Numerical simulation of fire in the underground parking of Annecy City Hall using the Phoenics code

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The aim of this work is to show how a complex problem of safety can be studied using CFD simulation and which practical solutions can be brought using this technique. The CFD simulation has been carried out by using the Phoenics CFD package.

The problem relates to the underground car park of the Town hall of Annecy (France). Its shape is a helical slab, which revolves around a central atrium.

A situation of fire developing at the bottom of the car park is simulated. Two methods for transfer of heat and smoke are identified. They are the invasion of the higher levels by the smoke, which forwards by the central atrium on the one hand, and of the progression along the helical slab on the other hand. These two modes of propagation are analysed from the point of view of the evacuation of the people and the organisation of the safety services.

An analysis of the practical provisions of safety is finally carried out. The final solutions suggested were agreed with by the first-aid organisations and to not very significant alteration work.

KEYWORDS : CFD model, Fields Models, Virtual Reality objects, fire, underground car park, security, Phoenics

1. INTRODUCTION

On March 24, 1999, a fire in the Mont Blanc tunnel causes the death of 39 people [1]. This tunnel connects the department of Haute-Savoie (France) with the province of Aosta (Italy). As a consequence of this event, the administrative services of the department of Haute-Savoie required the city of Annecy to carry out checks concerning the safety of the town hall car park.

This underground car park is located in front of the town hall of Annecy. It is composed of a helical slab ensuring at the same time the circulation and the parking of the vehicles. Six levels of parking are thus arranged. They open on a central atrium. The depth the work is about 20 m.

The emergency services of the department recommended heavy and expensive installations intended to organise the containment of a possible fire in the car park.

The city of Annecy asked the SCETAUROUTE Tunnelling Division to carry out numerical simulations of a fire in the car park. With this intention, and because of the complex geometry of the car park and the aims of the study, the use of a three-dimensional transient CFD model appeared more appropriate. These CFD simulations, which require a good knowledge of the models and phenomenology related to fire in confined spaces [2,3,4], aimed at understanding the flows induced by a fire in the car park, in order to evaluate and adapt the installations of safety. Scetauroute in turn asked ArcoFluid for consulting services to set up and run the cases.

Due to the complexity of the car park, the development of the numerical grid constituted a paramount stage of the study. Various techniques were considered for finally choosing a cylindrical type combined with a technique of VR object (virtual reality) to represent the various components of the car park (slab, ventilation ducts, staircases, vehicles...). The nice feature of such grid is that all elements coincide with the grid which makes the VR very advantageous. The CFD code PHOENICS, used for the study, makes it possible to implement these various numerical techniques.

The geometry of the car park, certainly makes the present study among the most complex performed in CFD and transient in an underground work.

2. PRESENTATION OF THE PROBLEM

Since the catastrophe of the Mont Blanc tunnel, the safety of public underground works has become the subject of numerous studies in order to define the installations and the procedures to be implemented in situation of fire. In this field, underground car parks seem to be places at the risks since, in situation of fire, many users can be blocked in the structure.

2.1 THE FIRE BRIGADE RECOMMENDATIONS

In the Annecy town hall car park, the fire brigade had recommended to install insulating doors in order to divide the car park into sections and to thus confine the smoke in part of the work. One of the consequences of this solution was to result in isolating the car park from its central atrium.

The fire brigade justified their recommendations on the basis of smoke tests carried out using a smoke generator.

These solutions appear very constraining because they impose very significant modifications and they do not respect the architectural choices of the work. For these reasons, the technical services of Annecy City Administration entrusted to SCETAUROUTE a study intended for better understanding the behaviour of a fire in the car park. The final objective is to propose alternative solutions of installation.

2.2 THE CAR PARK

The underground car park of the Annecy town hall is composed of 6 levels revolving around a spiral around an open air central atrium (Figure 1). The vehicles are parked on both sides of a central roadway. The internal radius of the atrium is 8.5 m and the width of the slab is 8.5m. At the centre of the slab, the slope is 2.5 %.

In this work ventilation is of two types: natural and mechanical (Figure 1). Natural ventilation is carried out by the central atrium and by shafts (two per level) emerging directly to the free air. Extraction shafts, equipped with fans (2 per level) carry out mechanical ventilation. The shafts are vertical and located on the external part of the slab (Figure 1).

To join the exit, the users of the car park must use one of the two staircases or elevators located in the central atrium (Figure 1). In the original situation, these staircases are open on the atrium. On each level, there are two accesses to go up to the surface.

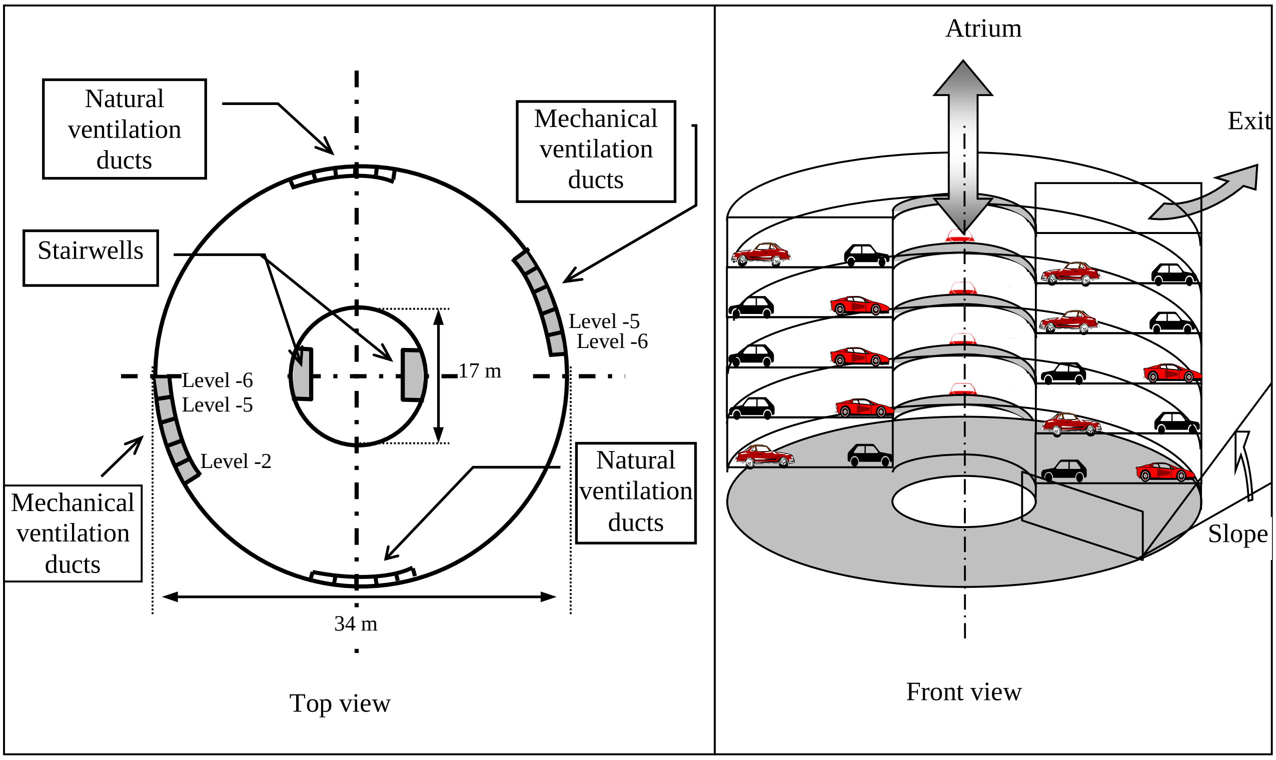

Figure 1 : Schematic presentation of the Annecy City Hall car park (France)

3. THE CFD MODEL

3.1 THE CAR PARK CFD MODEL

In order to model a fire in a confined space using a CFD code, in addition to the transitory nature and non-isothermal aspects of the problem, certain physical phenomena must be taken into account:

- turbulence (use of a k-ε model)
- buoyancy phenomena generated by the fire;
- heat and smoke release at the fire.

In addition, to simulate the flow correctly and thus to be able to estimate the evolution of the smoke as a function of time, it is essential to model the exact geometry of the car park as well as all of the infrastructure and obstacles composing the work (stairwells, system of ventilation, ventilation shafts, stationed vehicles, atrium, wall separating the car park from the atrium, etc).

Particular problems have to be solved in order to carry out these calculations.

3.2 THE MESH AND THE CALCULATION

The CFD code used in this study is the finite volume code PHOENICS [5,6]. The equations solved are the momentum, mass, energy and species conservation equations. These equations can be written as follows:

$$\frac{\partial \rho\phi}{\partial t} + \nabla \cdot (\rho V \phi) = \nabla \cdot \left(\Gamma_{\phi} \nabla \phi \right) + S_{\phi} \qquad \textbf{(1)}$$

where ϕ is the dependent variable considered, ρ, V are respectively the fluid density and the velocity, Γ_{ϕ} the generalised diffusion coefficient and S_{ϕ} the source term.

The equations are written in the conservative form.

The solutions are found by getting the solution of the coupled differential equations in an iterative manner. In order to achieve this goal, the PHOENICS code uses the SIMPLEST algorithm, on a staggered finite volume

To the latter, the problem-set-up, grid-generation and results - interpretation aspects of CFD present serious obstacles, round which easy paths must be found.

The first attempt to solve the problem has been made using the BFC coordinates. However with the numbers of objects (stairways, helical runway, ramps, vehicles and ventilation ducts), the task becomes unrealistic with structured grids.

So the Virtual Reality capabilities of the PHOENICS code have been used.

This option enabled to set up flow-simulation tasks for PHOENICS in "real-life terms", placing walls, apertures, heat sources, fans, etc., as wanted. Choosing for the virtual reality, cylindrical coordinates, objects and boundary conditions coincide nicely with the grids.

The computational grids for the simulation of the fifteen cases were selected through grid refinement studies, to obtain well-converged stable solutions and sufficient accuracy. The grid lines were more finely spaced near the walls and the ventilation ducts where the gradients are the steepest.

The numerical grid is composed of 430 000 cells (Figure 2).

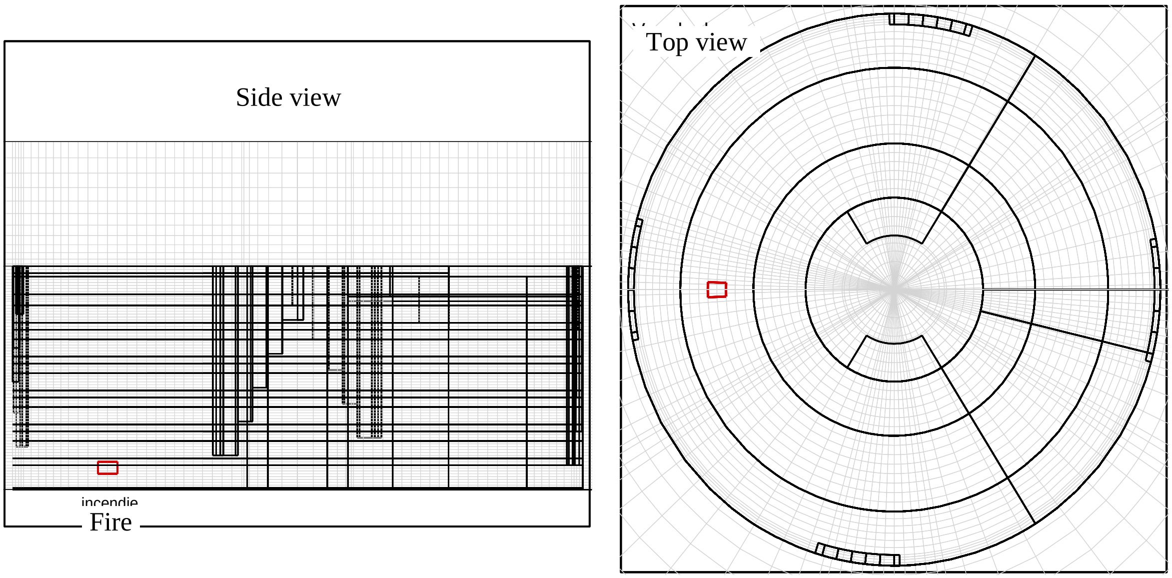

Figure 2 : Mesh used for the calculation

The great complexity involved in these computations meant that substantial computing resources were required to simulate a fire of 20 minutes in the car park, approximately 6 CPU days per complete simulation on a PC with a processor Pentium 800Mhz.

In order to account for the turbulence, we have used a k-ε model [7,8]. In this model, turbulence is characterised by the turbulence kinetic energy k and its rate of dissipation ε. Both these parameters are governed by differential equations of the form as Eq. (1). In the literature about fire in a tunnel, the k-ε model is often used even if it is not really appropriate. This is the reason why some authors modify the k-ε model [9]. In this study, we used a model k-ε RNG.

3.3 THE SOURCE TERMS AND THE BOUNDARY CONDITIONS

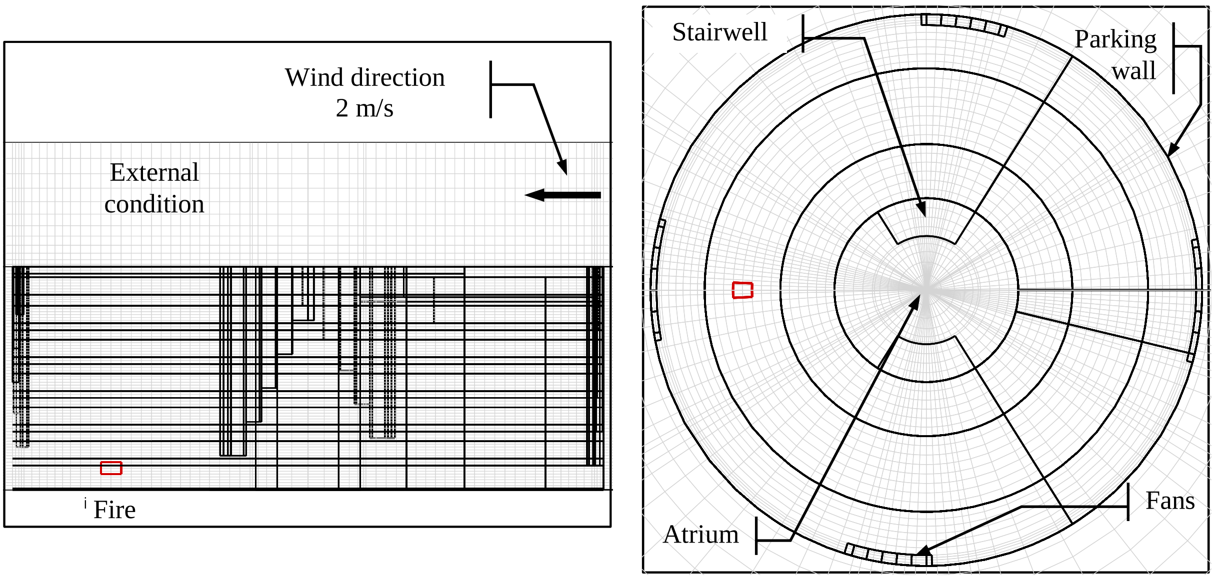

Figure 3 : The source terms and the boundary conditions

3.3.1 The fire representation

The fire is located in the lower part of the car park (Figure 3). It is in this place that it presents the most significant potential danger.

Calculations are carried out without a model of combustion. Fire is thus represented like a volume source of heat characterised by a heat release rate as a function of time.

In all the simulations the average heat release rate of fire was approximately 5 MW. This power corresponds to a fire of a large private car, or 2 or 3 vehicles of small size [10]. The evolution of the thermal heat release rate is as follows:

- a linear increase of 10 seconds;
- a constant maximum power of heat (5 MW) during 20 minutes.

The fire source takes into account a density of thermal emission of about 1 MW/m^3.

3.3.2 The walls

The walls are considered as isotherms (fixed temperature of 15°C). The boundary condition also relates to a speed of 0 m/s on the surface of the walls. Near the walls, the heat and momentum fluxes obey the standard wall-functions relations.

The specific materials of the walls and obstacles are taken into account: steel for the vehicles and concrete for all the other structures.

3.3.3 Fans representation

All fans are placed at the top of the ventilation duct. Each extraction fan is represented by a constant volumetric flow rate (8.8 m^3/s) with a turbulence intensity of 5%.

3.3.4 External conditions

In order not to force the flow in the interior volume of the car park by the choice of a pressure condition on the upper part of the atrium, the selected technique consists in representing part of the external atmosphere. The boundary conditions are located on it.

The choice relates to a wind of 2 m/s (Figure 3). The temperature is 15°C and the turbulence intensity is 5%. On the opposite surface, a condition of pressure is imposed (101 325 Pa).

4. THE RESULTS

Within the framework of the study, the influence of various parameters was studied. The results presented here are focused on the principal phenomena of thermal transfer and smoke, which was characterised by calculation. The technical proposals for an improvement of safety, formulated at the end of the study, are based on the analysis of these phenomena.

So only the most representative phenomena are presented.

4.1 SMOKE SPREAD IN THE CAR PARK

The smoke propagation in the car park occurs in two different ways:

- the transfer by the central atrium;
- progression along the helical slab.

These two mechanisms are very well represented by the smoke limit 60 seconds after the starting of the fire (Figure 4).

4.1.1 Transfer through the atrium

The starting of the fire is accompanied by a strong expansion of gases in the zone of the fire. This phenomenon allows the smoke to invade the internal space of the car park in both the downstream and upstream direction. A fraction of the gases is also pushed towards the atrium. This smoke is then propagated very quickly to the upper floors through the central atrium.

For the safety of the users present in the car park, the role of the central atrium appears very significant. The reason is that the thermal energy evacuated by the atrium strongly limits the progression of hot gases along the helical slab.

On the other hand, part of the smoke, which is evacuated by the atrium, invades the higher stages but, in contact with the fresh air, these gases are slightly cooled and diluted. Thus, at the higher levels, the risks to the users appear limited.

The limit of the smoke has a temperature of about 50°C. So, the temperature seems acceptable for the evacuation of the users. The representation of an isothermal surface at 100°C shows that the hot smoke only penetrates slightly to the higher stages of the car park (Figure 5).

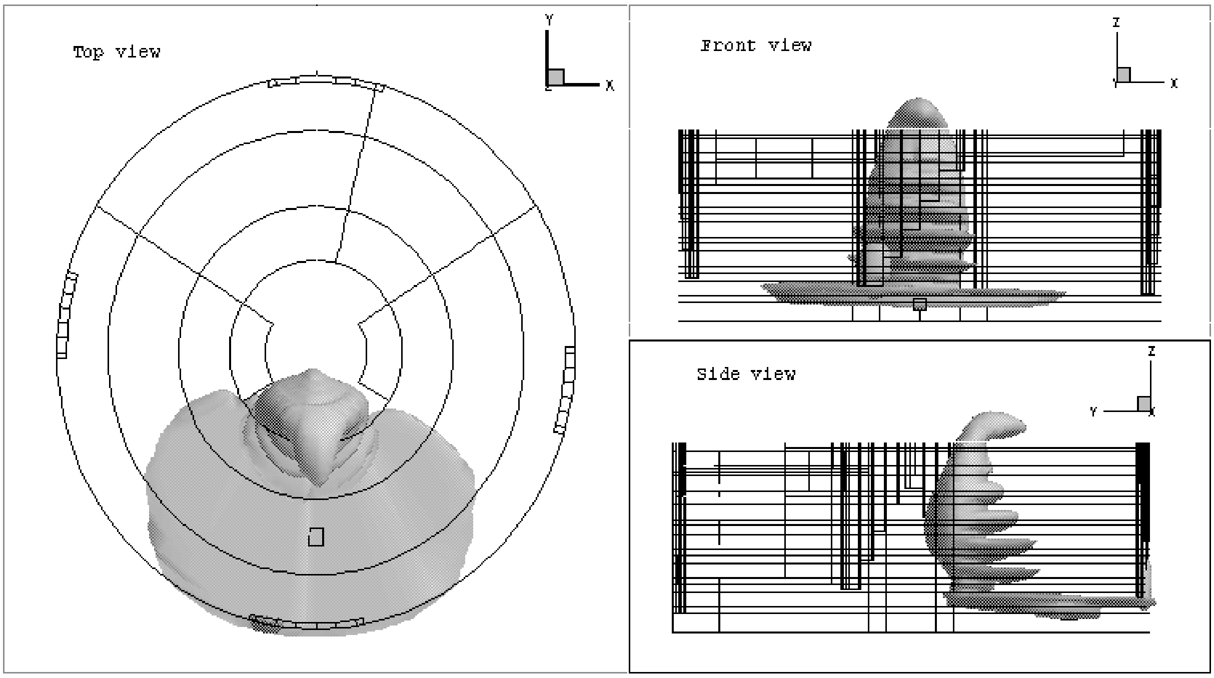

Figure 4: Smoke limit 60 seconds after fire ignition

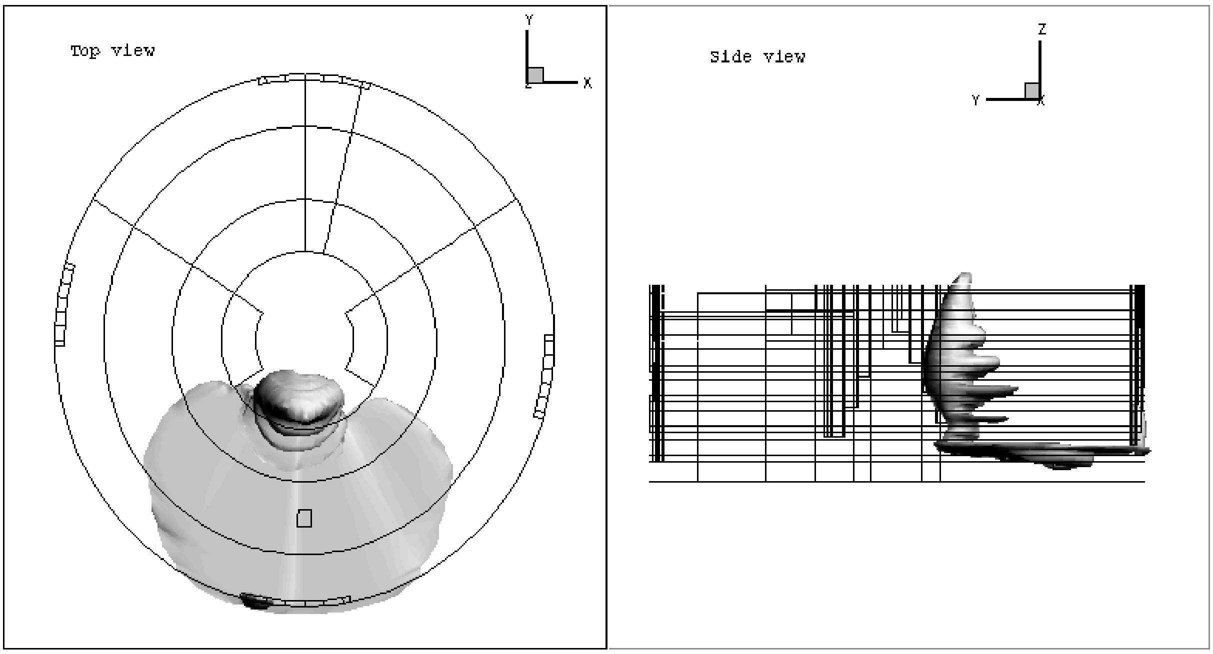

Figure 5: 100°C isotherm surface 60 seconds after fire ignition

4.1.2 Progression of the smoke along the helical slab

Thanks to the dissipation of the heat inside the atrium, the hot gazes coming directly from the fire have a low propagation velocity along the helical slab, about 0.2 m/s (Figure 6).

Simulation is transitory. It reveals that the smoke escapes towards the atrium in the form of puffs. The smoke seems to be diffused towards the helical slab and regular interval towards the atrium. In fact, the cyclic process of the puffs is directly connected with the quantity of smoke evacuated by shafts. For this reason, the atrium appears free from fume 120 seconds after the starting of the fire. On average, over the duration of the fire, one shows that the evacuation of the smoke was carried out mostly by the atrium and shafts and that the helical part receives only one weak part of it.

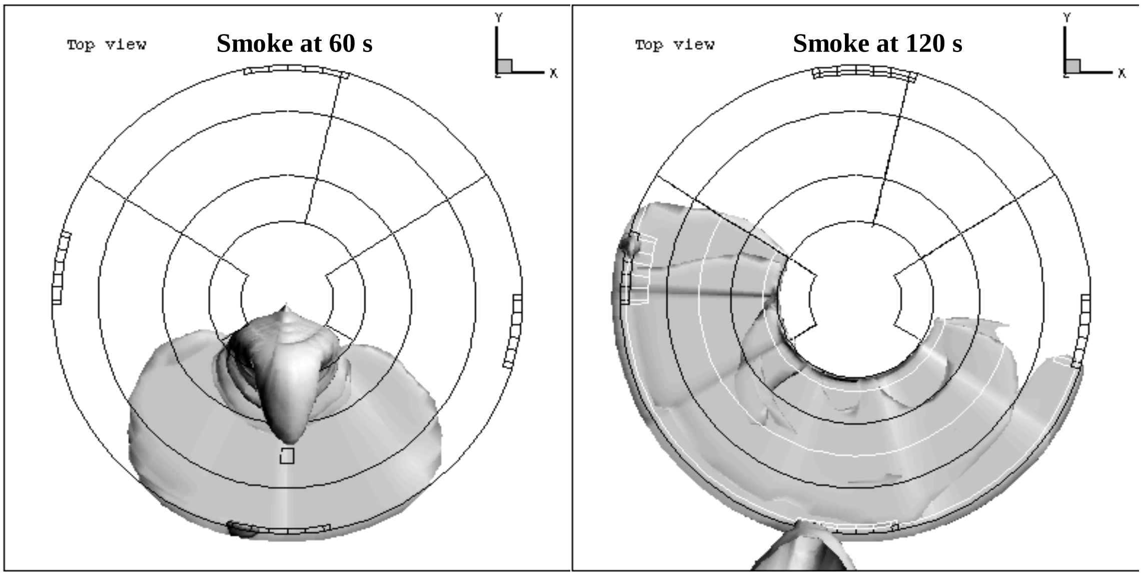

Figure 6: Smoke propagation 60 s and 120 s after ignition

4.2 SMOKE PROPAGATION IN THE ATRIUM

As indicated previously, the main part of the smoke is evacuated through the central atrium. The stairwells are surrounded by hot fume (Figure 7). In some simulations, it was evident that the atrium can be completely invaded by the smoke.

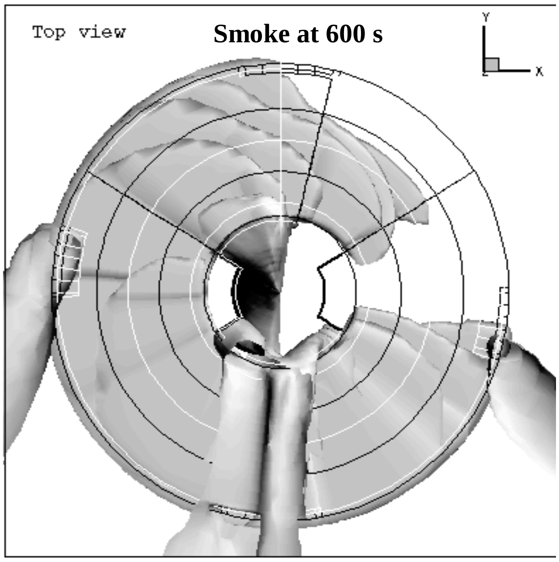

Figure 7 : Smoke limits after 600 s (the extraction fans are activated).

5. THE FINAL RECOMMENDATIONS

The analysis of the smoke transfer phenomena reveals situations, which must be exploited for the benefit of the peoples safety:

- the atrium plays the natural role of a chimney. Most of the heat released by the fire is evacuated through this volume. The free communication between the car park and the atrium must thus be maintained. It was shown that the higher stages are locally affected by the fume coming from the atrium. This situation constitutes a drawback from the positive role of the atrium;
- the evacuation of most of the heat release rate through the atrium and ventilation shafts strongly limits the progression of the smoke along the helical slab. So the people have a sufficient time to reach the emergency exits, whatever the level of the car park on which they are;
- in the current state, no gate has the characteristics of an emergency exit. The stair-wells can play this role as soon as they are isolated from the car park (this is the case, since they are already equipped with fireproof doors) and of the atrium (this will be the subject of future work);
- the central position of the two stair-wells is essential with respect to the distances to travel to reach them;
- the stair-wells are also used as the access for the first-aid organisations;
- the implementation of the mechanical systems of ventilation seems to play only a secondary role. This effect appears foreseeable given the semi-confined nature of the work.

The practical provisions of these improvements are studied. They result in defining three essential points:

- the means of insulation used between the stair-wells and the atrium (the temperatures in the atrium can exceed 100°C in the case of a fire of 5 MW);
- means of pressurising the stair-wells in order to ensure the role of emergency exit;
- means of alarm of the users (the people who are not directly concerned with the fire must evacuate themselves like the others since the fume coming from the atrium can affect them quickly).

These provisions appear more adapted to the physics of a fire than the initial recommendations of the fire brigade. Moreover, they respect the initial choices of the architects and the city of Annecy .

6. CONCLUSIONS

The use of CFD simulations within the framework of improving the fire protection in the Annecy town hall car park appears to be a good choice. This technique made it possible to characterise with a very high degree of accuracy the fluid phenomena, which develops in the event of a fire in this geometrically complex structure.

It appears that part of these phenomena can be used since it generates a first level of passive safety by evacuating most of the heat released by the fire through the atrium. This movement leads to the premature invasion of smoke at the higher levels but, on the other hand, it strongly slows down the progression of the smoke along the helical slab, which makes it possible to uses stair-wells with some slight modifications, as evacuation gates.

The final provisions retained for improving the safety of the car park appear lighter than the initial recommendations of the first-aid organisations. The savings and the real profits in safety thus fully justify the scientific approach

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