial x_j} \right) + s_e
\]

(Eq. 6.11)

To solve at the same time solid and fluid domains, conjugate heat transfer problems, energy equation for fluids and solids are solved simultaneously and continuity of energy fluxes is enforced at the fluid-solid interface.

6.1.3   Discretization method

The approach used by Star-CD is the finite volum method; the domain of
interest is subdivided into a finite number of control volumes and the conservation equation are applied to each Cv (integration, 1st stage). The calculated variables are then assigned to the centroids of every Cv used to calculate by interpolation the values on Cv’s surface nodes (2nd stage). Because of the geometry of the problems studied which are rather complex and require the use of the automatic generator of Star-CD (Proam) the grid produced is “unstructured”, i.e. it consists of straight-edged cells of various forms (predominantly hexahedral or tetrahedral in most cases). These may be shaped and joined face-to-face in an “arbitrary” manner to fill any volume.

The finite volume method uses the integral form of the conservation equation as starting point and it is convenient to analyse the integral formulation in a general coordinate-free form referred to a generic quantity \( \phi \). We can consider the exact form of the equation applied to a control volume \( V_p \) and its discrete faces \( S_j, (j = 1, N_f) \):

\[
\frac{d}{dt} \int_{V_p} \rho \phi dV + \sum_{j=1}^{N_f} \int_{S_j} \left( \rho \bar{u}, \phi - \Gamma_s \text{grad} \phi \right) \, dS = \int_{S_j} s_e dV \tag{Eq. 6.12}
\]

\( \Gamma_s \) and \( s_e \) are the terms of diffusion and source associated to the variable \( \phi \); \( \bar{u} = \bar{u} - \bar{u}_c \) is the relative velocity between the fluid absolute velocity \( (\bar{u}) \) and the local coordinate system velocity \( (\bar{u}_c) \).

From here onwards, approximations are introduced. The approximation made on the terms which constitute the last equation will be analysed separately. The first term will become:

\[
\frac{d}{dt} \int_{V_p} \rho \phi dV - \frac{\left( \rho \phi V_p \right)_o - \left( \rho \phi V_p \right)_n}{\delta t} \tag{Eq. 6.13}
\]

where the superscripts \( o \) and \( n \) refer to “old” and “new” time level, respectively, separated by an interval \( \delta t \). The second term is split into two separate contributions \( \mathcal{C}_j \) and \( \mathcal{D}_j \) due to convection and diffusion:
The diffusion term, $D_j$, is approximated by face-centered expressions of the form:

$$D_j = \Gamma_{\phi,j} \left\{ \left( \phi_N - \phi_p \right) + \left[ \nabla \phi \cdot \vec{S} - f_j \nabla \phi \cdot \vec{d}_{PN} \right] \right\}$$

(Eq. 6.15)

where the first term in the brackets represents the normal diffusion between P (actual cell centroid) and the neighbouring cell-centred node N and the second term within the square brackets is the cross-diffusion. Terms $f_j$ are geometrical factors, $d_{PN}$ is the distance vector between P and N, and it is the (interpolated) face diffusivity. The approximation of the convective terms $C_j$ for both steady-state and transient calculations is given by:

$$C_j = F_j \phi_j$$

(Eq. 6.16)

where $F_j = \left( \rho \vec{u} \cdot \vec{S} \right)$ is the mass flux through face $j$ and $\phi_j$ (the average value at the face), is interpolated from selected nodal values in accordance with the scheme used.

### 6.1.4 Turbulence model, $k$-$\varepsilon$

The need for turbulence modeling comes from the presence of Reynolds stresses and the scalar transport term which are unknown terms in the conservation equations. Therefore the aim of the turbulent modeling is to close the system of mean flow equation. For all the studies performed a $k$-$\varepsilon$ standard model is used. It is the most widely used and validated turbulence model and performs particularly well in confined flows but it is also used to study environmental flows. The $k$-$\varepsilon$ model is based on two quantities:
• The turbulent kinetic energy \( k \);
• The turbulent kinetic energy dissipation rate \( \varepsilon \).

The constitutive relations for the model are:

\[
-\bar{\rho} U \bar{U}_j = 2\mu \varepsilon D_y = \frac{2}{3} \left( \mu_t \frac{\partial u_k}{\partial x_k} + \rho k \right) \delta_y
\]

(Eq. 6.17)

where kinetic turbulent energy is: \( k = \frac{u^2}{2} \), turbulent viscosity is:

\[
\mu_t = f_\mu \frac{C_\mu \rho k^2}{\varepsilon}
\]

\( f_\mu \) is the dumping function depending on \( k-\varepsilon \) model used and \( C_\mu \) is an empirical coefficient. In the studies both the \emph{Low Reynolds number} \( k-\varepsilon \) turbulent model is used and the \emph{High Reynolds number} \( k-\varepsilon \) model are used. In the Low Re number approach, near-wall regions are treated in the same way as the interior flow; the only difference is that the \( \varepsilon \) value at the centroid of the near wall cells is fixed and depends on viscosity, turbulence energy, shear stress, normal distance to the wall. This approach requires a fine mesh close to the walls so that the \( y^+ \) value is \( \approx 1 \). Finer mesh close to the walls is necessary since close to the walls we have a sharp variation of \( \varepsilon \).

### 6.1.5 PISO Algorithm

The implicit algorithm is used to solve the algebraic finite-volume equation obtained from the discretization. This method employs predictor-corrector strategy which allows to temporary decouple the flow equations from each other so that they can be solved sequentially.

\[ y^+ = \frac{\rho \sqrt{\frac{\nu \omega}{\mu}}}{\mu}, \text{normal wall distance to the near-wall cell centroide.} \]
At first, a static pressure field is calculated solving an equation coming from a combination of Navier-Stokes and continuity equation; from this first trial pressure field is possible to calculate, in the predictor stage, a provisional velocity field from the momentum equation. In the corrector stage the provisional fields are modified to satisfy momentum and continuity balance. After the first corrector stage there are further corrector stages; the number of correctors executed can be modified as a function of splitting error. When predictor-corrector steps are over, a new iteration toward steady state convergence or a new iteration for time advancement starts.

6.2 The CFD model

The CFD model has been created starting from 3D Euclid / Catia models of point 5 and point 6 already available. In order to keep the number of cells below the maximum level, all details useless for the project aim will be neglected. Hence, it will be impossible to look for singularities and results will have to be analysed from a global point of view.

The LHC tunnel is an octagonal ring 26659 meter long. It is composed by eight arcs 2460 meter long separated by eight straight sections where experiments are placed. The tunnel diameter is 3.8 meters in the arcs and it varies from 4.4 to 5.5 meters on the straight parts. The tunnel encloses a total volume bigger than 300000 m$^3$ [Ref. 2].

The main concept for the ventilation of the LHC tunnel is that the tunnel itself is used as a duct for the ventilation air, with air inlets at points 2, 4, 6 and 8 and outlets at points 1, 3, 5 and 7. Where heat must be dissipated into the air locally, as in the cases of the so called “alveoles”, specific closed circuit air-cooling units are provided. The ventilation of the experimental caverns at point 1 and 5 uses a different layout. During the period when the accelerator is in operation, the main air volume stream is recycled. Only a fraction of fresh air is provided through the technical cavern [Ref. 3].
To simplify the geometry and make an accurate study of different cases only one octant of the ring has to be modelled, the octant between point 5 and point 6. The total airflow in this sector of the tunnel in a normal working situation is 36000 m³/h [Ref. 4]. The average air pressure along the tunnel is between 942 and 967 mbar.

![Diagram of the tunnel showing points 5 and 6 with airflow arrows]

Figure 6.1: coloured detail of the sector chosen to study the ventilation

### 6.2.1 Geometry and mesh

The 2D layout drawings consist of several views whose number and arrangement depend on the kind of drawing that is requested. An Oracle table contains the number of views represented for each drawing type, the equipment that appears on each view, the dimensions and notes included and a set of parameters for the proper distribution of the views in the output. Is important for this project to get the views from point 5 and point 6 to have an idea of how their components are and how they are distributed. Figure 6.2 shows the top view of both points one independently from the other with the different parts names.
To understand how it works the ventilation through these two points in figures 6.3 and 6.4 there is a complete drawing of the airflow way inside the ducts. As can be seen the air goes into the tunnel in point 6 and goes out of the tunnel in point 5 through some of the components named before (Fig. 6.2).

Figure 6.2: P5 and P6 top view, components code identification
Figure 6.3: airflow circulation and ducts P6

Figure 6.4: airflow circulation and ducts P5
Following these drawings all the utility components and functionalities in point 5 and point 6 can be obtained; the most important part to be considered is the ventilation system, ducts and supplies.

A complete 3D model of every point along the LHC and some parts of the tunnel are also available in an Oracle database and in the CERN Drawing Directory (CDD). Schematic linear layouts, in which components are represented by simples boxes, are produced with AutoCAD whereas more detailed representations are produced with the 3D CAD system Euclid, using a library of 3D models of the machine components. Only a few of them are saved to be imported to other programs like Catia; which allows to modify their components. Figures 6.5 and 6.6 show a 3D view of point 5 and 6, respectively, the identification of the different components and other general measurements.

Figure 6.5: P5 3D view, components identification and general measurements
Both points shown in the previous figures (P5 and P6) are exported from the Euclid database to open them in Catia separately.

During the exporting process some parts were corrupted and had to be reconstructed again in Catia, which constituted one of the main difficulties of the project.

The shaping process started considering which were the parts to be included in the StarCD model, the objective was to make it as simple as possible in order to minimises the number of future cells. As every point has a symmetric plane, the decision was taken to only consider the area between both symmetry planes (red parts in Fig. 6.7).
The following pictures show a general 3Dimensional view of the whole tunnel and an extended view of the sector 5-6 to be built (Fig. 6.8, Fig. 6.9). It is important to know that the tunnel middle part between P5 and P6 was not on the layout to be exported to Catia, so it has to be recreated on StarCD. Only P5 and P6 are exported on Catia independently.
Figure 6.8: general LHC 3D layout, components and points
The airflow enters to the tunnel through the tower PM65 (Point 6) and through a ventilation opening in the cavern UJ64. Only the caverns from UJ64 to point 5 (until UJ62) were taken into account to simplify the model. The cavern UD62 was deleted since the air ducts do not circulate in that direction. The air travels along the tunnel which is not still built and arrives to point 5; it follows the cavern UJ57, going inside the tunnel UL56, arriving at UJ561 first section and going up to the atmosphere following the tower PM56. The rest of the caverns and parts of point 5 were deleted. All the details inside the caverns were also deleted, and some parts were redone again. Figure 6.10 shows the final kept components. All these components or Catia parts have to be merged in two different files (one for point 5, another for point 6) to obtain a simplified geometry product for point 5 and point 6.
The creation and simplification of the points 5 and 6 geometry is then ready to be imported by StarCD.

### 6.2.1.1 Step 1: Import to Star-CD and surface cleanup

The first step is to import to Star-CD the three-dimensional simplified Catia model that was set up for the study. The model was saved using the .stl extension format. This format is an element-based representation that approximates surfaces and solid entities only. In other words, it keeps information of the surface closing the volume but not on the volume itself. Entities such as points, lines, curves, and attributes such as layer, colour, in the CAD systems will be ignored during the output process.
Under the Import/Organise CAD Data menu of PROAM window, the file .stl is selected and imported using “binary” format. The resultant geometry is displayed with surfaces containing long and thin elements.

6.2.1.2 Geometry creation: Creating the tunnel and creating the magnets line

Once the point 5 and point 6 models have been imported, the creation of the tunnel that connects them and the magnets line starts. It is really important to place both points in the correct spatial position following the program reference coordinate system, otherwise it will be impossible to fusion the two parts and the new tunnel part with the correct measures. To create the tunnel it is necessary to take into consideration some of the measurements written below:

- The position of the whole tunnel follows an inclination of 1.4% along the direction P4-P8, France-Geneva, because of the irregular geologic terrain (Fig. 6.11).

Figure 6.11: simplified geological section of LHC Tunnel. LHC inclination
The following graph shows the different elevation depending on the point position along the 27Km of the LHC (Fig. 6.12):

![Graph showing elevation difference along LHC tunnel]

- The tunnel's curvature relative to the reference coordinate system.

Firstly it is necessary to calculate an approximation of the curvature respect the centre of the whole octant. The next operations show how to estimate this curve in StarCD in function of the ring inclination.

As it can be seen in figure 6.6, point 6 has the starting part of the curve tunnel that will define the rest of the tunnel between P6 and P5. This curve part defines the arc, and with the help of this curve part the radius of the arc will be find and with this radius other necessary values. The point 6 will be kept on his position and the values of the new tunnel part will be approximated using the correct reference system. These estimated values...
have to be written in the extrusion command; the extrusion command is a code to give to the program that consists on: starting from one created line that defines the tunnel contour it creates the tunnel (make an extrusion from this line) with the angle an inclination specified on the command.

A local coordinate system will be placed just in the right corner of the P6, where the new tunnel starts, to define this contour line.

On the extrusion command it is required the number of longitudinal cells to be created, the maximum number of vertex in the model already done, the angle that defines the new tunnel curve and the inclination of this part, all expressed on the local coordinate system. All the calculations to find each of these parameters are detailed on the Annex D. The extrusion will build the tunnel surface from point 6 (starting point) to point 5.

The approach used to estimate the angle considers some values from the database pictures showed before (Fig. 6.5, 6.6 and 6.12) to compare them to the same values calculated.

Three points from the tunnel arc (R622, Fig.6.13) from P6 are considered to define the arc. The points are taken directly from the 3D model imported in StarCD, so the results will be an approximation. These three points are used to find an empirical radius that will help to approximate the traverse angle and the inclination.
The LHC is composed by eight octants, corresponding to the eight sectors, but it isn’t a circumference because between the different octants there are straight parts before and after the points. If these straight parts are not taken into account the angle of every sector could be considered 45° (360° / 8). Assuming the angle equal to 45° and taking the radius calculated previously, the longitude of the tunnel between point 5 and point 6 can be found and compared with the real value, 3334m (Fig. 6.12). All the operations are in the Annexe D, and the final result for this longitude is 3304.663m.

The percentage of error:

\[ E = \frac{3334 - 3304.663}{3334} \cdot 100 \approx 0.88\% \]

(Eq. 6.18)

which is reasonable, so the angle chosen is 45° divided by the number of longitudinal cells considered.

The following step is to calculate inclination sector. The LHC was built with a small % of inclination because of the terrain geological characteristics. In figure
6.12 the inclination from point 6 to point 5 (direction of extrusion) is 45.60m. But the inclination wanted corresponds only to the curve part, so some operations are required before its estimation [Annexe D].

Finally, the inclination taken for the extrusion is 31.62 divided by the number of longitudinal cells and expressed in mm.

The next operation is to move P5 to put it in the same reference space and make it coincident with the tunnel extruded before. The procedure consists of taking the global cartesian coordinate system and measuring the coordinates of one point from the end of the tunnel extruded; taking the same point from the tunnel part of P5 and calculate the increment of every coordinate \((\Delta x, \Delta y, \Delta z)\); then the coordinate system is changed by the cylindrical one and the same measures to calculate the rotation are repeated. The increments and the rotation are applied using two macros structures implemented into the Star-CD software.

Finally, the step after the tunnel construction is to create the magnets line inside the sector 5-6. So, keeping the tunnel on his position it is necessary to estimate the values of this magnets line and the correct reference system to make it pass through the tunnel but without touching it. These estimated values have to be written in the extrusion command. Figure 6.14 shows some of the necessary measurements to place the magnets line.
After some measurements, operations and approximations, the extrusion was divided into different parts, the straight ones and the curve one.

After the extrusion, the movement of point 5 and the creation of the magnets line, it is necessary to merge all the points in an automatically or manual way (it depends on the kind of junction) of both sides along the sector, point 5 and point 6. Once this is finished, the next steps are described bellow.

6.2.1.3 **Step 2: Surface wrapping and checking**

The next step to follow is to check the surface for errors, to locate them and try to solve them; then it is necessary to do a new check until the errors disappear.

In the *Prepare Surfaces* menu and under *Surface Tools*, selecting *Surface Checks*, performs a checking on the imported surface. Usually several errors are displayed. One way to solve them is to select the cells with free edges by clicking on the plot and deleting them. After every operation is necessary to save the model in the database of the programme using the *update* option.

![Diagram of tunnel components and dimensions](image)
6.2.1.4 Step 3: Define cell types

In order to better control the cell size at different parts of the model, different cell types are specified. In this model four different cell types are defined: the inlet and the outlet, the outside tunnel, the inside tunnel and the magnets line. This is done using the cells tools menu and it gives different colours to the different cell types. The model obtained on this way is saved in the database (numbered 2).

6.2.1.5 Step 4: Create feature lines

To maintain the original shape of the model, it is necessary to create lines for the contours of the geometry and also between the different cell types. This is done in Prepare Surfaces, feature tools, edge line/corner point generation, create lines & points.

An angle of 20° is chosen for the edge angle and the model is stored in the database (number 2). In case that too many (or too few) lines are created the edge line cleanup panel can be used to improve the feature definition.

6.2.1.6 Step 5: Surface remesh

The surface stored in database 2 contains long and thin elements so that they need to be remeshed. In this case the target edge length used is 0.3, like in a general case. In some corners of the model it is useful to apply local refinement by selecting local surface, properties, target length 0.05 and min. length 0.001.

The remeshed surfaces are stored in the database (number 3). After this process of remeshing, a surface check should be performed to verify that the surface is proper for the following volume meshing process.
6.2.1.7 Step 6: Surface optimization

Under *surface tools, surface remesh*, the option *optimise surface* allows to smooth the cells. After the optimisation, a surface check is performed to verify that the surface is proper for the following volume meshing process. Then, all the lines and points have to be deleted and saved in the database (number 4).

6.2.1.8 Step 7: Subsurface generation

The subsurface is created to make realer the fluid circulation and the model behaviour; its objective is to represent the limit layer that the airflow develops because of the friction with the wall (Fig. 6.15).

This option appears under *generate mesh, subsurface*, and requires the cell type for the subsurface. No subsurface is required for top surfaces, in that case inlet and outlet, so the cell type 3 that corresponds to the inlet and outlet is taken off. The starting surfaces are stored from database 4.

---

Figure 6.15: limit layer effect
In this step it is necessary to calculate the subsurface depth that corresponds with all the values that have been considered and optimize the volume meshing.

The subsurface has a specific depth that has to be calculated as follows:

\[ Q = 36000m^3 / h \]  [Ref. 4]

\[ A = 0.950462 \cdot 10^7 mm^2 \approx 9.5m^2 \]

\[ Q = v \cdot A \quad v = \frac{Q}{A} = \frac{36000}{9.50462} = 3787.63169911m / h \cdot \frac{1h}{3600s} = 1.05212m / s \]

(Eq. 6.19)

where \( Q \) is the flow, \( A \) is the approximation area of the tunnel modelled and \( v \) is the approximation of the velocity module of the airflow.

\[ y^+ = \frac{\rho \cdot u_c \cdot y}{\mu} = \frac{\rho \cdot C_{\mu}^{1/4} \cdot K^{1/2} \cdot y}{\mu} \]  (Eq. 6.20)

where \( y^+ \) is the subsurface depth, \( C_{\mu} \) and \( K \) are constant coefficients depending on the fluid model, \( \rho \) is the density of the fluid (air) and \( \mu \) the viscosity.

First, check if the model is turbulent or laminar:

\[ D = \frac{4\cdot S}{L} \quad D = 3.305145166m \]  (Eq. 6.21)

\( D \) is the characteristic dimension of the tunnel.

\( L = 11502.817mm \)

\( S = 9.5m^2 \)

\( L \) is the tunnel perimeter measured from the Star-CD model, and \( S \) is the surface that air cross circulating along the tunnel.

\[ \text{Re} = \frac{\rho \cdot v \cdot D_h}{\mu} = \frac{1.205 \cdot 1.05212 \cdot 3.305}{1.85 \cdot 10^{-3}} = 226148.9286 \rightarrow \text{highRe ynolds} \]  (Eq. 6.22)
The model is turbulent, the coefficients of the standard K-ε turbulence model are:

\[ C_\mu = 0.09 \]

\[ K = 0.419 \]

And the density and viscosity of the air:

\[ \rho_{\text{air}} = 1.205 \text{ kg/m}^3 \]

\[ \mu_{\text{air}} = 1.85 \times 10^{-5} \text{ kg/ms} \]

\[ y^* = 3.3 \text{ mm subsurface depth} \]

### 6.2.1.9 Step 8: Volume mesh

There are different volume cell types to generate the volume mesh:

Trimmed mesh: utilizes a template mesh constructed from hexahedral cells from which it cuts or trims the core mesh based on the starting input surface.

Tetrahedral mesh: Delaunay based method is used to construct the mesh, which iteratively inserts points into the domain. The starting quality of the surface must be good in order to ensure a good quality volume mesh.

Polyhedral mesh: dualization scheme used based on an underlying tetrahedral mesh, which is automatically created as part of the process. The polyhedral cells created typically have an average of 14 cell faces.

For this model the type that fits better is the polyhedral one because of the volume irregularities and dimensions. Under *generate mesh, grid generation*, the option *polyhedral* has to be chosen. Load the surface and subsurface information from databases 4 and 5, respectively. Set the *number of layers* and the *ratio value*, 1 and 0.6 respectively. *No extrusion type* should be automatically selected. A global view of all the Star-CD model is shown below (Fig. 6.16) with a detail of
the outlet volume mesh. The right view represents the global view of all the sector model that is built by near 2000000 cells and with real dimensions, for these reasons the details can not be appreciated.

Figure 6.16: whole sector top view and zoom of the outlet part situated in point 5

Figure 6.17: tunnel section simplified, polyhedral volume mesh generated

In Figure 6.17 a drawing of the model geometry is shown. All the values
have been specified in a general way to approximate the model without useless details.

6.3 Boundary Conditions

In Star-CD, space is divided into regions separated by boundaries. A region is a volume in three-dimensional space, or a surface in two-dimensional space, which don’t need to be contiguous. It is discretized by a conformal mesh consisting of connected faces, cells and vertices.

Boundaries are what surround and define a region. A boundary is a surface in three-dimensional space, or a line in two-dimensional space. The number of boundaries around a region will depend on how the mesh was set up and on the particular problem being solved. At a minimum, a separate boundary will be required for each boundary type in the problem, but one boundary type (for example, an inlet) could consist of multiple boundaries in the simulation.

Regions never share the same boundary; each boundary belongs to only one region, and can coincide with a boundary belonging to a neighbouring region.

Models need additional information to deal with the boundary type. Conditions provide this information. For example, with a boundary of type wall, the conditions will specify whether this is to be a no-slip wall, a slip wall or a moving wall. The conditions will also tell whether we want to apply a specified temperature (Dirichlet) thermal boundary condition or a specified heat flux (Neumann) thermal boundary condition.

The types and conditions inform models how to deal with a boundary (or region or interface) but they do not specify actual numerical input. These numbers are provided by values.

- Inlet
The inlet is placed on the top of the cavern in point 6. The approximated dimensions of the inlet are:

![Diagram of inlet with measurements](image)

**Figure 6.18: inlet part zoom and measurements, situated in P6**

These dimensions are necessary in order to calculate the velocity vector of the air incoming in the model in a standard operation way:

\[ S = 1 \cdot 0.929082 m^2 \text{ surface of inlet} \]

\[ Q = \frac{36000 m^3}{h} \cdot \frac{1 h}{3600s} = 10 m^3/s \text{ flow in a standard normal operation way} \]

[Ref.4]

(Eq. 6.23)

\[ Q = v \cdot S \rightarrow v_i = \frac{10}{0.929082} = 10.7633126 m/s \text{ velocity module in the inlet} \]

(Eq. 6.24)
\[ v_{in} = 10.7633126 \cdot \frac{\sqrt{2}}{2} = 7.6108m/s \]  
(Eq. 6.25)

\[ v_{in} = 10.7633126 \cdot -\frac{\sqrt{2}}{2} = -7.6108m/s \]  
(Eq. 6.26)

\[ v_{uv} = 0m/s \]  
(Eq. 6.27)

velocity vectors in the inlet.

The coordinate system used is number 1, defined in Star-CD model.

It is necessary to calculate the turbulence intensity and the length scale for this geometry:

\[ D_h = \frac{4 \cdot A}{L} = 3.305145166m \text{ characteristic dimension of the tunnel} \]  
(Eq. 6.28)

\[ Re = \frac{\rho \cdot v \cdot D_h}{\mu} = \frac{1.205 \cdot 1.05212 \cdot 3.305}{1.85 \cdot 10^{-5}} = 226148.9286 \]  
(Eq. 6.29)

\[ Turbulence\, Intensity = 0.16 \cdot \left(Re_{D_h}\right)^{1/8} = 0.0342626276 \]  
(Eq. 6.30)

\[ Length\, Scale = l = 0.07 \cdot L = 0.23136m \]  
(Eq. 6.31)

**Outlet**

The ventilation extraction system goes up until the end of the extraction pipe in point 5, directly to the atmosphere. The outlet is considered as a pressure boundary with reference pressure equal to 0.

**Inside Wall**

The inside wall is defined as all the external surface of the magnets that are in contact with the air circulating in the tunnel. The values to consider are:

- roughness standard, no slip and heat flux.
The magnets along the sector between point 5 and point 6 dissipate heat in the air. To estimate this heat dissipation there is the table below [Ref. 4]:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4 – 5</td>
<td>3</td>
<td>6</td>
<td>20</td>
<td>21</td>
<td>61</td>
<td>0</td>
<td>111</td>
</tr>
<tr>
<td>5 – 6</td>
<td>5</td>
<td>6</td>
<td>20</td>
<td>21</td>
<td>61</td>
<td>5</td>
<td>118</td>
</tr>
<tr>
<td>6 – 7</td>
<td>19</td>
<td>20</td>
<td>20</td>
<td>21</td>
<td>32</td>
<td>5</td>
<td>117</td>
</tr>
<tr>
<td>7 – 8</td>
<td>26</td>
<td>10</td>
<td>20</td>
<td>21</td>
<td>32</td>
<td>0</td>
<td>109</td>
</tr>
<tr>
<td>8 – 1</td>
<td>9</td>
<td>8</td>
<td>20</td>
<td>21</td>
<td>61</td>
<td>0</td>
<td>119</td>
</tr>
</tbody>
</table>

Table 6.1: power dissipation along the tunnel

The heat dissipations of the power converters, their cables and racks in RR caverns will be added to the dissipations of the tunnel sector concerned. It is necessary to calculate the heat dissipation per square meter:

\[ L = 3304m \]
\[ \Phi = 1.1m \]

where \( L \) is the longitud of the magnets line and \( \Phi \) the diameter of the magnets line.
$S = 1.1 \cdot \Pi \cdot L = 11417.83 m^2$  

surface of magnets  

(Eq. 6.32)

$heat\;lux = \frac{118000}{S} = 10.3347 W / m^2$  

(Eq. 6.33)

• Outside Wall

The outside wall is defined as the most external part of the tunnel. In this case is important to take in account the roughness of the concrete around the tunnel. The values taken are:

- Specific roughness: 0.002 0.002
- Wall temperature fixed at $T = 287 K (14^\circ C)$
- Wall resistance considering the depth of the tunnel and concrete as the material around: $R = 0.1 m^2 K / W$
7 Simulation

The Star-CD model obtained for P5, P6 and the tunnel in between consists of approximately 2000000 cells (1918393 cells). Once the model has been obtained it has to be proved that it works properly and follows a reasonable behaviour. It is pretended to study a starting steady state only with the nominal airflow to get a developed stable point and three different situations, one considering the smoke from a fire cables combustion, another considering an helium leakage and the last one considering a radiation propagation, but the scope of this project only considers the first one, the smoke produced by a fire cable combustion.

7.1 Air handling of the LHC tunnel and its underground areas

The main tunnel is divided into eight independent volumes, called “sectors” which are treated separately. Two air handling units are providing air supply at each even point of a sector, and two extraction units are providing the extraction at the odd point of the corresponding sector. The nominal airflow rate of each unit for supply or extraction is 36000m$^3$/h (Table 7.1).

The air is supplied via air handling units located in SU2, SU4, SU6 and SU8 surface buildings. The treated air is transported by air ducts, via PM25, PM45, PM65 and PM85 shafts down to UJ24, UJ26, UJ44, UJ46, UJ64, UJ66, UJ84 and UJ86 junction chambers (Fig. 6.8). In the machine side of these junction chambers, the air is pulsed in the tunnel [Ref. 5].

The exhaust air is extracted from the odd points UJ14, UJ16, UJ32, UJ561, UP56, and UJ76 junction chambers. In the UJ32, UP56 and UJ76, partitions are separating the airflows coming from points 2 and 4, 4 and 6, 6 and 8 [Ref. 5].
7.1.1 Functions of the air handling

The air handling installations shall be designed to:

- Supply fresh air for people
- Provide heating and ventilation
- Provide destratification and maintain at the surface of the different equipment a suitable temperature
- Dehumidify in order to prevent condensation
- Permit cold smoke extraction
- Purge the air of the tunnel before access
- Filter the exhaust air
- Supply sound attenuation of the exhaust air

7.1.2 Operating modes

In each tunnel sector, the ventilation system will provide four operating modes. The first one is the reduced consumption mode activated only while the sector is opened and there is nobody working on it; the second one is the tunnel accessible mode activated while the sector is opened and there is people working on it; the third one is the tunnel not accessible mode activated while the tunnel is closed and the installation is working (this is the mode considered in the model); and the last one mode is the emergency sector activated in case of an emergency. To each mode it corresponds a given air flow rate, as shown in the table below [Ref. 4].
<table>
<thead>
<tr>
<th>Tunnel sector</th>
<th>Reduced consumption mode [m³/h]</th>
<th>Tunnel accessible mode [m³/h]</th>
<th>Tunnel not accessible mode [m³/h]</th>
<th>Emergency sector mode [m³/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – 2</td>
<td>9000</td>
<td>18000</td>
<td>36000</td>
<td>64000</td>
</tr>
<tr>
<td>2 – 3</td>
<td>9000</td>
<td>18000</td>
<td>36000</td>
<td>64000</td>
</tr>
<tr>
<td>3 – 4</td>
<td>9000</td>
<td>18000</td>
<td>45000</td>
<td>64000</td>
</tr>
<tr>
<td>4 – 5</td>
<td>9000</td>
<td>18000</td>
<td>36000</td>
<td>64000</td>
</tr>
<tr>
<td><strong>5 – 6</strong></td>
<td><strong>9000</strong></td>
<td><strong>18000</strong></td>
<td><strong>36000</strong></td>
<td><strong>64000</strong></td>
</tr>
<tr>
<td>6 – 7</td>
<td>9000</td>
<td>18000</td>
<td>36000</td>
<td>64000</td>
</tr>
<tr>
<td>7 – 8</td>
<td>9000</td>
<td>18000</td>
<td>36000</td>
<td>64000</td>
</tr>
<tr>
<td>8 – 1</td>
<td>9000</td>
<td>18000</td>
<td>36000</td>
<td>64000</td>
</tr>
</tbody>
</table>

Table 7.1: airflow depending on the operating modes and the sector

### 7.2 Setting up the models for the simulation

Models define the primary variables of the simulation, including pressure, temperature and velocity, and what mathematical formulation will be used to generate the solution. In this study, the flow is turbulent and compressible. The Coupled Flow model will be used together with the default K-Epsilon Turbulence model.

In Star-CD, the models are defined on a continuum. A continuum essentially represents the substance (fluid or solid) being modelled.
A simulation can have multiple continua and continua can be defined in a simulation before any mesh import is performed, and once defined they do not have to be used (associated with a region).

In addition to the models comprising the continuum, the continuum also contains initial conditions and reference values.

In the study an idealized gas (air) is used with the following properties:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (Kg/m$^3$)</td>
<td>1.18415</td>
</tr>
<tr>
<td>Molecular viscosity (Kg/ms)</td>
<td>$1.85508 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>Specific Heat (J/KgK)</td>
<td>1003.62</td>
</tr>
<tr>
<td>Thermal conductivity (W/mK)</td>
<td>0.0260305</td>
</tr>
<tr>
<td>Molecular weight (Kg/Kmol)</td>
<td>29</td>
</tr>
</tbody>
</table>

Table 7.2: air properties implemented in Star-CD

Certain models, when activated in a continuum, require other models also to be enabled in that continuum. For instance, once a continuum contains a liquid or a gas, it needs a flow model. Once it has a flow model it needs a viscous model (inviscid, laminar or turbulent). Once turbulence is enabled within a fluid continuum, a turbulence model must be selected. All this is defined like:

- ideal Gas in the Equation of State
- Steady in the Time
- Turbulent in the Viscous Regime

Other settings to be activated in the model are:

- Buoyancy: centroid of pressure reference cell, using initial values of pressure and temperature.
- Initialization: $T = 293 \text{ K (20°C)}$
- Molecular properties: density $= f(T,P)$

### 7.3 Setting the Initial Conditions

Initial conditions in a continuum specify the initial field data for the simulation. Examples of initial conditions are: pressure, temperature, velocity components, and turbulence quantities. Each model requires enough information so that the model's primary variables can be set. In most cases this is done directly but for some models, such as turbulence models, the information has to be specified in a more convenient form (for example, turbulence intensity and turbulent viscosity ratio instead of turbulent kinetic energy and turbulent dissipation rate).

In steady-state simulations, the solution ought to converge independently of the initial field. However, the initial field still affects the path to convergence and with it the cost in computing power.

The initial conditions set in the model are:

- $T = 293 \text{ K (20°C)}$
- $P = 101300 \text{ Pa}$
- Turbulence quantities $= 0.001$
- Velocity components in the inlet:
\[
\bar{v}_{w} = 10.7633126 \cdot \frac{\sqrt{2}}{2} = 7.6108 m/s
\]  
(Eq. 7.1)

\[
\bar{v}_{w} = 10.7633126 \cdot \frac{-\sqrt{2}}{2} = -7.6108 m/s
\]  
(Eq. 7.2)

\[
\bar{v}_{w} = 0 m/s
\]  
(Eq. 7.3)

### 7.4 Results and discussion

#### 7.4.1 Study of a steady state: ventilation distribution inside the tunnel

The model is initially run in a transient state for a few seconds in order to obtain a starting point. After this short simulation of only 25 seconds, a steady state calculation of 500s (8min 20s) is performed in order to get a developed stable solution (from which to apply the smoke) for the ventilation distribution inside the tunnel.

As a first approximation of the ventilation operation the model runs with the nominal airflow rate of 36000 m³/h (Table 7.1). Figure 7.1 shows a 3D view of the air inlet into the tunnel and the velocity vectors on the inlet cavern.
Airflow supplying

The airflow is moving along the tunnel following the forced ventilation extraction to P5.

After studying the movement and behaviour of the air entering the tunnel the model is ready to simulate critical conditions. The studied case is a cables fire in the inlet cavern.

7.5 Study of the transient state: fire in cables, cables trays and conduits

7.5.1 Cables combustion

The objective of this simulation is to create an abnormal mode in sector 5-6 to analyse the model. The abnormal situation chosen is a smoke source produced by a fire. One of the cases that can produce fire into the tunnel is the cavern

Figure 7.1: 3D view of the inlet and the air supplying. Inlet surface velocity profile. Second 16 of simulation
7.5.2 **Minimising the fire risk in cables. Prevention tips**

Some prevention rules are taken in account to chose which kind of cables are going to be installed underground; the main objective is minimizing as much as possible the risks they are going to be submitted.

Conduits used for passing cables through walls, ceilings, etc., must be plugged with a material that meets or exceeds the fire rating of the original barrier.

Non-metallic cable trays or conduits shall consist of halogen-free flame-retardant material.

Cable trays shall be engineered and properly installed according to the technical description of the supplier so as to preclude mechanical failure.

The maximum admissible mechanical load per unit length of a cable tray shall be respected.

Access to cable trays must kept free at all times, in particular maintenance access to connection points. A vertical space of 30 cm and an unilateral space of 45 cm shall be kept free at all times.

One must not walk on cable trays. Appropriate guidance shall be sign-posted at strategic locations where the cable tray could easily be confused with an access path or where the cable tray obstructs access to other equipment.

Metallic cable trays, conduits or enclosures containing electrical equipment shall be earthed in such a way as to handle the maximum earth current. Metallic sections of cable trays shall be interconnected electrically by earth straps designed to withstand the maximum earth current.

Electrical or other equipment shall not be located on cable trays. Cable trays shall not be utilised for storage. No combustible materials other than cables or cable ties shall be present.
Cleanliness of cable trays is a prerequisite for fire prevention. Any debris deposition resulting from finished work shall be removed painstakingly, in particular metallic particles and combustible rubbish.

Particular attention must be given to cables connected directly to printed circuit boards. Printed circuit boards shall neither be bent nor pulled out of their foreseen position by mechanical forces originating from cables.

7.5.3 **Cable material. Required properties of cable insulating materials**

The choice of the cable material is intended to ensure a very high level of safety and must be applied to all new cable installations at CERN, including the addition of cables to existing installations. CERN attaches an increased importance to the hazards associated with smoke, toxicity and corrosivity from burning plastics.

Different standard test methods have been used to select suitable materials for the insulation and sheathing of power, control and signal cables and wires with respect to their resistance to the fire and ionizing radiation.

The requirements for all types of cables are the following:

- Electrical, mechanical, thermal and environmental endurance properties conforming to the appropriate standards
- Flame retardant characteristics satisfying the relevant standards
- Halogen and sulphur free
- Low smoke density
- Low toxicity of gases from fires
- Low corrosivity of gases from fires
- Retention of functional capabilities up to the specified Radiation Index (up to an integrated radiation dose of $5 \times 10^5$ Gy for general purpose cables
and $10^7$ Gy for special radiation resistant cables).
The requirements of low smoke density, low toxicity and corrosivity of gases from fires exclude some very commonly available materials such as polyvinyl chloride (PVC), chlorosulphonated polyethylene (Hypalon), polychloroprene (Neoprene), fluorocarbons (e.g. Teflon) and other halogenated or sulphur containing compounds.

7.5.4 Criteria for specification and selection of cable insulating materials

7.5.4.1 Flame propagation and fire resistance

A distinction is made between the fire properties of materials and those for cables. Using flame retardant materials is a pre-requisite but does not guarantee that the finished cable will have the required fire properties. In order to guarantee those properties the following is needed:

1. Small, single-core, insulated wires with conductors smaller than 0.8mm diameter (0.5mm$^2$) shall be tested according to IEC 60332-2.

2. Single-core insulated wires with conductors greater than 0.5mm$^2$ and all multiconductor cables, round or flat of any dimension, shall pass IEC 60332-1.

3. All types of finished cables having an outer diameter exceeding 10mm and all those to be used in bunches.

4. Fire resistant cables are those which must continue to function for a defined time during and after the fire.
7.5.4.2 Smoke density

Samples of finished cables and wires shall be tested according to ASTM E 662, or ISO 5659-2. The required value of the specific optical density, $D_s$, is less than 250 in both the flaming and non-flaming modes.

7.5.4.3 Corrosivity of gases from fires

All constituent materials of cables, including tapes and fillers, must be halogen and sulphur free. The materials must pass the IEC 60754-2 test with pH greater than 4.3 and conductivity less than 100 $\mu$S/cm.

7.5.4.4 Radiation resistance

The specification requirements below apply to all installation of cables in areas of CERN where the life dose is expected to exceed 100 Gy. A distinction is made between general purpose cables and special cables used in high-radiation areas. Common optical fiber cables are very sensitive to radiation. It is recommended not to use them in radiation areas.

7.5.5 Existing materials satisfying the specified criteria

1. Power cables

The specification of an ethylene propylene rubber polymer (EPR or EPDM) should be used for both the insulation and the outer sheath of power cables.

Ethylene vinyl-acetate (EVA) or a copolymer of polyolefin may be accepted as an alternative if the properties are equivalent to those of EPR. In view of the fact
that these materials show more severe degradation after long-term irradiation than EPR, this option is not recommended for use of power cables in radiation areas.

A polyethylene insulation may be used for high voltage cables where its electrical properties represent a distinct advantage.

2. Control and signal cables
The preferred dielectric and/or insulation material is polyethylene (PE). For the outer sheath a flame retardant material such as ethylene vinylacetate (EVA) or a polyolefin copolymer should be used.

3. Miniature wires and cables for electronics
Miniature wires are used in electronics circuits where there are often severe space limitations and functional requirements. For these cables and wires it is recommended that the insulation and/or sheath be based on polymide (e.g. Kapton), polyetherimide (e.g. Ultem), polyetherether ketone (PEEK), polyphenylene oxides (Noryl) or similar materials.
### Combustion

The most part of the cables inside the tunnel that present risk of fire are control and signal cables and power cables. So to model the amount of fire and estimate the values resulting of the combustion, only these types of cables are taken in

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard*</th>
<th>Requirements</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flame and fire propagation</td>
<td>CEI 60352-2</td>
<td>Pass</td>
<td>Applies to all single wires.</td>
</tr>
<tr>
<td></td>
<td>CEI 60332-1</td>
<td>Pass</td>
<td>Applies to all cables and to all single wires &gt; 0.5 mm².</td>
</tr>
<tr>
<td></td>
<td>CEI 60332-3 Category 24</td>
<td>Pass</td>
<td>Applies to all cables with outer diam. &gt; 10 mm.</td>
</tr>
<tr>
<td>Fire resistance</td>
<td>CEI 60331</td>
<td>Pass</td>
<td>For cables with special safety functions (eg. emergency lighting, alarm, lift, etc.)</td>
</tr>
<tr>
<td>Smoke density</td>
<td>ASTM E 662 or ISO 5659</td>
<td>$D_1 &lt; 250$ in the flaming and non-flaming modes</td>
<td>For all cables.</td>
</tr>
<tr>
<td></td>
<td>CEI 61034-1 and 2</td>
<td>Pass</td>
<td>For all major CERN cable contracts.</td>
</tr>
<tr>
<td>Toxicity of fire gases</td>
<td>CEI 60693-7 30 and 51</td>
<td>Calculation of the Fractional Effective Dose</td>
<td>The conditions of the test have to be agreed with SC, and the results must be acceptable to all parties.</td>
</tr>
<tr>
<td>Convulsivity of fire gases</td>
<td>CEI 60754-2</td>
<td>pH $\geq 4.3$, conductivity $&lt; 100$ mS/cm</td>
<td>Cables shall be halogen and sulphur free.</td>
</tr>
<tr>
<td>UV Resistance</td>
<td>CEI 60066-2-5</td>
<td>No discoloration, No stickiness</td>
<td>Procedure C, 10 days, 40°C</td>
</tr>
<tr>
<td>Radiation resistance</td>
<td>CEI 60344-2 and 4 and ISO R 527</td>
<td>Radiation Index in relation to application recommended RI &gt; 5.7</td>
<td>Elongation at break (ISO 377) 50% of initial value or 100 % absolute value at specified absorbed dose. Test at high dose rates (≈ 1 Gy/s).</td>
</tr>
</tbody>
</table>

* See Appendix 3.  
NB: Alternative ISO, IEC and other International Standards, or National Standards may be considered in agreement with CERN's Safety Commission, and should preferably be selected from survey of test methods listed in IEC 60693-1-1 section 3 and Appendix A, or IEC safety Handbook. All the standards quoted above are available for consultation, via CERN's safety commission.

Table 7.3: required properties for the selection of electric cables and wires with respect to fire safety and radiation resistance
account. The total composition is given in %, independently of the cables quantity and mass.

Polyethylene (PE) $\rightarrow C_2H_4 \rightarrow 70\%$

Ethylene vinyl acetate (EVA) $\rightarrow 30\%$

The composition in % of EVA is:

$$\text{Ethylene} \rightarrow C_2H_4 \rightarrow 60\%$$

$$\text{Vinyl acetate} (10 - 40\%) \rightarrow C_4H_6O_2 \rightarrow 40\%$$

\[
(0.4 \cdot C_4H_6O_2 + 0.6 \cdot C_2H_4) \cdot 0.3 = 0.12 \cdot C_4H_6O_2 + 0.18 \cdot C_2H_4
\]

(Eq. 7.4)

% total of burned material:

\[
0.7 \cdot C_2H_4 + 0.3(0.6 \cdot C_2H_4 + 0.4 \cdot C_4H_6O_2)
\]

\[
(0.7 + 0.18) \cdot C_2H_4 + 0.12 \cdot C_4H_6O_2 = 0.88 \cdot C_2H_4 + 0.12 \cdot C_4H_6O_2
\]

(Eq. 7.5)

% of mass of every component in $C_2H_4$:

\[
C_2H_4 + \frac{6}{2} \cdot O_2 \rightarrow 2 \cdot H_2O + 2 \cdot CO_2
\]

(Eq. 7.6)

\[
\begin{align*}
M_{\text{total}} &= M_{\text{totalC}} = 24 \\
M_{\text{totalH}} &= 4 \\
M_{\text{total}} &= M_{\text{totalC}} + M_{\text{totalH}} = 28
\end{align*}
\]

\[
\begin{align*}
\frac{24}{28} &= 0.8571 \rightarrow 85.71\%C \\
\frac{4}{28} &= 0.1428 \rightarrow 14.28\%H
\end{align*}
\]

(Eq. 7.7)

% of mass of every component in $C_4H_6O_2$:

\[
C_4H_6O_2 + \frac{11}{2} \cdot O_2 \rightarrow 3 \cdot H_2O + 4 \cdot CO_2
\]

(Eq. 7.8)
\begin{align*}
M_{\text{total}C} &= 48 \\
M_{\text{total}H} &= 6 \\
M_{\text{total}O} &= 32 \\
M_{\text{total}} &= M_{\text{total}C} + M_{\text{total}H} + M_{\text{total}O} = 86 \\
\frac{48}{86} &= 0.5581 \rightarrow 55.81\%C \\
\frac{6}{86} &= 0.0697 \rightarrow 6.97\%H \\
\frac{32}{86} &= 0.3721 \rightarrow 37.21\%O
\end{align*}

(Eq. 7.9)

% (grams per mol) total in weight of the cables burned:

<table>
<thead>
<tr>
<th>C (g/mol)</th>
<th>H$_2$ (g/mol)</th>
<th>O$_2$ (g/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.754248</td>
<td>0.125664</td>
<td></td>
</tr>
<tr>
<td>0.066972</td>
<td>0.008364</td>
<td>0.044652</td>
</tr>
<tr>
<td>0.82122</td>
<td>0.134028</td>
<td>0.044652</td>
</tr>
</tbody>
</table>

\textit{Table 7.4:} composition (weight percentage) of the cables

In the model the combustion is not taken in account, it is only considered the smoke produced by a scalar source. To implement this scalar source in the geometry model, a sort of different cell type is defined from which the smoke is going to be produced, and a heat power dissipation is imposed to represent the fire heating.
In figure 7.2 the different cell type is coloured in purple. These cells are placed around the cable trails inside the cavern and along the tunnel. They represent the mass of cables that will be considered in the fire and from which the smoke will originate. The red cells represent the mass of air inside the cavern and along the tunnel.

The model runs for a few seconds only with the heating enthalpy condition and afterwards the smoke source is added to make the simulation as real as possible. The smoke properties are estimated using a mathematical software from the Lausitz German University [annexe C]. The initial settings to run this calculation software are:

- Composition of the cables (Table 7.4)
- Air excess factor: 1.15
- Quantity burned: 100%
• Environmental temperature: 15°C

• Environmental humidity: 45 – 55%

Once this German software has been executed, the smoke properties obtained are written bellow:

<table>
<thead>
<tr>
<th>Smoke properties implemented on the model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
</tr>
<tr>
<td>Molecular weight (kg/kmol)</td>
</tr>
<tr>
<td>Thermal expansion coefficient (1/K)</td>
</tr>
<tr>
<td>Molecular viscosity (kg/ms)</td>
</tr>
<tr>
<td>Specific heat (J/kgK)</td>
</tr>
<tr>
<td>Conductivity (W/mK)</td>
</tr>
<tr>
<td>Heat of formation (J/kg)</td>
</tr>
<tr>
<td>Temperature of formation (K)</td>
</tr>
</tbody>
</table>

Table 7.5: approximated smoke properties considerate

7.5.7 **Smoke simulation**

After all the considerations the properties above can be implemented in the Star-CD final model ~2000000 cells (1918393 cells) just adding them to the scalar source tables. Then the model is ready to simulate the case of smoke produced by the cables combustion.
### General description of case simulated

<table>
<thead>
<tr>
<th>Control and signal cables fire</th>
<th>Polyethylene (PE) C₂H₄ + Ethylene vinyl acetate (EVA) C₄H₆O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material of the cables</td>
<td></td>
</tr>
<tr>
<td>Power dissipation of the fire</td>
<td>2 MW [Ref. 7]</td>
</tr>
<tr>
<td>Power dissipation of the beam</td>
<td>10.3347 W/m²</td>
</tr>
<tr>
<td>Volume to burn</td>
<td>21.55 m³</td>
</tr>
<tr>
<td>Scalar source</td>
<td>1.16 kg/s/m³</td>
</tr>
<tr>
<td>Enthalpy source</td>
<td>92794.076 W/m³</td>
</tr>
<tr>
<td>Air supplying</td>
<td>36000 m³/h</td>
</tr>
</tbody>
</table>

---

Table 7.6: description of the case simulated

The power dissipation fire has been estimated following the nominal power dissipations for different situations given in reference 7. The kg per second of smoke produced (expressed in kg/s) has been approximated using the professor Schutz’s tables [Ref. 6, pg. 18]; the scalar source has been calculated dividing the mass flux by the volume to be burnt; and the enthalpy source has been calculated dividing the power dissipation by the volume to be burnt as well.

To implement all the values in the StarCD program it is necessary to create two subroutines, one for the scalar source and the other for the enthalpy source that the program will use during the calculations [annexe B].
The model has been run in transient state. The simulation has run without the scalar source, only with the enthalpy source in order to better represent better the fire starting, which on his early stage doesn’t only produce smoke but heating. The enthalpy simulation lasts 2s, with low time step (it forces to work better when the time step is lower); using 4 openlab processors which one with four cpu; the real time processing is approximately 28h.

After this 2s of simulation the smoke scalar source is activated. The model starts simulating with a low time step that is been incremented slowly; the smoke model is too huge to start directly with a high time step. This consideration improves the computational operations and lets the program work faster. The simulation runs during a total of 1450s (24min 10s).

Once the simulation is done some plots are made to check if the behaviour of the smoke is the expected one and consequently if the model works properly. The following pictures show the development and behaviour of the smoke inside the tunnel in early step of the simulation (Fig. 7.3, Fig. 7.4).

![Figure 7.3: mesh 3D view and the same part with the starting smoke development, 16s](image)
These figures show that the smoke is going up and the air is pushing this smoke into the tunnel, the airflow follows the expected development, which means the model works correctly and is properly created. There are other interesting aspects to observe on the model and which will help to conclude the model reflects accurately the reality, like the smoke evolution in function of the distance to the fire focus, a section time evolution or two separate sections on the same time step.

The following plots (Fig. 7.5) are made to point out four useful sections. The first figure shows the density of the smoke after 1150s of simulation along the first part of the model (inlet, Point 6); 2 relevant sections are placed (section1 where the tunnel starts and section2) to indicate the sections that will be represented in next plots to understand different evolutions. The second one shows the tunnel between the inlet air cavern and the next cavern from point 6 to point 5; another two sections are placed (section3 which is placed at the tunnel where the second cavern starts and longitudinal section); they will be used for the next plots.

Figure 7.4: development of the starting fire and the smoke into the cavern (first figure, 16s) and along the tunnel (last figure, 116s)
The first interesting aspect to observe is the development of the smoke in function of the distance to the fire focus. Figure 7.6 shows this development; on the left top part the scalar source is creating the smoke that slowly will fill the tunnel. The temperature of the smoke is higher so it is going up on the tunnel and creating a small loop around the beam for the ventilation system supplying. The graphic reflects the smoke concentration from the bottom to the top of the section.

Figure 7.5: on the right the density distribution, 1150s, and position of section1 and section2. On the left, top view of the inlet cavern and a part of the tunnel, longitudinal section of the tunnel and position of section 3
The second important fact to emphasize is the time evolution and how it reflects on the model. Figure 7.7 shows the evolution of the smoke density in function of time in the same section, section 1, the smoke is filling the section while the simulation is going on.
Figure 7.8 shows the smoke density in two separated sections at the same time step of the simulation, 1450s, one near the fire (section1) the other some metres away (section3). After 1450s the smoke has not arrived yet to section 3, 226308mm far away from the beginning of the tunnel, 211859 mm far away from the fire.
Other different aspects can be interesting to be studied like the velocity distribution and values along the tunnel or in a cross section, the temperature distribution or the movement of the smoke along the tunnel to observe the phenomenon of the limit layer and the wall treatment.

The velocity of the air and smoke mass moving are represented in the following plots (Fig. 7.9, Fig. 7.10). Figure 7.9 shows the velocity vectors along the tunnel (longitudinal section):
After some minutes of simulation the airflow circulating into the tunnel has an stabilized velocity with a value between 0.9649 m/s and 0.001966 m/s; the average velocity is 0.483433 m/s, and with this value it can be approximated that the smoke will arrive to the second cavern (section3) after 7 minutes 18 seconds. These calculations are an example of the new important and useful information that can be drawn thanks to the model and the simulations performed.

Figure 7.10 shows the velocity vectors distributed and temperature on section1:
Investigation of the Ventilation System of the LHC Tunnel using CFD Techniques

The air handling together with the high temperature smoke gives this profile around the magnets. In one of the pictures, the left one, the temperature is also presented, increasing from 293.15 K to 301.5 K in the coldest part (on the bottom of the tunnel) and 373.7 K in the hottest part (on the top-left of the tunnel). After 1450 seconds the temperature has increased in 80.5 K (the higher) and 8.3 K (the lower).

The temperature varies according to the distance to the fire. The temperature considered inside the model is 283 K, while the wall involving the model is considered around 287 K. At the top the temperature is increasing while the smoke is moving along with the ventilation inlet initialized at 293 K. The air around the beam is getting hotter for the power dissipation; otherwise the air around the outside wall is getting cold because of the external low temperature. All these aspects are reflected in figure 7.11.

Figure 7.10: velocity vectors distribution in Section1 and velocity vectors distribution and temperature in the same section, 1450s
Finally, it is interesting to observe the limit layer phenomenon and the wall treatment. The smoke moves along the tunnel going faster on the upper part and going slower on the bottom, and creating a layer on the wall, so it can be seen the detachment of the limit layer. Figure 7.12 shows this phenomenon (longitudinal section).
Figure 7.12: smoke and temperature behaviour. Limit layer phenomenon. Longitudinal section, 216s
8  Cost Benefit Analysis (CBA) of the Project

8.1  Background

The Cost-Benefit Analysis (CBA) estimates and totals up the equivalent value of
the benefits and costs to the community of projects to establish whether they are
worthwhile.

This analysis is done to determine how well, or how poorly, a planned action will
turn out. Moreover, cost benefit analysis finds, quantifies, and adds all the
positive factors. These are the benefits. Then it identifies, quantifies, and
subtracts all the negative factors, the costs. The difference between the two
indicates whether the planned action is advisable.

8.2  Cost of the project

The cost of this project is expressed in terms of the cost of the work done by
myself in this period of 14 months, 12 moths working at CERN and 2 months
typing the project.

In the calculation it has been assumed a working week of 40 hours distributed in
5 working days of 8 hours. During the first six months only 4 hours were
considered per working day as other projects had to be attended, due to this, the
working day during these months was reduced to 20 weekly hours.
<table>
<thead>
<tr>
<th>Period</th>
<th>Working day</th>
<th>Days</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>July-December (2007)</td>
<td>Half (4 hours)</td>
<td>121</td>
<td>484</td>
</tr>
<tr>
<td>January-June (2008)</td>
<td>Complete (8 hours)</td>
<td>105</td>
<td>840</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>226</td>
<td>1324</td>
</tr>
</tbody>
</table>

Table 8.1: working hours at CERN in the project

To calculate the personnel cost it has been supposed a cost of 15€ per hour:

<table>
<thead>
<tr>
<th>Hours</th>
<th>Salary</th>
<th>Personnel cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1324</td>
<td>15€/hour</td>
<td>19860</td>
</tr>
</tbody>
</table>

Table 8.2: personnel cost of the project
Other costs to take in account:

<table>
<thead>
<tr>
<th>Work</th>
<th>Hours</th>
<th>€/hour</th>
<th>€</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCM+ course</td>
<td>16</td>
<td>12</td>
<td>192</td>
</tr>
<tr>
<td>French course</td>
<td>180</td>
<td>10</td>
<td>1800</td>
</tr>
<tr>
<td>Editing</td>
<td>180</td>
<td>10</td>
<td>1800</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>3792</strong></td>
</tr>
</tbody>
</table>

Table 8.3: other costs hours

Taking into account everything before detailed, the total cost of the project is:

<table>
<thead>
<tr>
<th>Concept</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work at CERN</td>
<td>19860</td>
</tr>
<tr>
<td>Training courses</td>
<td>1992</td>
</tr>
<tr>
<td>Editing</td>
<td>1800</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>23652</strong></td>
</tr>
</tbody>
</table>

Table 8.4: total cost of the project
8.3 Benefits of the project

The client of this project has been CERN and particularly the CV group, CFD team.

This project bases principally on the study of the airflow handling along the sector 5-6 of the LHC using computational domains and fluid techniques analysis of the team. Therefore, the obtained benefits cannot be measured quantitatively as they are intangible assets. There has been created a model that in spite of not producing money, gives the possibility of different and new analysis to draw conclusions to be applicable in the LHC ventilation system and provide an improvement of the whole system.

The principal benefits are:

- 3dimensional model in Catia (*.model, *.dlv, *.exp, *.CATPart, *.CATProduct), *.stl and StarCD (*.mdl)
- a working volume mesh (it is difficult and important to get a volume which doesn’t collapse the software) with real boundary conditions
- the possibility to implement new analysis on the model
- a development map of the air, temperature and density in normal conditions
- a development map of the air, temperature and density in abnormal conditions
- a 3 dimensional real simulation of how the ventilation along the sector 5-6 is working and applicable to the other sectors in a general way
9 Environmental effects

9.1 Environmental Management

Nowadays, environmental protection is carried out with the aid of environmental management systems. An Environmental Management System (EMS) is part of the overall management of an organization that includes organizational structure, planning activities, responsibilities, practices, procedures, and processes for effective environmental protection. The CERN EMS is based on the ISO14000 standards [Annexe A]. An efficient EMS is equally important as technical measures taken to protect the environment.

The basic philosophy of the CERN EMS is continual improvement. The system itself is subject to periodic audits to evaluate its effectiveness and to highlight any areas needing improvement. The criteria for effectiveness concern reaching environmental objectives and examining how human and material resources have been used.

9.2 Environmental aspects

9.2.1 Air quality

The following sources of atmospheric releases (emissions) on the CERN sites are monitored:

- Ventilation of accelerator installations
- Cooling of accelerator installations
- Industrial activities
Investigation of the Ventilation System of the LHC Tunnel using CFD Techniques

- Heating plants

From all these sources, only the first one is considered under the scope of this project because affects directly what is being studied.

9.2.1.1 Ventilation of accelerator installations

![Ventilation diagram](image)

Figure 9.1: ventilation of CERN accelerator installations

Accelerator installations (accelerators, experimental halls, transfer tunnels, etc.) need continuous ventilation and air renewal especially in closed areas like tunnels. The ventilation systems maintain the required air temperature and humidity suitable for operating the installed devices and for removing possible pollutants.

High-energy particle beams may induce two types of pollution:

- Radioactivity
- Ozone and nitrogen oxides
Radioactivity is either created in air by direct nuclear interactions of high-energy particles, or gets into the air from other targets in the form of fragments, as aerosol (air contamination by dust) or as volatile fraction (tritium, 75Se, radioactive iodine, etc.).

Ozone is created by radiolysis of oxygen molecules resulting from ionising radiation. Ozone can then oxidise nitrogen and produce nitrogen oxides (NO, NO2).

The accelerator ventilation systems work at under-pressure regime: the air supplied from outside, may be conditioned, passes through the installation premises, and is finally released in a controlled way from ventilation outlets. All ventilation outlets are equipped with monitoring stations that measure radioactive emissions. Every sector has an independent ventilation flow as has shown in the picture above and has her own control system.

In that way the correct working way of the ventilation system is really important to avoid accumulations of pollution all along the tunnel. These accumulations could mean a dangerous situation for operations of maintenance, and obviously an increment of the emissions permit for the environmental management programme. A simulation like the one did in this project let know how approximately will develop the air inside the tunnel in a non-usual situation. Every simulation can accuracy approach more to the reality model and it is important for future improvements and changes on the LHC.

So far, the CERN monitoring programme which measures ozone and nitrogen oxides has not observed any effect of the CERN accelerators operations on the quality of released air. The concentrations of ozone and nitrogen oxides at the monitoring stations are comparable to those detected at locations far from any accelerators (ROPAG\(^2\) stations in Meyrin and Passeiry). They, thus, reflect the influence of other sources than accelerators such as sunshine, heating, traffic, etc.

\(^2\) Réseau d’Observation de la Pollution Atmosphérique à Genève
9.2.1.2 The origin of radiation at CERN

High-energy particle beams can generate showers of secondary particles and produce radioactive substances when hitting matter, for example accelerator components, beam dumps or particle detectors. Some of the secondary particles, namely photons, muons and neutrons, can penetrate shielding structures and reach the environment. They form the so called prompt stray radiation that ceases when the accelerator is stopped.

The greatest part of the radioactive substances remains contained in the accelerator components, so generating some radioactive waste. A considering part may however be carried out to the environment by fluids, such as ventilated air and in to lesser extent cooling water.

Most radionuclides produced in accelerators are very short-lived, and quickly disappear from the environment, for example $^{11}$C (half-life of 20 minutes), $^{13}$N, or $^{41}$Ar.
The most important longer-lived ones (7Be, 22Na, 60Co, etc.) have half-lives not exceeding few years. Being only beta/gamma emitters, these radionuclides have much lower radio-toxicity compared to those produced in nuclear fuel cycle.

Figure 9.3: radiation fields in an access pit to an underground facility. Part of the radiation penetrates up to the surface into the environment. Note the logarithmic scale

9.2.1.3 Control and minimization

Levels of stray radiation as well as radioactivity in discharges of air and water into the environment are under permanent control. The Organization carries out an extensive monitoring programme completed with independent monitoring programmes performed by the competent authorities in the CERN Host States (OFSP in Switzerland, IRSN in France). This allows us stopping any operation
leading to high ambient radiation levels or releases of radioactive substances in the environment.

CERN teams have tools (e.g. FLUKA) and a competence to carry out computer simulations of radiation fields, such as the one shown above, for existing and planned facilities. With the help of environmental dispersion models, the effective dose to the members of the public due to releases of radioactive substances is evaluated. In this way, the environmental impact of any installation can be predicted and minimized before the installation is built. Of course, the results are validated in the real monitoring programme.

9.2.1.4 The real environmental impact

The real radiological impact of CERN can be quantified by the effective dose to members of the public due to CERN activities. In the year 2004, the CERN-related annual effective dose to everyone outside the Organization was about 1.4% of the Swiss and French annual limit of 1 mSv. The majority of the effective dose is due to stray radiation, involving only external exposure that ceases when the accelerators are stopped.

The CERN-related component is one order of magnitude smaller than the typical variation of the natural exposures measured at different locations in the surrounding Geneva and French area. Moving from one municipality to another in the region may cause more extra dose than living on the CERN’s fence. This proves that the actual radiological impact of CERN is indeed negligible.
9.2.1.5 Other pollutants on the ventilation

A limited number of industrial-like activities, which may result in the emissions of pollutants mostly via the ventilation systems of various workshops, are carried out on the CERN sites. The main industrial pollutants are: acids and cyanides vapours coming from electroplating baths, vapours from baths with solvents (e.g. alcohol, perchloroethylene), gaseous effluents of welding and exhausts of oil vacuum pumps (hydrocarbons). Technical systems are set up to minimize the extent of these emissions.
9.2.2 Noise at CERN

The potential sources of noise at CERN come mainly from the accelerators operation and from civil-engineering activities. These can be of two types:

- Fixed sources
- Mobile sources

Noise emissions emanating from CERN installations may be irritating for local population and fauna. Their environmental impact changes according to three parameters:

- Source noise level
- Localization (outside or inside a building)
- Sources or buildings acoustic treatments

The number of sound sources at CERN is considerable (several thousands) but their environmental impact remain insignificant thanks to the technical solutions set up to reduce their extent. In addition, noise levels are continuously monitored and noise barriers are raised whenever required.

9.2.2.1 Fixed sources

The main fixed sources are electric generators, transformers, power converters, High Voltage zones (HT), compressors, pumps, heat exchangers and air treatment units.

At the LHC and SPS sites, except for zones HT located outside buildings, noisy installations are concentrated in specific buildings for noise reduction.
In the Meyrin and Prévessin sites, noisy installations are located in insolated areas within buildings. Levels higher than 100 dB(A) inside these buildings can be translated in levels lower than 55 dB(A) outside these buildings.

9.2.2.2 Environmental aspect of noise

The only environmental aspect related to these sound emissions is the rise of background noise for the neighborhoods due to CERN installations.

To minimize its impact, CERN takes the following measures to protect the environment:

• Choice of equipments according to their acoustic performances
• Acoustic treatment of LHC buildings
• Acoustic barriers between noise sources and areas to protect
• Setup of measuring devices for continuous monitoring of sound levels near work sites.

3 dB(A) is one way to measure noise or rather sound levels. The dB(A) levels quantify the discomfort generated by noise on the human hear (i.e. the mean value of a busy restaurant is 70 dB(A)).
9.2.3 The electricity consumption

Particle accelerators and detectors as well as infrastructure equipment need to be supplied with electricity. Electricity consumption is, therefore, one of the important CERN environmental aspects.

The nominal annual electricity consumption reaches some 1000 GWh when all accelerators are in operation. Only about 8% of this figure corresponds to the basic consumption necessary for the laboratory infrastructure. The remaining 92% is attributed to accelerator facilities.

The Large Hadron Collider (LHC), which has just started its operation, will gradually reach its nominal consumption of 390 GWh per year.

A large fraction of the LHC electrical consumption will be to keep the superconducting magnet system to the operating temperatures (1.8 and 4.2 K) depending on the magnets. Thanks to the superconducting technology employed for its magnets, the nominal consumption of the LHC is not much higher than that of the Super Proton Synchrotron (SPS), even though the LHC is much larger and stronger in energy.
9.2.3.1 Saving electricity when it is most needed

CERN accelerators are typically operated from spring to autumn when the public demand of electrical energy is low.

The contract with the French supplier EDF contains a special reduced power consumption clause. This clause stipulates that, on notice given by EDF, CERN considerably reduces its electricity consumption to avoid paying a hefty surcharge.
10 Conclusions and future developments

As a result of this project a complete 3Dimensional volume mesh model, real but simplified, of the sector 5-6 of the LHC has been developed in order to perform several simulations using CFD techniques. The final goal was to have a better knowledge of the behaviour of the tunnel under steady state conditions or accidental transient conditions.

After doing several simulations this 3D model has proven to be a suitable tool in order to get a better knowledge of the fluid behaviour inside the tunnel.

The simulations performed prove that this model fulfills all the requirements that had been imposed at the beginning of the project:

- The inlet opening is enough to introduce the nominal airflow (36000m³/h).
- The velocity of the air is well dimensioned to keep the ambient temperature around 20°C.
- The ventilation system circulates like it has been studied, after the closing of the tunnel connections.

Some other abnormal situations were proposed to be simulated, like smoke production, helium leakage or radiation propagation. Only the first case – smoke production due to cable fire - is considered under the scope of this project.

The simulation performed shows that the model runs correctly after implementing the smoke source.

The temperature rise along this octant due to the heat dissipated by the fire and the pipes around is expected to be approximately 373 K after 24 minutes of transient simulation; 80 K higher than the normal temperature.
The smoke pushed by the ventilation system arrives to the second cavern after 7 minutes.

These values could give very useful information for the safety procedure and installations in that kind of events.

The aim is to continue using the model applied to other cases. The mesh is prepared to simulate a helium leakage for a broken pipe. It could be quite interesting to simulate as well the effect of radiation in some parts of the magnets.
11 References

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[6] Prof. Dr. Schutz, 2007, Ingenieurmethoden fur die Auslegung der Entrauchung, Fachhochschule Lausitz, University of applied Sciences


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- J. Schabacker, M. Bettelini, Ch. Rudin, *CDF study of temperature and smoke distribution in a railway tunnel with natural ventilation system*, HBI Haerter AG, Bern, Switzerland.


