

# 3D Some proposals on 3D Simulation of air velocity and temperature evolution in buildings

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# INTRODUCTION

- ▶ Design new buildings as *Nearly zero-energy buildings nowadays* it is an important ( necessary) target and to hold confort inside building
  
- ▶ Phenomena related to energy efficiency in buildings show a great complexity , since they involve the relationship between:
  1. the levels set for the thermal confort,
  2. the complex geometry of the buildings (different materials,...)
  3. the exchange of energy with the exterior : airflow, solar radiation, thermal radiation from different sources, convection process, HVAC (Heating, Ventilating and Air-Conditioning systems), etc.

# CONSIDERATIONS

- ▶ The inlet airflow in the building is a boundary condition which is established from data of predominant wind ( wind trade) and from the corresponding atmospheric stability. We use an adjust model named CMM (consistent matrix mass ) (Winter,1995 & Ferragut & Montenegro & Montero).
- ▶ For inside building we consider a DNS (Direct Numerical Simulation) method (thus avoiding parametrisations and calibrations).  
Buoyancy effects are included in the numerical simulation (Boussinesq approximatio)
- ▶ The success will be to choise and to adpat a suitable model to get fast results for an acceptable accuracy: for it we propose a projection method where velocity and pressure is P1 in each finite element
- ▶ As a boundary condition we do not consider the simplification of the fixed the temperature on the walls exterior surfaces of the buildings. We compute this temperatura considering convection and radiation heat transfer
- ▶ The exterior roof and some walls surface are exposed to outdoor solar radiation. We consider also radiactive cooling from the sky.

# MATHEMATICAL MODEL IMPLEMENTED

$$\rho_o \frac{\partial u}{\partial t} + \rho_o \mathbf{u} \cdot \mathbf{grad} u - \mathit{div}(\mu \mathbf{grad} u) = -\frac{\partial p}{\partial x}$$

$$\rho_o \frac{\partial v}{\partial t} + \rho_o \mathbf{u} \cdot \mathbf{grad} v - \mathit{div}(\mu \mathbf{grad} v) = -\frac{\partial p}{\partial y}$$

$$\rho_o \frac{\partial w}{\partial t} + \rho_o \mathbf{u} \cdot \mathbf{grad} w - \mathit{div}(\mu \mathbf{grad} w) = -\frac{\partial p}{\partial z} + \rho \mathbf{g}$$

$\mathit{div} \mathbf{u} = 0$  in the projection method solving NS  $\mathit{div} \mathbf{u} \rightarrow 0$

$$\rho_o c \frac{\partial T}{\partial t} + \rho_o c \mathbf{u} \cdot \mathbf{grad} T - \mathit{div}(k \mathbf{grad} T) = -p \mathit{div} \mathbf{u}$$

$$\rho = \rho_o (1 - \beta (T - T_o)) , \quad \beta = -\frac{1}{\rho} \frac{\partial \rho}{\partial T} \quad \text{which is obtain to be with good accuracy} \approx \frac{1}{T}$$

# RADIATION AND CONVECTION HEAT TRANSFER IN BUILDING ENVELOPE

On the roofs and the walls the heat flux is imposed as boundary condition (in the variational formulation of the element finite method as integral in the boundary multiply by test function) :

$$\blacktriangleright -K \frac{\partial T}{\partial n} = (1 - \gamma)E - h_{ext}(T - T_{ext}) + \sigma \epsilon (T_{sky}^4 - T^4)$$

▶  $K$  : thermal conductivity                       $\epsilon$  : emissivity

▶  $\gamma$  solar reflectivity of rooftop and walls surface

▶  $\alpha = (1 - \gamma)$ : absorptivity coef               $E$  : solar radiation (W/m<sup>2</sup>) in daytime

▶  $h_{ext} = 5.7 + 3.8W$                        $W$  : wind velocity (m/s) , a correlation proposed by McAdams

▶  $T_{sky} = 0.0552T_{ext}^{1.5}$               the sky temperature (K) by Swinbank in daytime & nighttime

## A.1 Temperatura de rocío

Para la obtención de los valores del archivo .MET se ha empleado la fórmula de Peppers (1988).

Así mismo, la fórmula de Magnus permite calcular la temperatura de rocío ( $\theta_{dp}$ , en °C) a partir de la temperatura seca ( $\theta_s$ , en °C) y la humedad relativa ( $\varphi$ , en %):

$$\theta_{dp} = 243,5 \cdot \left( \frac{\gamma(\theta_s, \varphi)}{17,67 - \gamma(\theta_s, \varphi)} \right) \quad (1)$$

donde,

$$\gamma(\theta, \varphi) = \ln(\varphi/100) + \left( \frac{17,67 \cdot \theta}{243,5 + \theta} \right) \quad (2)$$

## A.2 Temperatura efectiva del cielo = $T_{sky}$

La correlación de Walton (1983) que utiliza la corrección de nubosidad dada por Clark y Allen (1978) permite obtener la temperatura efectiva del cielo (en °C):

$$\theta_{cielo} = \left( \frac{H_{IR}}{\sigma} \right)^{0,25} - 273,15 \quad (3)$$

donde,

$\theta_{cielo}$  es la temperatura efectiva del cielo en °C;

$H_{IR}$  es la intensidad de la radiación infrarroja sobre el plano horizontal en  $W \cdot h/m^2$ ;

$$H_{IR} = \varepsilon_{cielo} \cdot \sigma \cdot (\theta_s + 273,15)^4 \quad (4)$$

$\varepsilon_{cielo}$  es la emisividad del cielo;

$$\varepsilon_{cielo} = (0,787 + 0,764 \cdot \ln((\theta_{dp} + 273,15)/273,0)) \cdot (1,0 + 0,0224N - 0,0035N^2 + 0,00028N^3) \quad (5)$$

$\sigma$  es la constante de Stefan-Boltzmann  $\sigma = 5,6697 \cdot 10^{-8} W/m^2 \cdot K^4$ ;

$\theta_s$  es la temperatura seca del aire en °C;

$\theta_{dp}$  es la temperatura de rocío del aire en °C;

$N$  es la cobertura del cielo en tanto por diez, de valor 3 para los meses de abril a octubre (ambos incluidos) y 5 para el resto.



# Documento descriptivo climas de referencia

FEBRERO 2017

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## 3. Climas de referencia en soporte informático

### 3.1. El formato .MET

Los datos climáticos correspondientes a los climas de referencia se publican en formato .MET.

Este formato se estructura en líneas de texto con campos separados por espacios y su organización es la siguiente:

1. Primera línea con una cadena de texto identificativa del archivo de datos.
2. Segunda línea con datos de: latitud, longitud, altitud y longitud de referencia para el cálculo de la hora oficial.
3. Siguen 8760 líneas con datos horarios formados por los campos siguientes:
  - a) Mes (1 a 12);

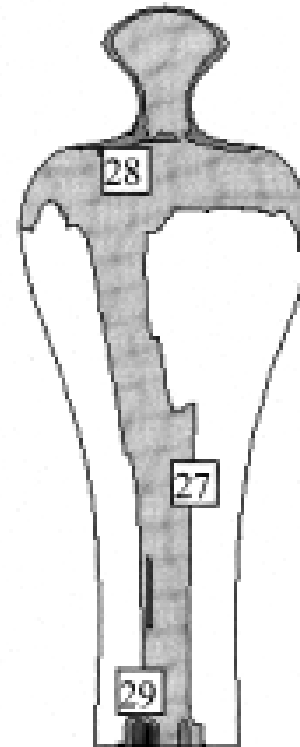


- b) Día (1 a 31);
- c) Hora (1 a 24);
- d) Temperatura seca ( $^{\circ}\text{C}$ );
- e) Temperatura efectiva del cielo ( $^{\circ}\text{C}$ );
- f) Irradiancia solar directa sobre una superficie horizontal ( $\text{W}/\text{m}^2$ );
- g) Irradiancia solar difusa sobre una superficie horizontal ( $\text{W}/\text{m}^2$ );
- h) Humedad específica ( $\text{kgH}_2\text{O}/\text{kgaire seco}$ );
- i) Humedad relativa (%);
- j) Velocidad del viento ( $\text{m}/\text{s}$ );
- k) Dirección del viento (grados respecto al norte, E+, O-);
- l) Azimut solar (grados);
- m) Cénit solar (grados).

We can include the mean radiant temperature of the body :

$$-K \frac{\partial T}{\partial n} = \sigma \epsilon (T_{air\ domain}^4 - T_{body}^4)$$

Mean value: 27.1°C

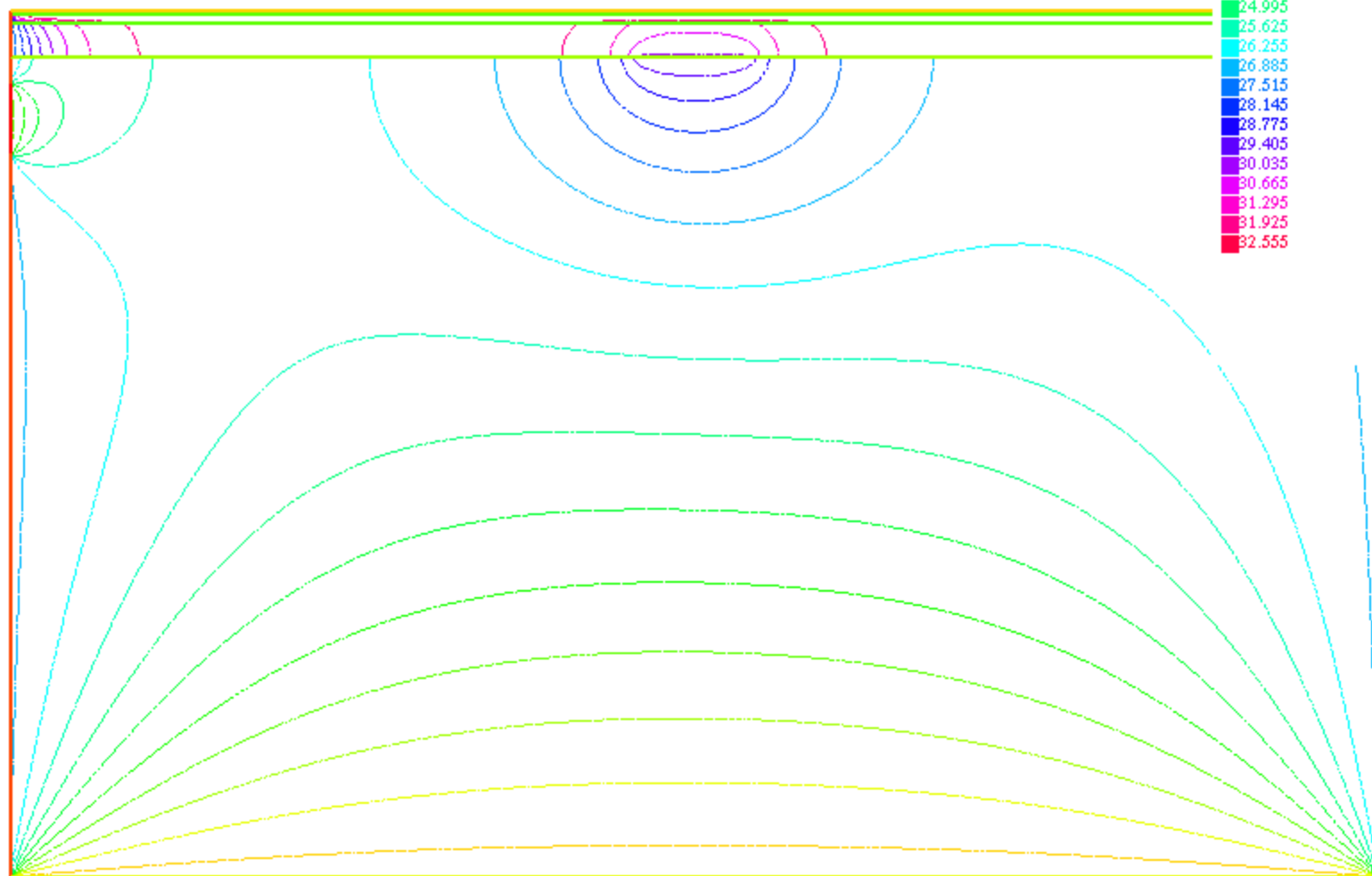


(2) Mean radiant temperature (°C)

```
min 294.05 max 305.39
r seminorma H1 = 1.20567e-007
r L2 = 1.19256e-005
r norma H1 = 1.19262e-005
eratura en cubierta = 32.2399
eratura interfase baldosa con EPS= 32.2396
eratura interfase EPS con forjado= 32.2309
eratura interfase forjado con aire espacio interior= 26.456
eratura en aire habitacion a 4m del suelo = 25.6478
eratura en aire habitacion a 3m del suelo = 24.8493
eratura en aire habitacion a 2m del suelo = 23.8006
eratura en aire habitacion a 1m del suelo = 22.4631
eratura en aire habitacion a 0,5 m del suelo = 21.6987
```

```
Solve :
min 294.05 max 305.39
r seminorma H1 = 1.64522e-009
r L2 = 1.67482e-007
r norma H1 = 1.6749e-007
eratura en cubierta = 32.2399
eratura interfase baldosa con EPS= 32.2396
eratura interfase EPS con forjado= 32.2309
eratura interfase forjado con aire espacio interior= 26.456
eratura en aire habitacion a 4m del suelo = 25.6478
eratura en aire habitacion a 3m del suelo = 24.8493
eratura en aire habitacion a 2m del suelo = 23.8006
eratura en aire habitacion a 1m del suelo = 22.4631
eratura en aire habitacion a 0,5 m del suelo = 21.6987
ca580 VTK_FILE 1
: compile 0.252s, execution 29.652s, mpirank:0
```

temperatura



- ▶ mesh mallasolida =  
buildmesh(c(15\*n)+d(10\*n)+e(8\*n)+f(100\*n)+gg(15\*n)+h1(10\*n)+p1(15\*n)+o(-100\*n)+l(100\*n)+m(100\*n));
- ▶ mesh Th =  
buildmesh(a(100\*n)+b3(40\*n)+b2(15\*n)+b1(10\*n)+b31(10\*n)+b32(10\*n)+o(100\*n)+p21(10\*n)+p22(10\*n)+j11(10\*n)+j2(15\*n)+j3(40\*n));
- ▶ // Th malla aire
- ▶ mesh mallatotal=Th+mallasolida; // SUMA DE MALLAS
- ▶ fespace Vht(mallatotal,P1);
- ▶ Vht reg=region;
- ▶ int material1 = reg(75,32); // plaqueta o baldosa ceramica 3 cm
- ▶ int material2 = reg(75,28); // EPS 6cm
- ▶ int material3 = reg(75,10); // entrevigado 25 cm

- ▶ `real k1,k2,k3,ka;`
- ▶ `k1=1*0.01; // (W/cm k)`
- ▶ `k2=0.029*0.01; // (W/cm k)`
- ▶ `k3=0.256*0.01; // (W/cm k)`
- ▶ `ka=0.02624*0.01; // AIRE (W/cm k)`
  
- ▶ `k =`  
`k1*(region==material1)+k2*(region==material2)+k3*(region==material3)+ka*(re`  
`gion==airerom);`
  
- ▶ `aire= 1.*(region==airerom)+`
- ▶ `0.*(region==material1)+0.*(region==material2)+`
- ▶ `0.*(region==material3)`
- ▶ `;`

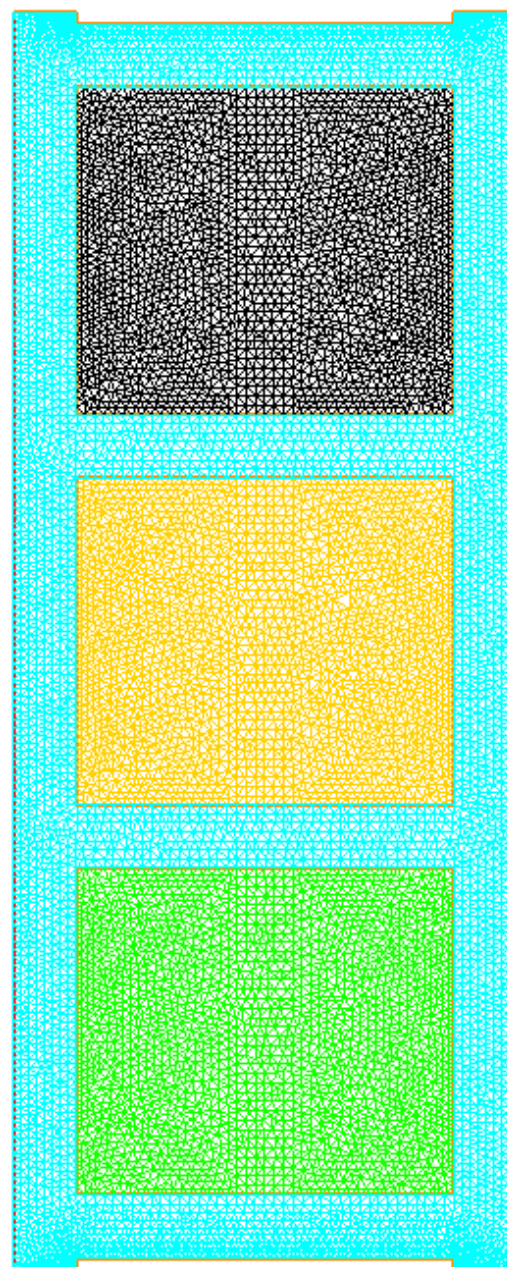
```
problem temp(T,v) =
int2d(mallatotal) (k*dx(T)*dx(v)+k*dy(T)*dy(v))
+int1d(mallatotal,4) (sigma*emisivity*B*T*v)
- int1d(mallatotal,4) (sigma*emisivity*B*T0*v)
+int1d(mallatotal,2,4) (hext*T*v)
-int1d(mallatotal,2,4) (hext*T0*v)
-int1d(mallatotal,4) (A*RADSOLAR*v)
+int1d(mallatotal,4) (sigma*emisivity*B*T*v)
- int1d(mallatotal,4) (sigma*emisivitySKY*B*Tcielo*v)
+on (5,T=Tsuelo)+on (1,T=296.15);
// temperatura 23 °C entrada aire acondicionado en label 1
real ErrorL2 = 1.;
real ErrorH1 = 1.;

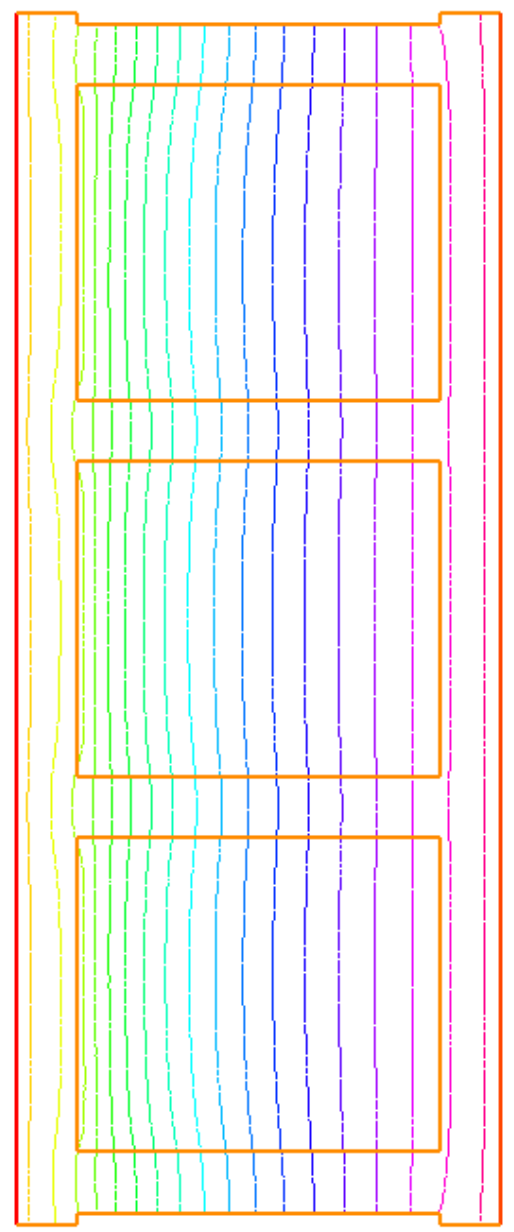
while(sqrt(ErrorL2+ErrorH1) > 1.e-6)
{
    B = (Told^2 + T^2)*(Told+T);
temp; //aquí calcula la temperatura

Tc = T-273.15;

    if ( !(iter % 5) ) //cada multiplo de 5 imprime el plot de la
linea siguiente
    plot(Tc,cmm=" temperatura ", value=1);

    error=T-Told;
ErrorH1 = int2d(mallatotal) (dx(error)^2+dy(error)^2);
ErrorL2 = int2d(mallatotal) (error^2);
cout << " Error seminorma H1 = " <<sqrt( ErrorH1) <<endl;
cout << " Error L2 = " << sqrt(ErrorL2) <<endl;
cout << " Error norma H1 = " << sqrt(ErrorL2+ErrorH1)
```







To get outside wind velocity around the building we use CMM Model

$$\left\{ \begin{array}{ll} \operatorname{div} \mathbf{u} = 0 & \text{in } \Omega \\ \mathbf{u} \cdot \mathbf{n} = 0 & \text{on } \Gamma_1 \\ \text{free flow} & \text{on } \Gamma_2 \end{array} \right.$$

$$\begin{aligned} J : [H^1(\Omega)]^3 &\rightarrow \mathbf{R} \\ \mathbf{v} &\rightarrow J(\mathbf{v}) \end{aligned}$$

$$J(\mathbf{v}) = \frac{1}{2} \int_{\Omega} (\mathbf{v} - \mathbf{u}_0)^t (\mathbf{v} - \mathbf{u}_0) d\Omega$$

To find  $\mathbf{u} \in K$  such that

$$J(\mathbf{u}) = \min_{\mathbf{v} \in K} J(\mathbf{v})$$

# CMM Model

$$L(\mathbf{v}, q) = J(\mathbf{v}) + \int_{\Omega} q \operatorname{div}(\mathbf{v}) \, d\Omega$$

Tratamos de encontrar el par  $(\mathbf{u}, \lambda)$  tal que :

$$L(\mathbf{u}, q) \leq L(\mathbf{u}, \lambda) \leq L(\mathbf{v}, \lambda)$$

$$\forall \mathbf{v} \in \hat{H}(\operatorname{div}, \Omega) \quad \forall q \in L^2(\Omega)$$

dando lugar a encontrar un punto silla,

y así obtenemos :

$$\int_{\Omega} \mathbf{v}^t (\mathbf{u} - \mathbf{u}_0) d\Omega + \int_{\Omega} \lambda \operatorname{div}(\mathbf{v}) d\Omega = 0 \quad \text{from Green :}$$

$$\int_{\Omega} \mathbf{v}^t (\mathbf{u} - \mathbf{u}_0) d\Omega - \int_{\Omega} \mathbf{v} \operatorname{grad} \lambda d\Omega + \int_{\Gamma} \lambda \mathbf{v} \cdot \mathbf{n} d\Omega d\Gamma = 0$$

imposse  $\mathbf{v} \cdot \mathbf{n} = 0$  on  $\Gamma_1$

$$\int_{\Omega} \mathbf{v}^t (\mathbf{u} - \mathbf{u}_0) d\Omega - \int_{\Omega} \mathbf{v} \operatorname{grad} \lambda d\Omega + \int_{\underline{\Gamma_2}} \lambda \mathbf{v} \cdot \mathbf{n} d\Omega d\Gamma = 0$$

*imposse*  $\lambda = 0$  en  $\Gamma_2$  and regularity to the Lagrange multiplier ,



$$\left\{ \begin{array}{ll} (\mathbf{u} - \mathbf{u}_0) = \nabla \lambda & \text{en } \Omega \\ \lambda = 0 & \text{en } \Gamma_2 \end{array} \right.$$

$$\mathbf{u} = \mathbf{u}_0 + \text{grad } \lambda$$

*and then*

$$\text{div} \cdot (\text{grad } \lambda) = \text{div } \mathbf{u}_0 \quad \text{en } \Omega \quad \text{because of } \text{div } \mathbf{u} = 0 \quad \text{en } \Omega$$

$$\left\{ \begin{array}{l} \text{div} \cdot (\text{grad } \lambda) = \text{div } \mathbf{u}_0 \quad \text{en } \Omega \\ \mathbf{u} \cdot \mathbf{n} = 0 \quad \text{en } \Gamma_1 \\ \lambda = 0 \quad \text{en } \Gamma_2 \end{array} \right.$$

# first publications team CEANI-SIANI & Luis Ferragut on CMM model

Autores (p.o. de firma): G. Winter, R. Montenegro, G. Montero y J. Estany

Título: SOBRE MODELIZACION NUMERICA DE DISTRIBUCION DE VELOCIDADES DE CAMPOS DE VIENTO EN PARQUES EOLICOS Y APLICACIONES

Ref.  revista:

Libro

Clave: A Volumen: 3 Páginas, inicial: 81 final: 82 Fecha: 1988

Editorial (si libro):

Lugar de publicación: Revista Dinámica. Colegio Oficial de Ingenieros Industriales de Canarias

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Autores (p.o. de firma): L. Ferragut, G. Montero, G. Winter y R. Montenegro

Título: WIND FIELD ADJUSTMENT: RESOLUTION BY ADAPTIVE MIXED FINITE ELEMENT AND MULTIGRID ALGORITHM. APPLICATIONS.

Ref.  revista:

Libro

Clave: A Volumen: Páginas, inicial: 140 final: 144 Fecha: 1990

Editorial (si libro): North-Holland

Lugar de publicación: European Community Wind Energy

# first publications team CEANI-SIANI & Luis Ferragut on CMM model

Autores: L.Ferragut, R.Montenegro, G.Montero y G.Winter

Título: AJUSTE DE UN CAMPO DE VIENTO MEDIANTE ELEMENTOS  
FINITOS MIXTOS

Tipo de participación:

Congreso: I Congreso de Métodos Numéricos en Ingeniería

Lugar celebración: Las Palmas de Gran Canaria

Fecha: del 11 al 15 de junio 1990

## first publications team CEANI-SIANI & Luis Ferragut on CMM model

Autores (p.o. de firma): G.Winter, G.Montero, L.Ferragut, R.Montenegro

Título: ADAPTIVE STRATEGIES WITH STANDARD AND MIXED FINITE  
ELEMENT FOR WIND  
FIELDS ADJUSTEMENT

Ref.  revista:  Libro

Clave: A Volumen: 54 Páginas, inicial: 49 final: 56

Fecha: 1995

Editorial (si libro):

Lugar de publicación: Solar Energy

Autores: G. Winter, L. Ferragut, R. Montenegro y G. Montero

Título: MODELIZACION NUMERICA DE DISTRIBUCION DE VELOCIDADES EN REGIMEN  
LAMINAR MEDIANTE EL METODO DE LOS ELEMENTOS FINITOS

Tipo de participación: Actas

Congreso: XIV Jornadas Hispano-Lusas de Matemáticas

# Solving mathematical model:

- ▶ In each step time we calculate velocity and temperature
- ▶ We propose a variation of the Chorin modified solver by Rannacher (a particular method belong to the family of the projection methods)  
advantage : fast solver, velocity and pressure is P1
- ▶ we consider buoyancy flow to take into account air moving by the action of changes of the density (heat air up)



R. Rannacher *On chorin's projection method for the incompressible Navier-Stokes equations.*. Institut Angewandte Mathematik. Universitat Heidelberg.1992. *The Navier-Stokes Equations II - Theory and Numerical Methods.* Oberwolfach, Germany, August 18-24, 1991.

The formulation (1.4) expresses that the pressure  $p^m$  in the projection method automatically satisfy the non-physical boundary condition  $\partial_n p^m|_{\partial\Omega} = 0$ . This has caused a lot of controversial discussion about the quality of these pressure approximations, which has even led to the believe that these are mere fictitious quantities without any physical relevancy (see, e.g., [15]). The main purpose of this paper is to show that this point of view is wrong. The quantities  $p^m$  are indeed proper approximations to the true pressure  $p(t_m)$ , even in the pointwise sense, in some distance to the boundary  $\partial\Omega$ . This view is also strongly supported in a recent paper of Gresho, et al., [6]. In fact, the practical success of the projection method has frequently been reported in the literature even for nonstationary flows with complicated vortex structures; see, e.g., Shen [12]. The best known theoretical result is the following error estimate due to Shen [11],

$$\|u^m - u(t_m)\| + \left( k \sum_{\mu=0}^m \|p^\mu - p(t_\mu)\|^2 \right)^{1/2} = O(\sqrt{k}), \quad 0 < t_m \leq T, \quad (1.5)$$

which is proved for the classical projection method including a first order linearization in the step (i). Furthermore, for a slightly modified scheme Shen [13] obtained the optimal order  $O(k)$  in (1.5). Whether this is true also for Chorin's original method was an open question.

# Navier Stokes model

- ▶ The CMM solution is considered as the initial solution in the domain solving of the Navier Stokes.
- ▶ We use a modied Chorin projection method with improvement accuracy the pressure :

$\partial_t u + u \cdot \nabla u$  is approximated by the method of the characteristics

$$\frac{1}{\delta t} [u^{m+1} - u^m \circ X^m] + \nabla p^m - \nu \Delta u^{m+1} = 0, \quad u|_{\Gamma} = u_{\Gamma}$$

where  $u^m \circ X^m(x) = u(x - u(x)\delta t)$

# Navier Stokes model

► An improvement of the original Chorin algorithm consists in to consider “pressure stabilization”:

$$-\Delta q = \nabla \cdot u - \overline{\nabla \cdot u}$$

And then:

$$\text{► } u^{m+1} = \bar{u} + \nabla q \delta t, \quad p^{m+1} = p^m - q - \overline{p^m - q}$$

One interest advantage is the parale

$$\int_{\Omega} (\mathbf{grad} q \cdot \mathbf{grad} w) \cdot d\Omega - \frac{1}{\Delta t} \int_{\Omega} \frac{(\nabla \mathbf{u})^n - (\nabla \mathbf{u})^{n+1}}{\Delta t} w \cdot d\Omega$$

▶▶  $\int_{\Omega} (\mathbf{grad} q \cdot \mathbf{grad} w) \cdot d\Omega - \frac{1}{\Delta t} \int_{\Omega} \frac{(\nabla \mathbf{u})^n - \int_{\Omega} \frac{\nabla \mathbf{u}^n}{\text{area}} d\Omega}{\Delta t} w \cdot d\Omega = 0$

Approximates by  
the mean value in  
the current step

▶  $q = -p$  in an iterative process in which  $p^n \rightarrow \bar{p}^n = \frac{\int_{\Omega} p^n d\Omega}{\text{area}(\Omega)}$

It is established that:

$$q = (p^n - p) - \overline{(p^n - q)}$$

$$= \frac{\int_{\Omega} (p^n - q) d\Omega}{\text{area}(\Omega)} = \frac{\int_{\Omega} p^n d\Omega}{\text{area}(\Omega)} - \frac{\int_{\Omega} q^n d\Omega}{\text{area}(\Omega)} = \bar{p}^n - \bar{q}^n$$

$$q = p^n - \bar{p}^n + \bar{q} - p$$

When converges  $p^n - \bar{p}^n \rightarrow 0$ , so  $q = \bar{q} - p$

# third equation to solve vertical velocity ,Navier Stokes ) implementation in freefem++ :

// our implementation of the third NS equation:

```
solve pb4w(u3,w3,solver=UMFPACK)
```

```
// GMRES sometimes
```

```
w3 test function
```

```
= int3d(Th)(u3*w3/dt) -int3d(Th)((g2/dt-dz(p))*w3)
```

```
// material derivate on time
```

```
// g2=convect([u1,u2,u3],-dt,u3old);
```

```
▶ +int3d(Th) (cinematicviscosity(Toldt)*(dx(u3)*dx(w3)+dy(u3)*dy(w3)+dz(u3)*dz(w3)))
```

```
▶ +int3d(Th) ((g*beta*Toldt)*w3)+int3d(Th) (-g*(1+beta*T0)*w3) // buoyancy terms
```

```
▶ +int3d(Th)(epsilon*p*w3) // because of not Dirichlet condition on pressure p)
```

```
▶ +on(boundaries,u3=0);
```

```
▶ .....
```

# VALIDACIÓN DEL MODELO

## CASO TEST 1

**6.1. Green-Taylor vortex.** For the first test we select the velocity field given by the Green-Taylor vortex, [GT37], [Tay23], which is used as a numerical test in many papers, e.g., Chorin [Cho68], Tafti [Taf96], John and Layton [JL02], Barbato, Berselli and Grisanti [BBG07] and Berselli [Ber05]. The exact velocity field is given by

$$\begin{aligned}u_1(x, y, t) &= -\cos(\omega\pi x) \sin(\omega\pi y) e^{-2\omega^2\pi^2 t/\tau}, \\u_2(x, y, t) &= \sin(\omega\pi x) \cos(\omega\pi y) e^{-2\omega^2\pi^2 t/\tau}, \\p(x, y, t) &= -\frac{1}{4}(\cos(2\omega\pi x) + \cos(2\omega\pi y)) e^{-4\omega^2\pi^2 t/\tau}.\end{aligned}\tag{6.1}$$

NUMERICAL ANALYSIS OF MODULAR VMS METHODS WITH  
NONLINEAR EDDY VISCOSITY FOR THE NAIVER-STOKES EQUATIONS

WILLIAM J. LAYTON <sup>\*</sup>, LI SHAN <sup>†</sup>, AND HAIBIAO ZHENG <sup>‡</sup>

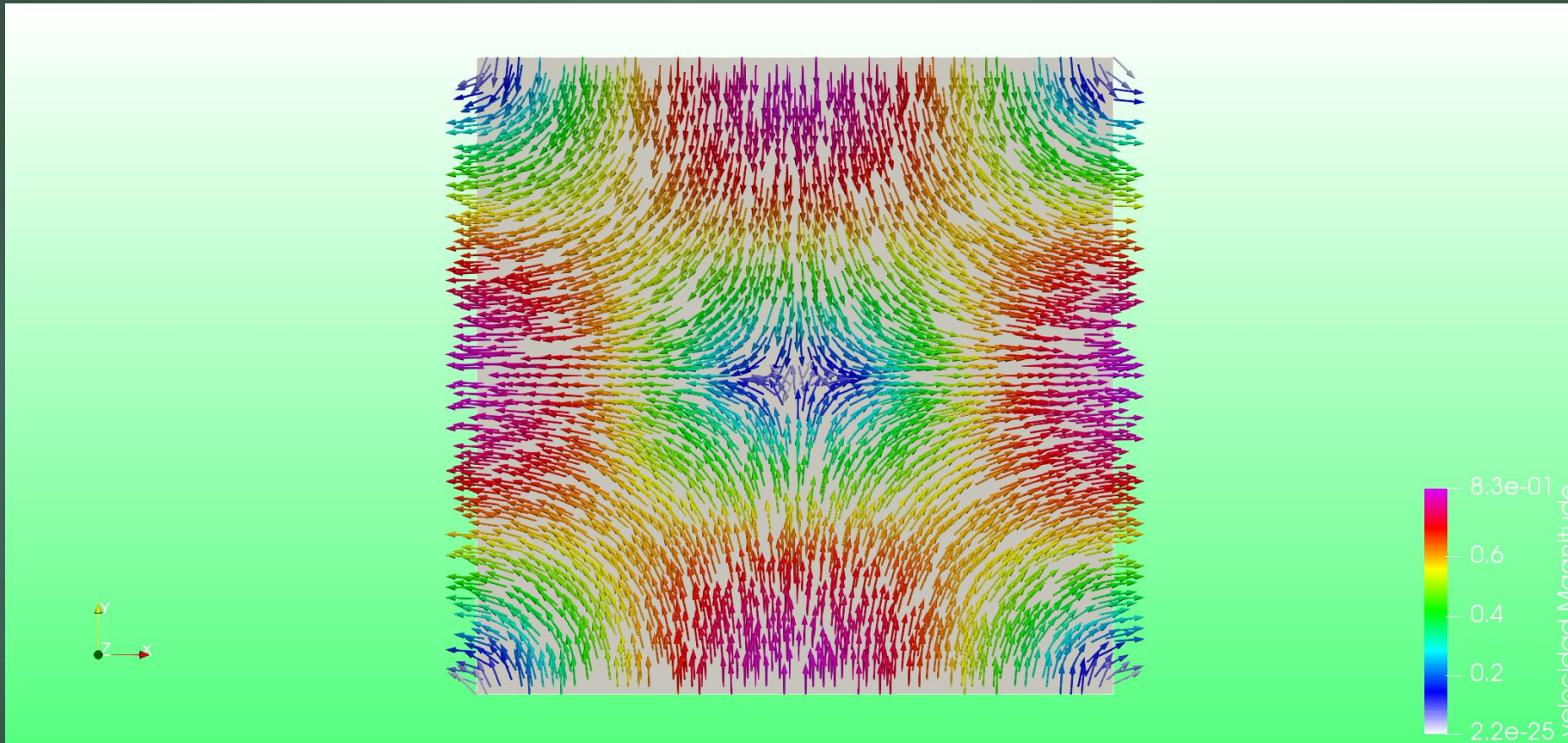
EXPLICITLY UNCOUPLED VMS STABILIZATION OF FLUID FLOW

WILLIAM LAYTON<sup>\*</sup>, LARS RÖHE<sup>†</sup>, AND HOANG TRAN<sup>‡</sup>

# VALIDACIÓN DEL MODELO

## CASO TEST 1

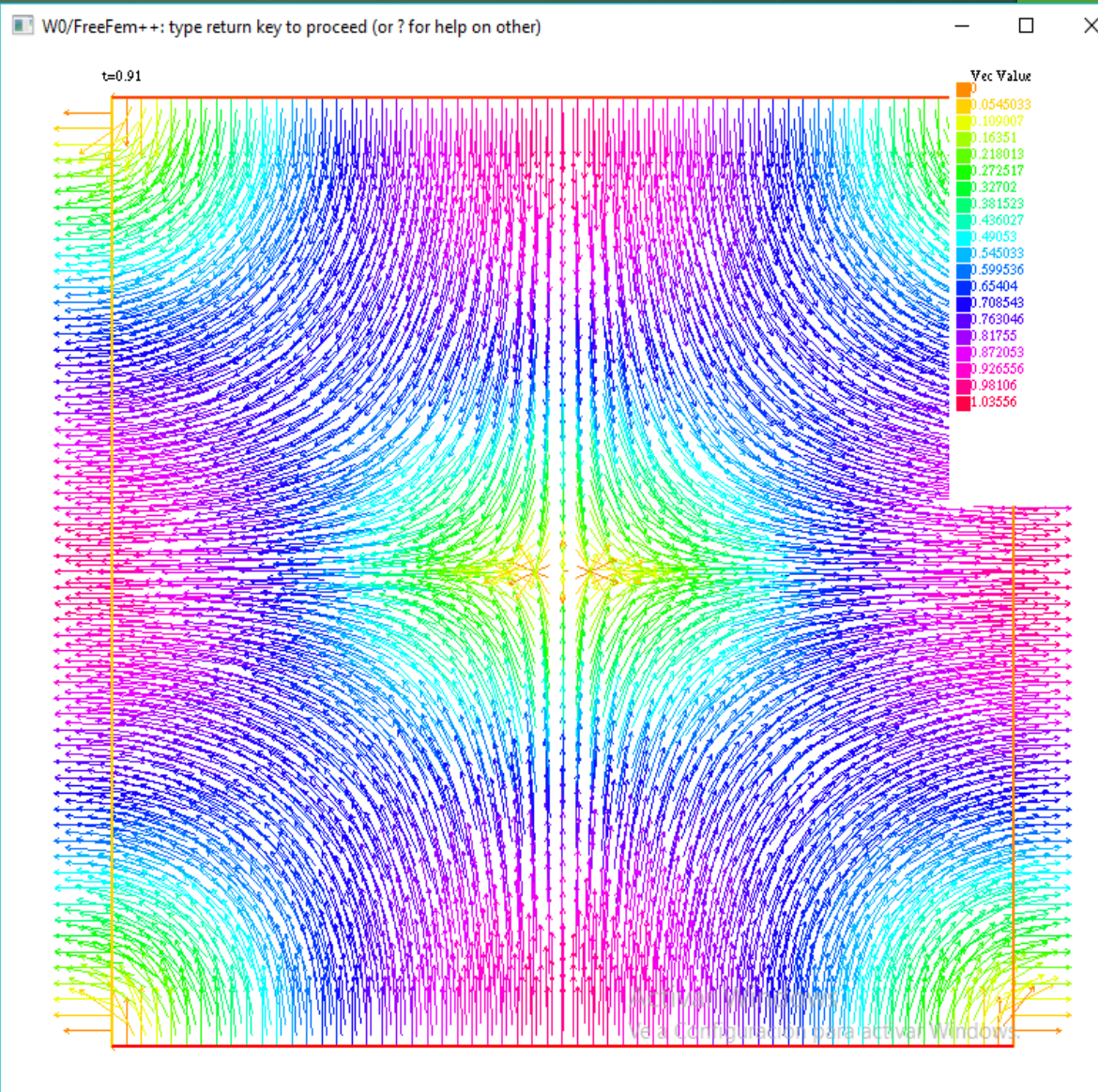
SOLUCIÓN FINAL

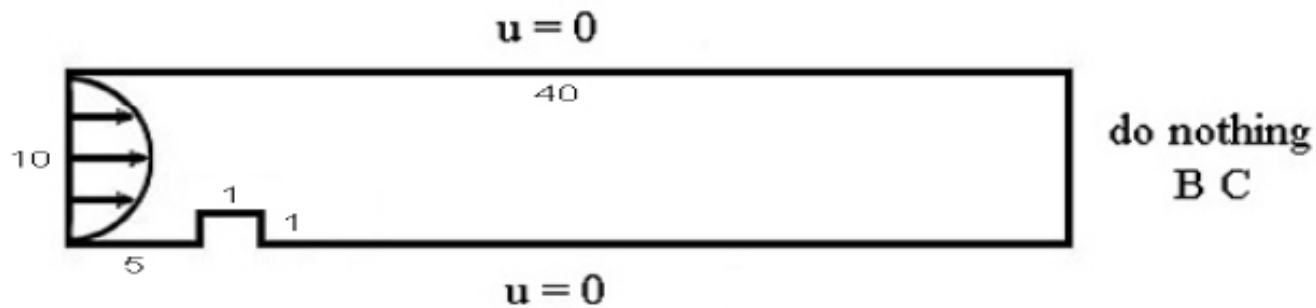




# 4400 nodos dt=0.01 comparativa con Talor Hood

```
C:\Program Files (x86)\FreeFem++\launchff++.exe
Arch
min -23.398 max 23.3968
-- Solve :
min -0.72958 max 0.250112
-- Solve :
min -0.569188 max 0.282109
u Taylor Hood = -0.348485
u ChorinRannacher = -0.475038
u exact = -0.475443
U no meanpq = -0.475038
v Taylor Hood = 0.348569
v ChorinRannacher = 0.465244
v exact = 0.475443
V no meanpq= 0.465244
error velocidad L2 THood= 0.0629392
error velocidad L2 ChorinRannacher = 0.000242397
error velocidad NO MEAN PQ L2 = 0.000242397
presiones posteriori from TaylorHood = 0.427914
p ChorinRannacher = 0.156417
p exact = 0.154453
P no meanpq = 0.446854
presiones posteriori from V Chorin = 0.412405
p ChorinRannacher = 0.156417
p exact = 0.154453
P no meanpq = 0.446854
presiones posteriori from V Chorin = 0.412405
presiones posteriori from TayloHood = 0.427914
error presiones ChorinRannacher = 0.00092544
error presiones Chor no meanpq = 0.0852789
error presiones posteriori from ChorinRannacher = 0.0681241
error presiones posteriori from TaylorHood = 0.0905868
error presion en contornos= 5.28197e-015
integral total de presion en el dominio= 5.73327e-015
comprobacion promedio integral de presion en el dominio= 5.73327e-015
mean q = 4.11499e-005
-- Solve :
min -0.999818 max 1.02866
-- Solve :
min -0.999818 max 0.999803
-- Solve :
min -0.00157791 max 0.0017628
-- Solve :
min -0.999818 max 1.02866
```





```

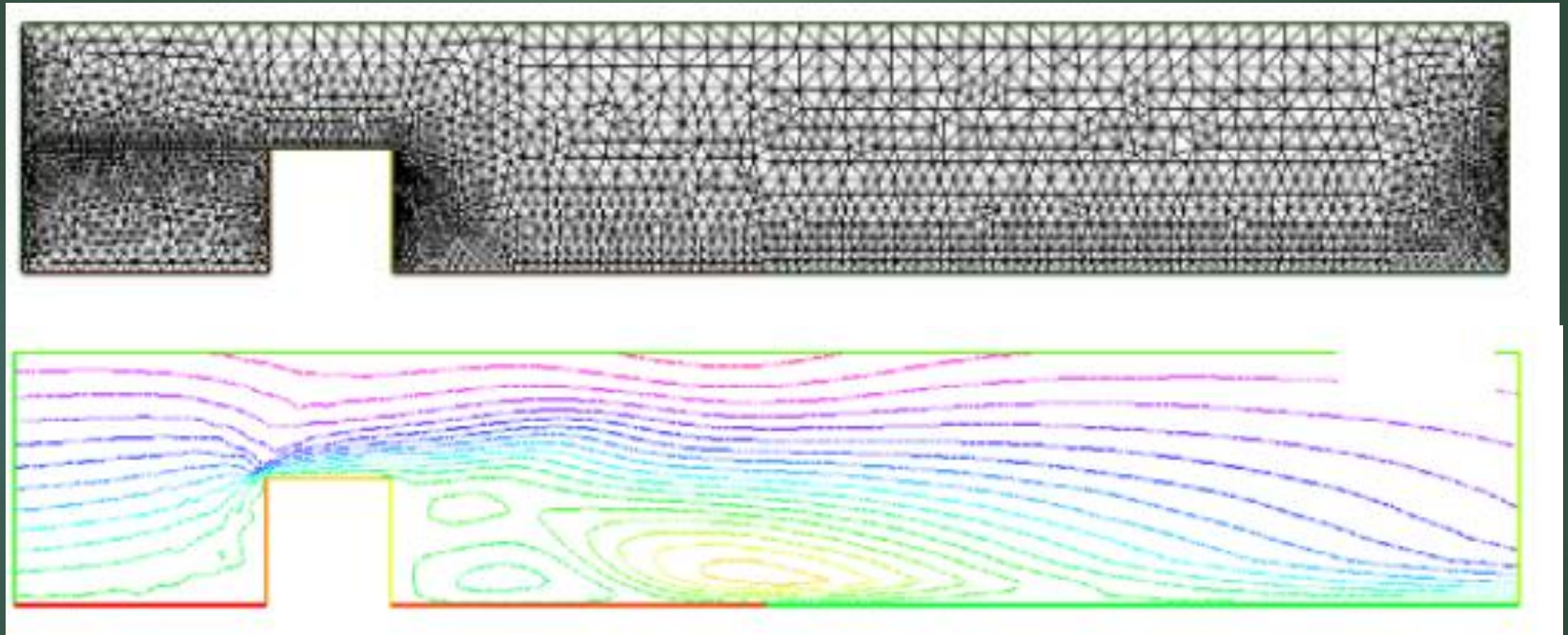
C:\Program Files (x86)\FreeFem++\launchff++ .exe
119 : ZVh Zv=v;
120 :
121 : plot([Zu,Zv],coef=1.2,cmm=" vector velocidad",value=1,w
122 : plot(Zu,coef=1.2,cmm=" velocidad horizontal",value=1,wa
123 :
124 : fespace Vh1(Th,P2);
125 : Vh1 psii,wv;
126 : solve streamlines(psi1,wv) =
127 :     int2d(Th)( dx(psi1)*dx(wv) + dy(psi1)*dy(wv))
128 :     +int2d(Th)(-wv*(dy(u)-dx(v)))
129 :     +on(6,8,psii-ue*y)
130 :     +on(1,2,3,4,5,7,9,10,psii=0.);
131 :
132 : ZVh Zpsii=psii;
133 : plot(Zpsii,cmm="lineas de corriente",nbiso=80);
134 : sizestack + 1024 -8192 ( 7168 )

-- mesh: Nb of Triangles = 22331, Nb of Vertices 11468
-- mesh: Nb of Triangles = 4966, Nb of Vertices 2656
hmax = 0.458995
hmin = 0.0558466
meanh = 0.0558466
-- Solve :
    min -0.330437 max 0.999999
-- Solve :
    min 0 max 0
-- Solve :
    min -2518.78 max 3076.87
mean q = 297.09

```



zoom



# J.Connors Convergence analysis and computational testing of the finite element discretization of the Navier-Stokes alpha model. Numerical Methods for Partial Differential Equations, December 2008

obtained from this exact solution. Indeed, choose  $u(x, y, t) = 2^{-t}(1 - x^2 - y^2) \langle y, -x \rangle$  and  $p(x, y, t) = -\frac{1}{6}2^{-2t}((1 - x^2 - y^2)^3 - \frac{1}{4})$ . Then differentiation gives  $\nabla \cdot u = 0$  and

$$\begin{aligned} \frac{\partial u}{\partial t} - \nu \Delta u + u \cdot \nabla u + \nabla p = \\ 2^{-t}(\ln 2(1 - x^2 - y^2) - 8\nu) \langle y, -x \rangle = f(x, y, t) \end{aligned}$$

This choice of pressure satisfies  $\int_{\Omega} p \, d\Omega = 0$ , and  $\text{curl}(u)$  is uniformly bounded on  $(0, T)$ . The viscosity is  $\nu = 1$ .

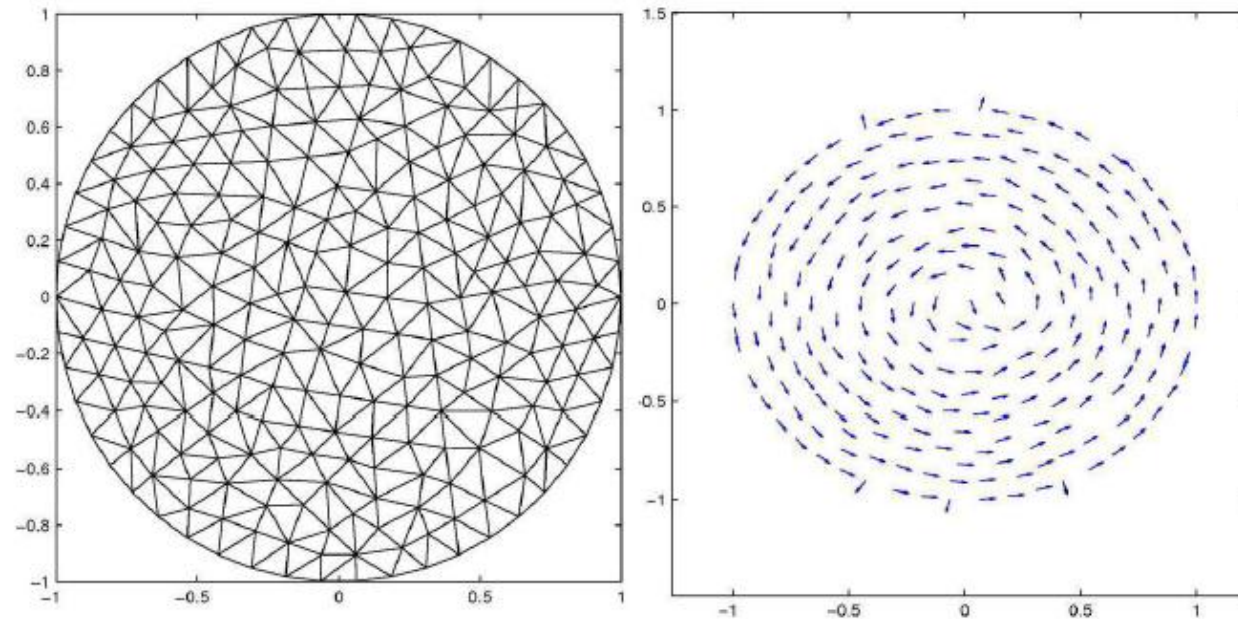
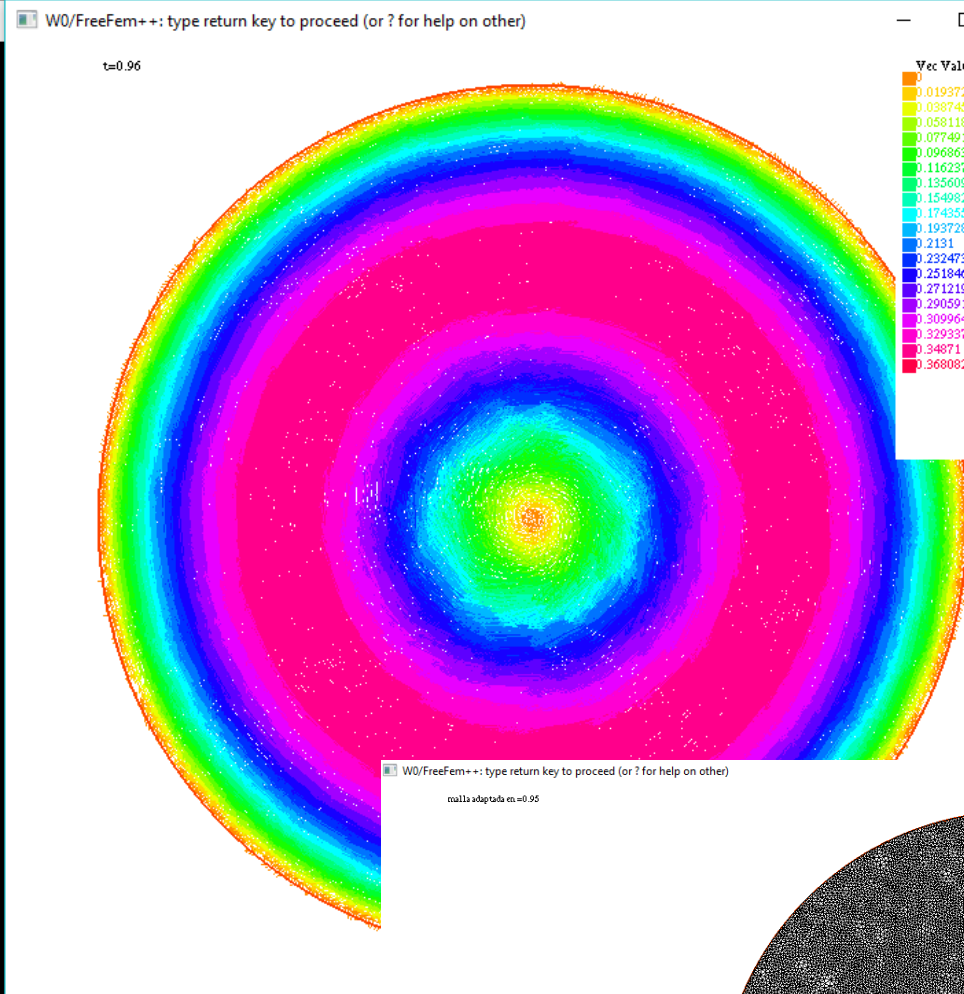


Figure 1: Left: example mesh, Right: normalized velocity solution.

```
C:\Program Files (x86)\FreeFem++\launchfem++.exe
min -0.366089 max 0.366085
-- Solve :
min -0.366054 max 0.366072
-- Solve :
min 0.00487349 max 0.00545179
GMRES converges: 169 1.08833e-007 0.116777 9.31972e-007 < 1e-006
-- Solve :
min -0.366088 max 0.366084
GMRES converges: 172 1.17386e-007 0.123722 9.48791e-007 < 1e-006
-- Solve :
min -0.366053 max 0.366071
GMRES converges: 1606 2.5166e-010 0.000252822 9.95404e-007 < 1e-006
-- Solve :
min -0.000209043 max 0.000367563
error velocidad NO MEAN PQ L2 = 0.0406976
error presion NO MEANPQ L2= 8.12998e-005
hmax = 0.0584353
hmin = 0.0247538
error velocidad L2 = 0.0406972
error presion L2= 4.83954e-008
hmax = 0.0584353
hmin = 0.0247538
dt = 0.01 TIME = 0.85
u = 0.258538
u exact = 0.151951
U = 0.258539
v = -0.258535
v exact = -0.151951
V = -0.258536
p = -0.00993066
p exact = -0.00599909
P = 1.10454

-- Solve :
min -0.366088 max 0.366086
-- Solve :
min -0.366078 max 0.36609
-- Solve :
min 0.000742974 max 0.00122422
GMRES converges: 62 1.11977e-007 0.116781 9.58862e-007 < 1e-006
-- Solve :
min -0.366087 max 0.366085
```



```
C:\Program Files (x86)\FreeFem++\launchfem++.exe
P = 1.10955

number of required edges : 0
-- adaptmesh Regulary: Nb triangles 59344 , h min 0.00655265 , h max 0.0377817
area = 3.14154 , M area = 31415.4 , M area/( |Khat| nt) 1.22255
infny-regulaty: min 0.463735 max 3.83551
anisomax 2.8993, beta max = 1.3325 min 0.272651
-- mesh: Nb of Triangles = 59344, Nb of Vertices 29987
```

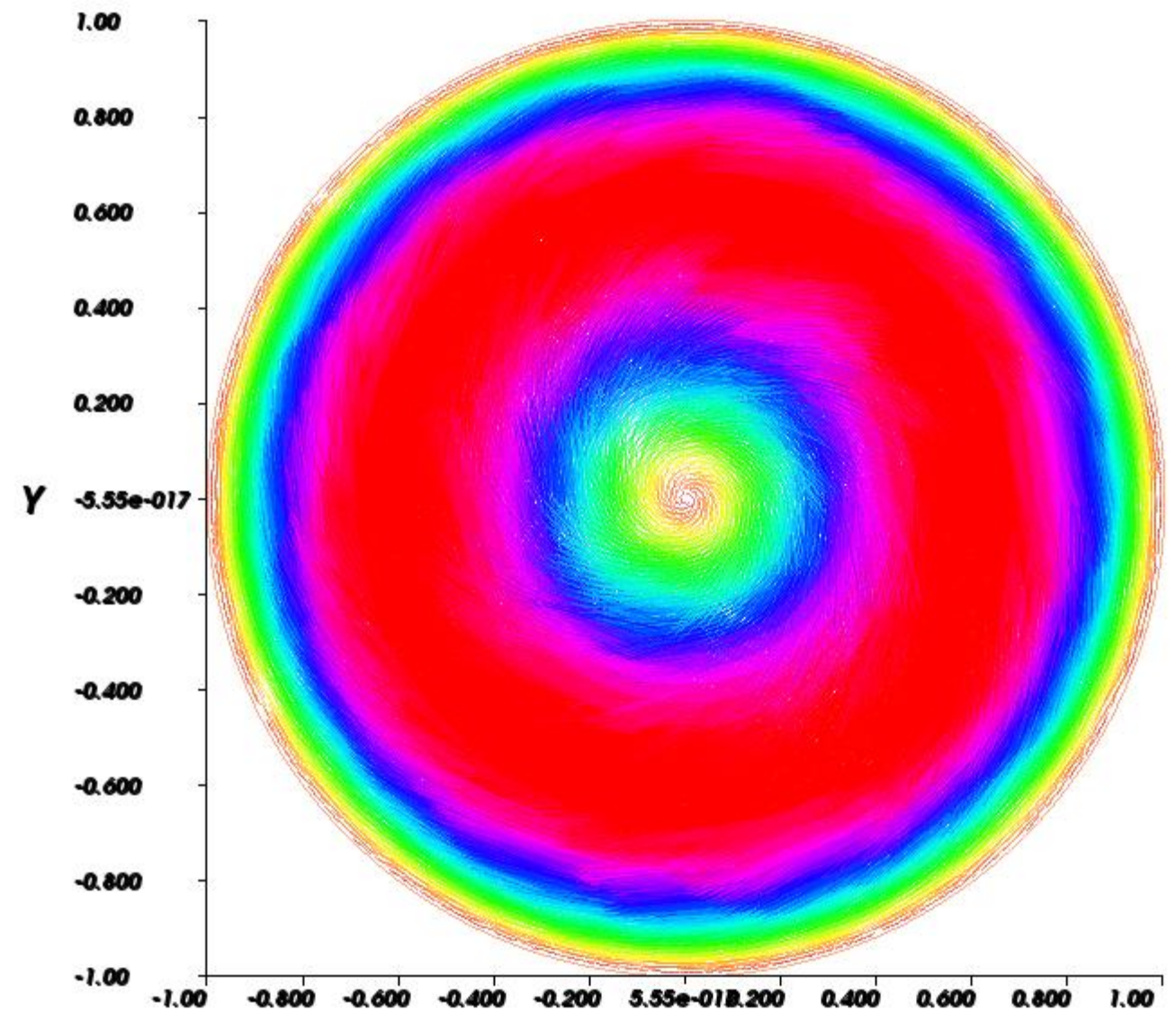
```

FreeFem++-cs circulo test NStokes38 v1 - no meanpq comparativa - epsilon con adapmesh1
File Edit Compute Graphics Options Help
t=1.95 malla adap
1 //
2 // el algoritmo Chorin modif de NStokes
3 // y luego va empeorando la convergenci
4
5 real m=200;
6 real t,T;
7 real err2,errpress,err2U,errpressP, int
8
9 T=2.;
10
11 border C1(t=0,2*pi) {x=cos(t);y=sin(t);
12
13 mesh Th = buildmesh(C1(m));
14 plot(Th,wait=1);
15
16 real reynods=1.;
17 real nu=1./reynods;
18 real dt = 0.01;
19 real s0=clock();
20 real TIME;
21
22 fespace Vh(Th,P1);
23 Vh u1,u2,p0;
24
25 func uexact= (2^(-t))*(1-x*x-y*y)*y;
26 func vexact = -(2^(-t))*(1-x*x-y*y)*x;
27 //func pexact= -(0.16666666)*(2^(-2*t))
28 func pexact= -(0.16666666)*(2^(-t))*((
29
30
31 integpress = int2d(Th)(pexact);
32 cout << " comprobacion integral de pres
33 // plot(p0,cmm=" presion en t=0 ",value
34
t=1.98

```

Y

t=1.96



# CONSIDERACIONES DE CÁLCULO

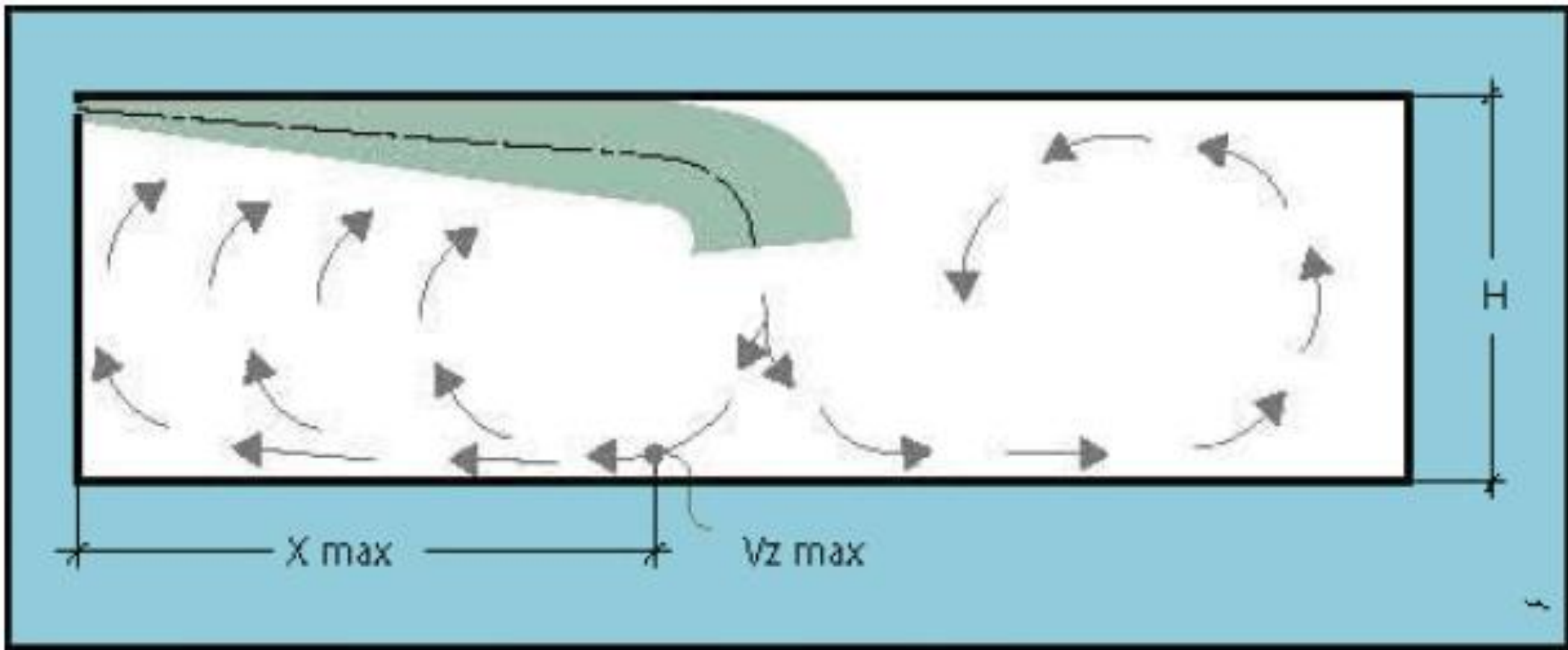
## COMPORTAMIENTO FLUJO DE AIRE IMPULSADO POR UN CLIMATIZADOR

- ▶ LOS SIGUIENTES CÁLCULOS, LO HAREMOS PARA UNA EXTENSIÓN DE 16 METROS Y UNA ALTURA DE 6 M DEL LOCAL:

# CONSIDERACIONES DE CÁLCULO

## COMPORTAMIENTO FLUJO DE AIRE IMPULSADO POR UN CLIMATIZADOR

- ▶ SEGÚN EL MANUAL DE AIRFLOW, EL FLUJO DE AIRE SIGUE EL PATRÓN DE VENTILACIÓN POR MEZCLA:





En ese caso la vena se retroalimenta con un fenómeno de autoinducción, con un incremento de la velocidad de inyección. La distancia de penetración permanece constante, pero las velocidades en la vena y en el local aumentan.

La distancia de penetración  $X_{max}$  es igual a la distancia entre la pared y el punto donde la velocidad  $V_z$  es la más elevada (Fig. 29)

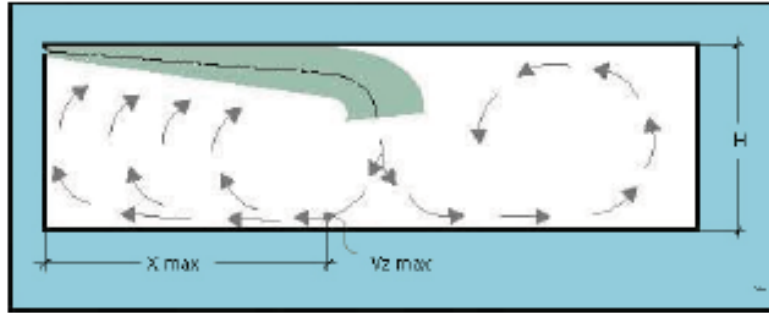


Fig. 29 – Penetración de la vena en un local profundo

La distancia de penetración  $X_{max}$  depende de las dimensiones del local, del tipo de vena y de la constante de la U.T.D.

Para anchos del local inferiores a cuatro veces su altura, se puede calcular  $X_{max}$  por las ecuaciones siguientes (Ref. B):

Vena cónica:  $X_{max} = 0.40 \cdot K_1 \cdot \sqrt{A} \cdot H$

Vena plana:  $X_{max} = 0.24 \cdot K_2 \cdot H$

Vena radial:  $X_{max} = 1.50 \cdot K_3^2 \cdot H$

En el caso de impulsión desde encimeras, a lo largo de la pared:

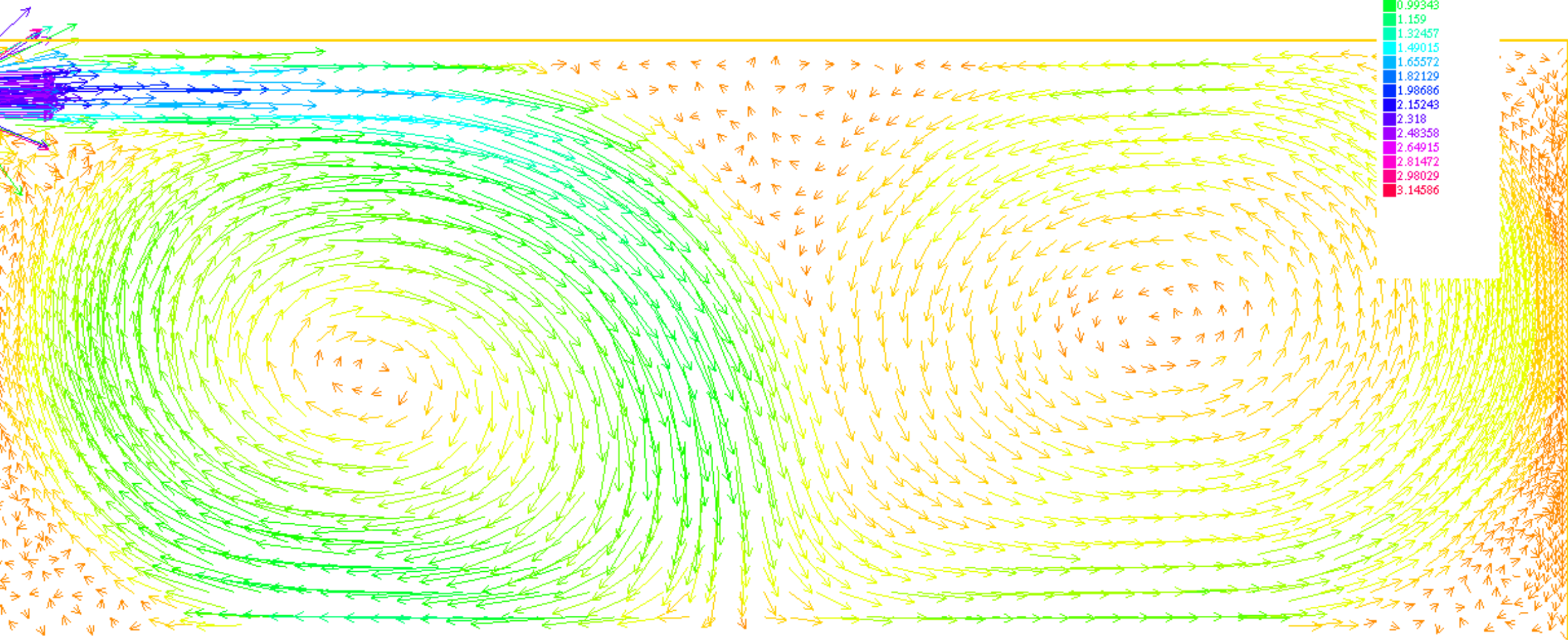
Vena cónica:  $X_{max} = 0.07 \cdot K_1^2 \cdot H$

Vena plana:  $X_{max} = 0.24 \cdot K_2 \cdot H$



*“taming the air”*

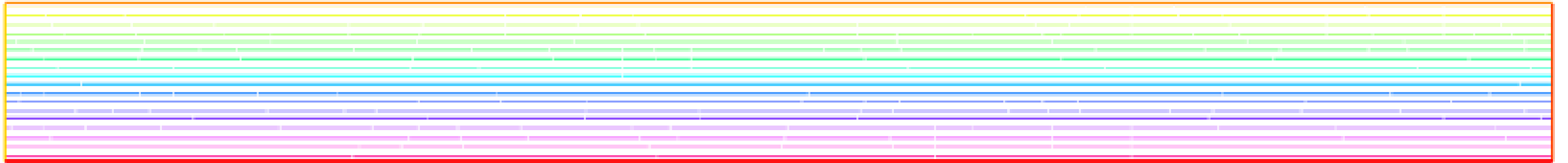
po = 120



# Rayleigh Bernard Problem

## Natural convection

$$T = 15^{\circ} \text{C}$$



$$T = 20^{\circ} \text{C}$$

# Numerical Analysis and Computational Testing of a high accuracy Leray-deconvolution model of turbulence

William Layton<sup>1,5</sup> Carolina C. Manica<sup>2,5</sup>

Monika Neda<sup>3,5</sup> Leo G. Rebholz<sup>4,5</sup>

Department of Mathematics

University of Pittsburgh PA 15260

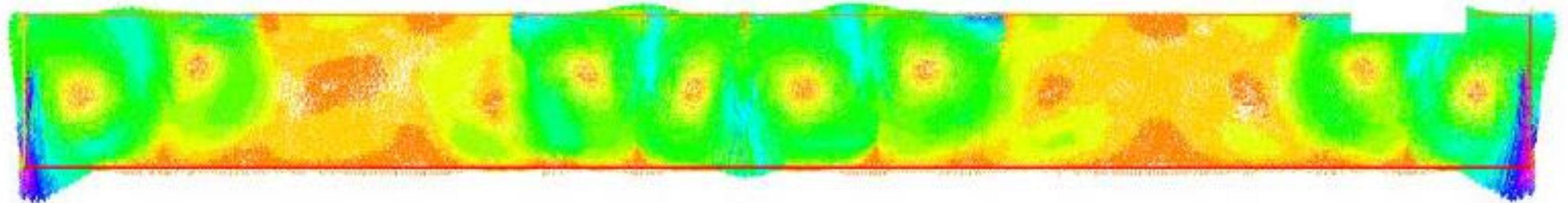
## Abstract

We study a computationally attractive algorithm (based on an extrapolated Crank-Nicolson method) for a recently proposed family of high accuracy turbulence models (the Leray-deconvolution family). First we prove convergence of the algorithm to the solution of the Navier Stokes equations (NSE) and delineate its (optimal) accuracy. Numerical experiments are presented which confirm the convergence theory. Our 3d experiments also give a careful comparison of various related approaches. They show

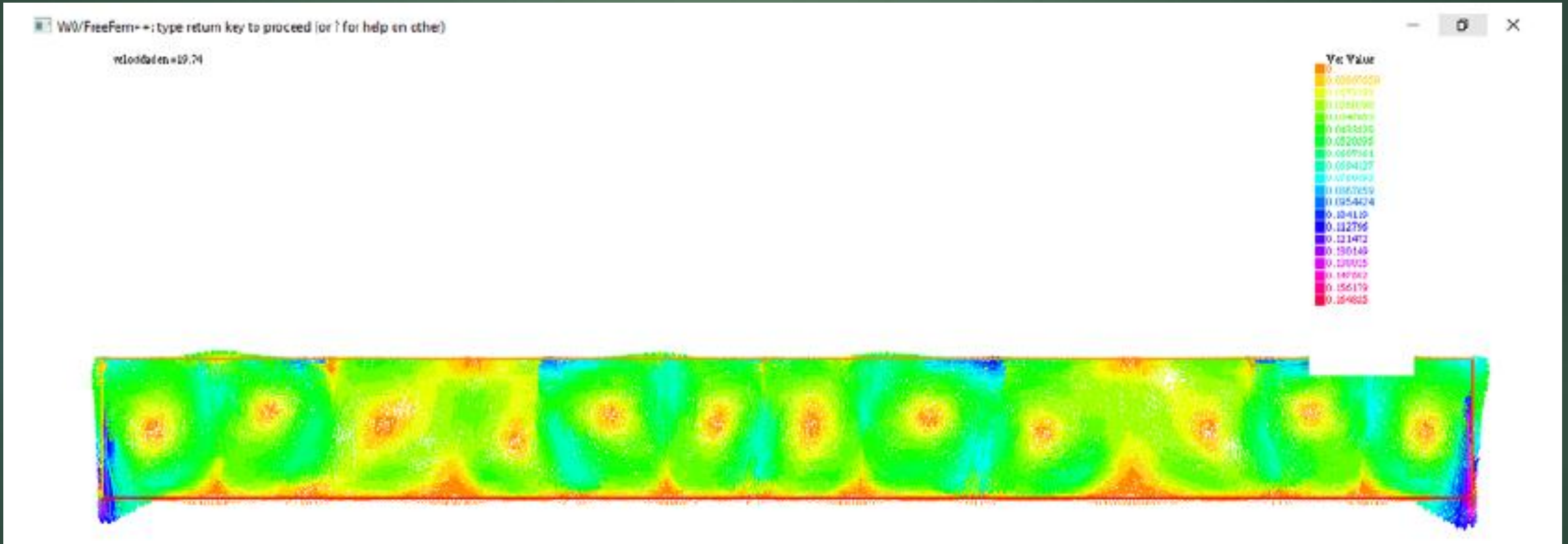
Bernard cells at  $t = 18$  s  
solver = Leray N=2 & Chorin-Rannacher and  
Boussinesq (thermal buoyancy)

FreeFem++: type return key to proceed (or ! for help on other)

v100000n=17.20

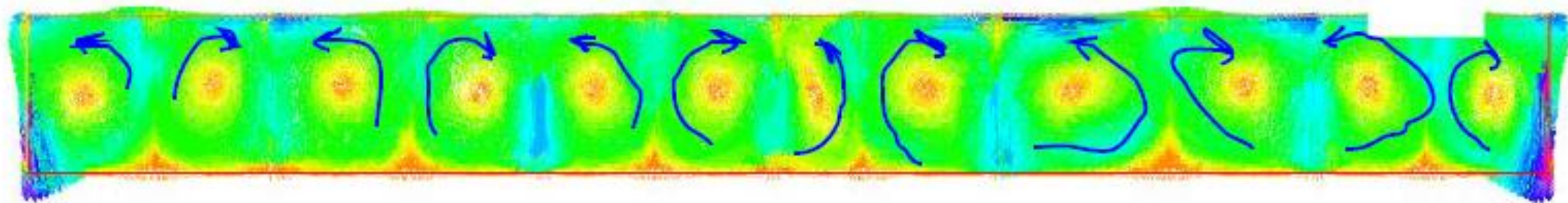


# Bernard cells at $t = 20$ s



VW/FreeForm-: type return key to proceed (or ? for help on other)

Moddaten+26.065



# Temperature at $t = 24$ s

W0/FreeForm: type return key to proceed (or ? for help on other)

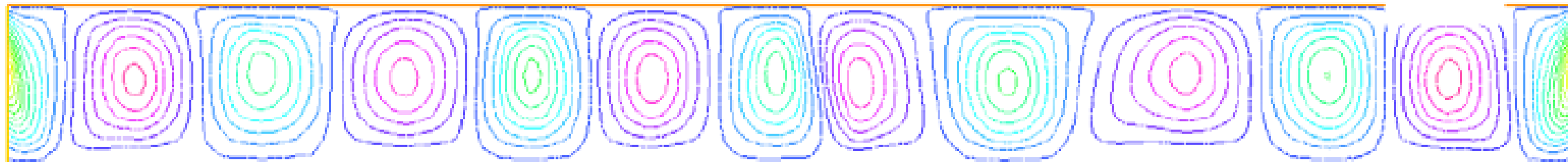
temperature = 21.58

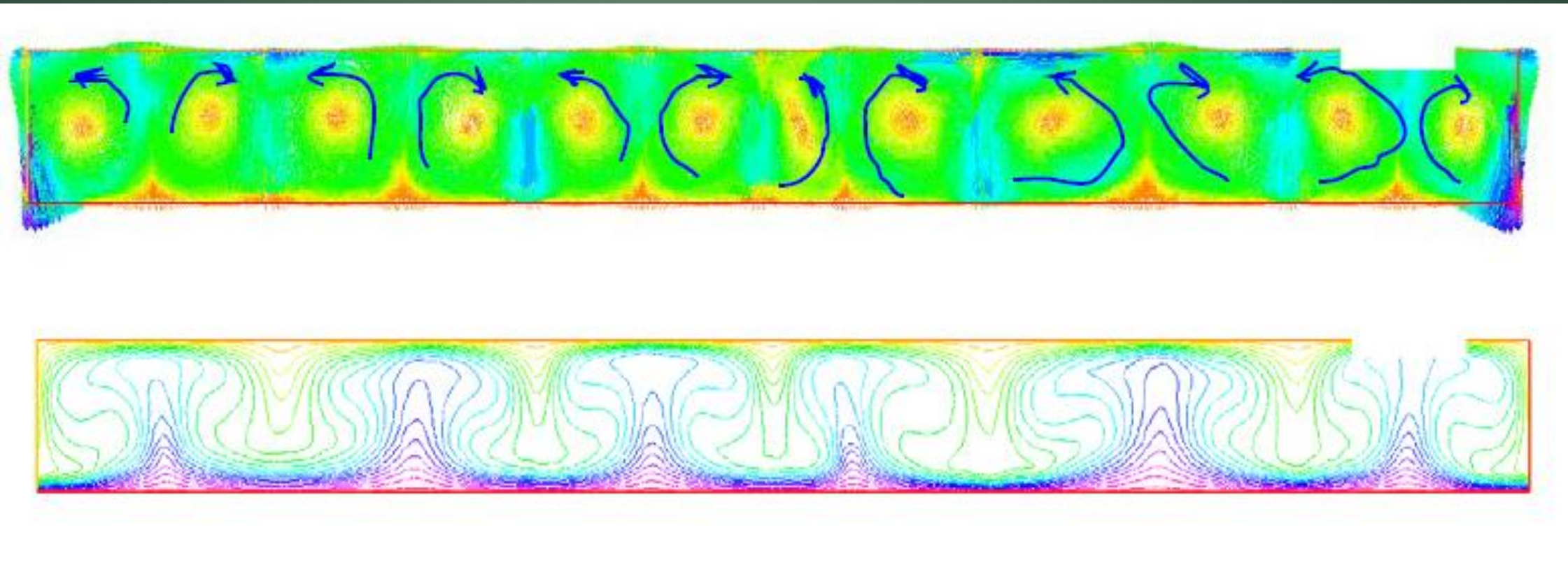




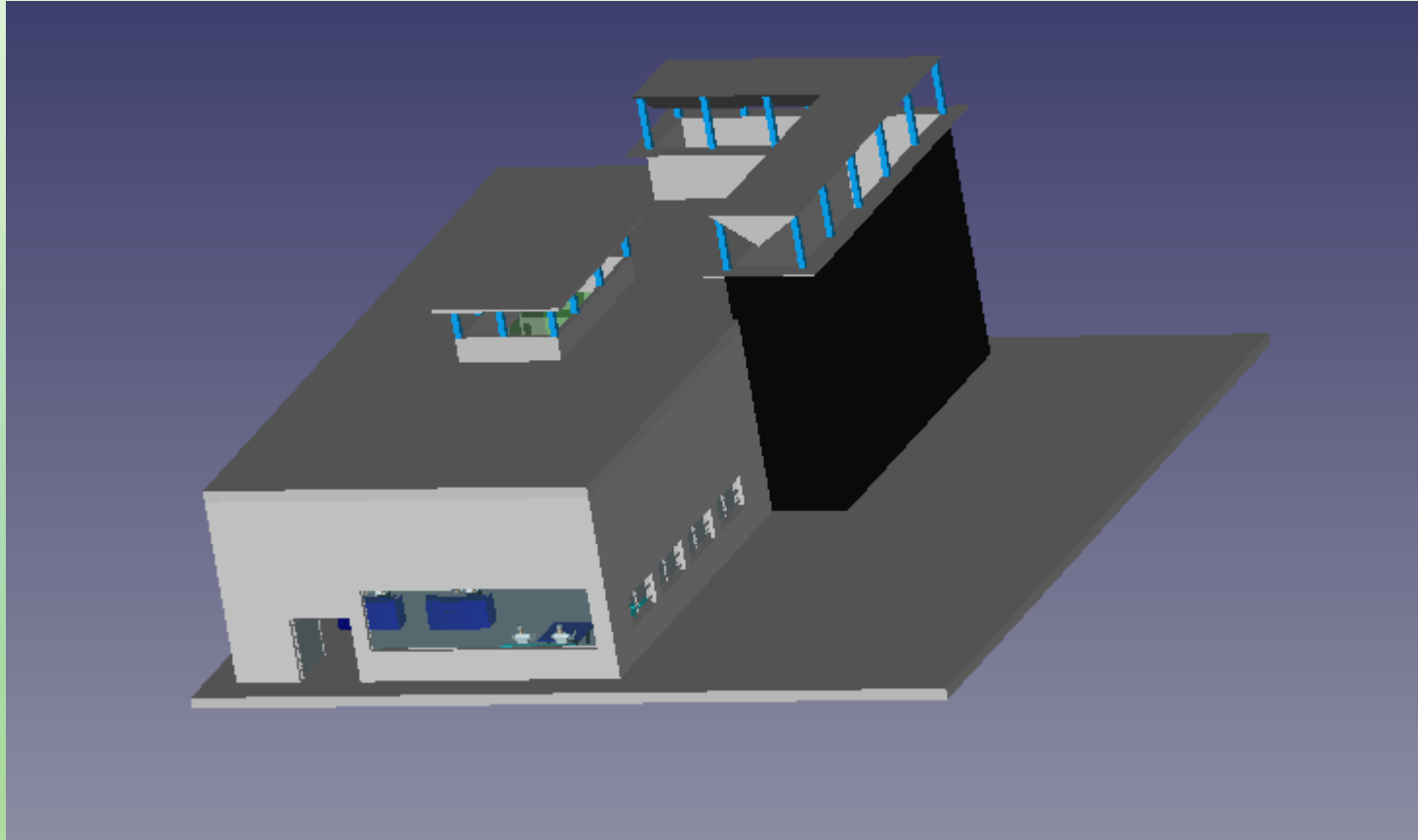


0.0797109  
0.09381





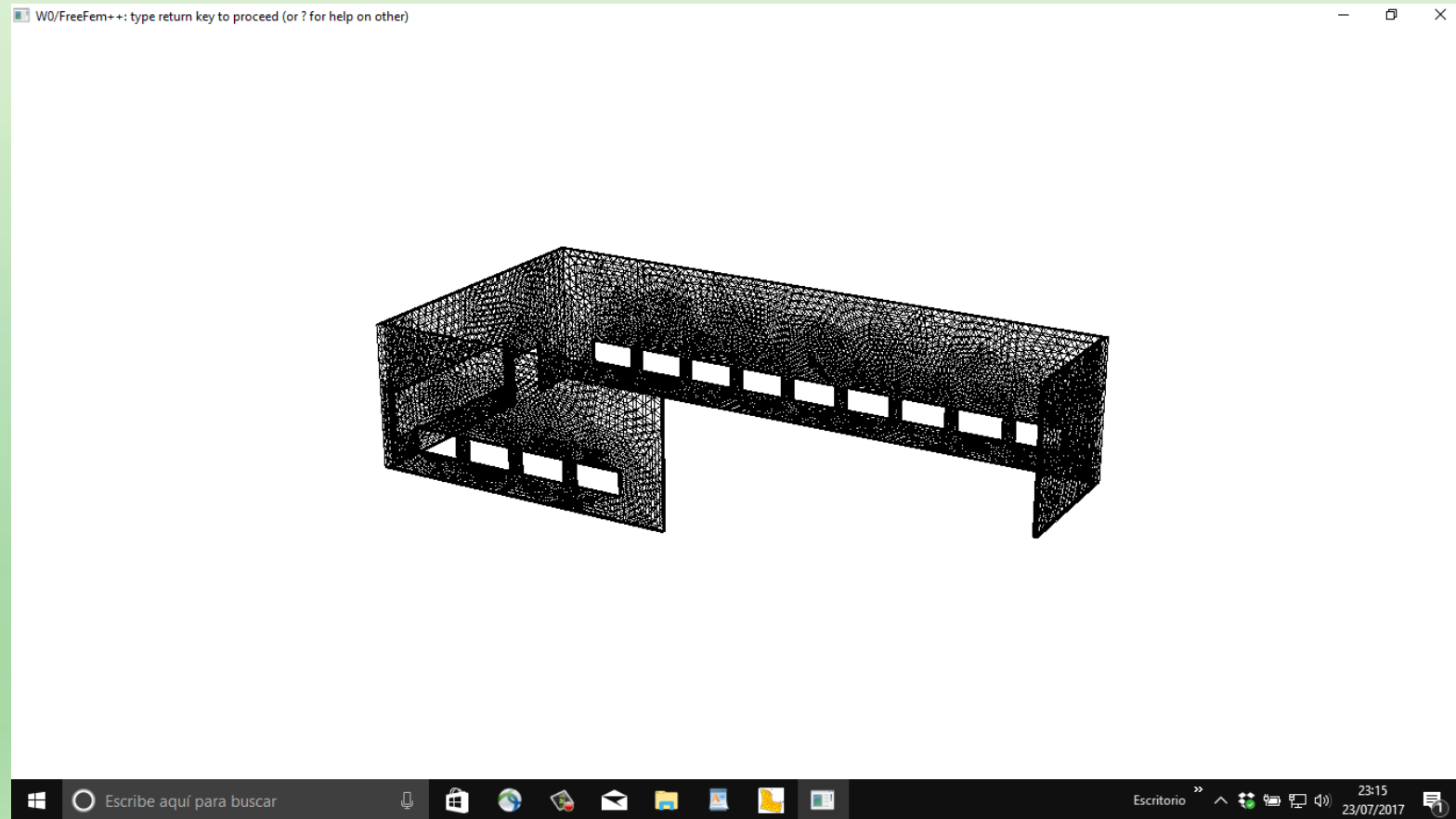
# PROPOSED GEOMETRY



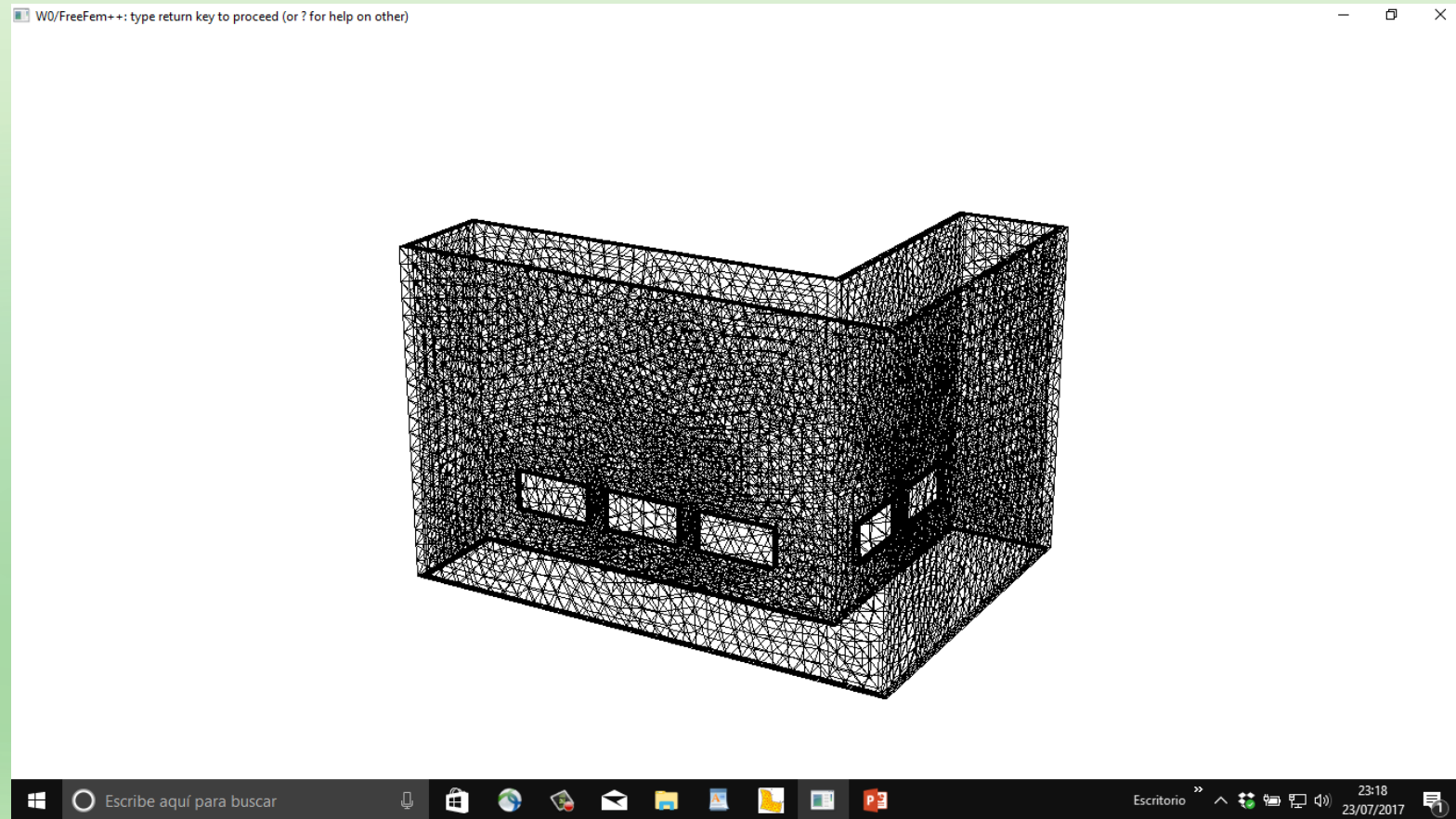
## ELEMENTS

1. MAIN WALL
2. COURTYARD WALL
3. GLAZED WALL
4. ROOF
5. CENTRAL COURTYARDS  
COLUMNS
6. CENTRAL COURTYARD  
ROOF
7. SIDE COLUMNS
8. SIDE COURTYARD ROOF
9. EXTERNAL FRAMES
10. INTERNAL FRAMES
11. INTERNAL FRAMES
12. EXTERNAL PROTRUSION  
WALLS
13. INTERNAL PROTRUSION  
WALLS

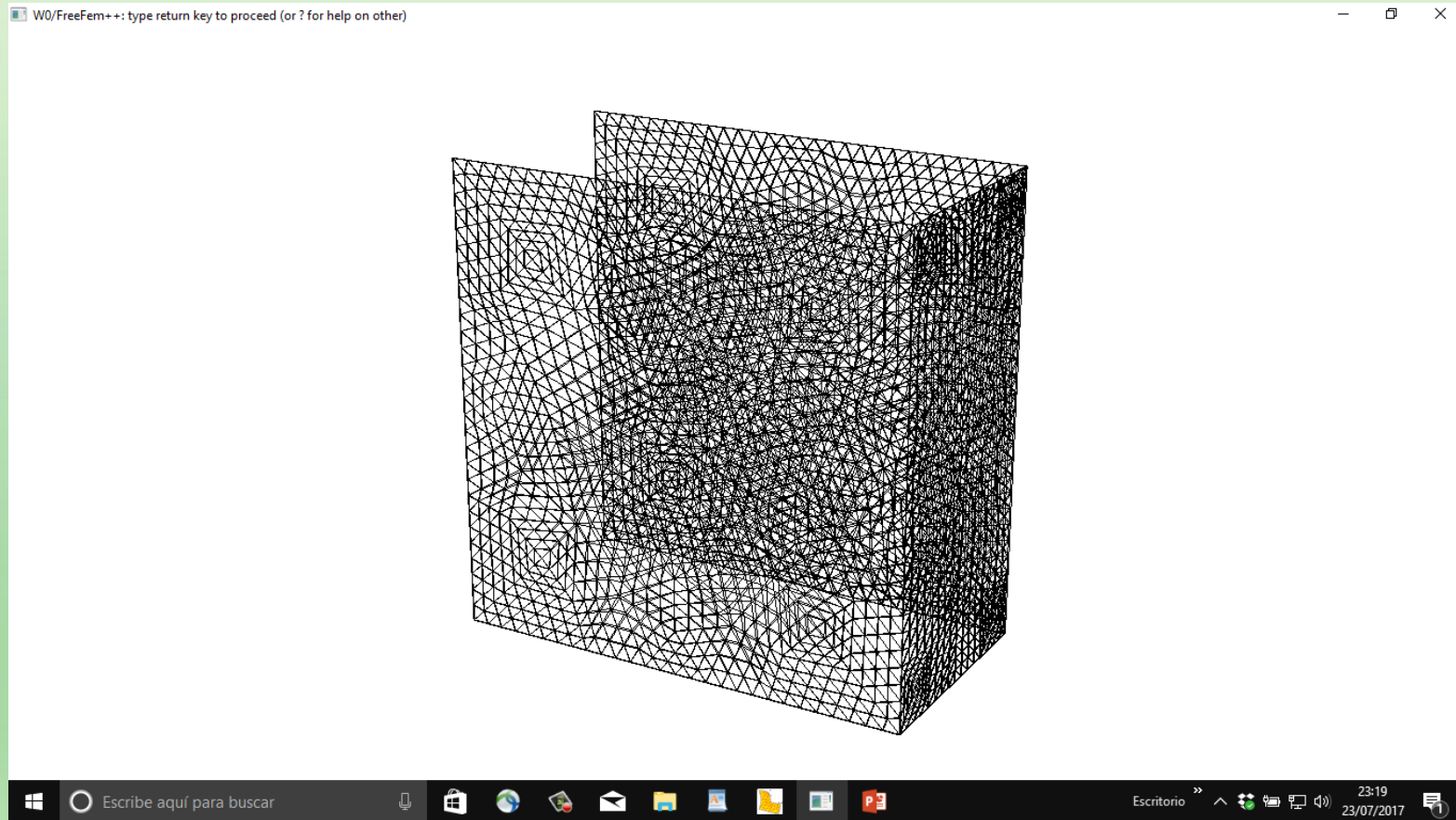
# MAIN WALL



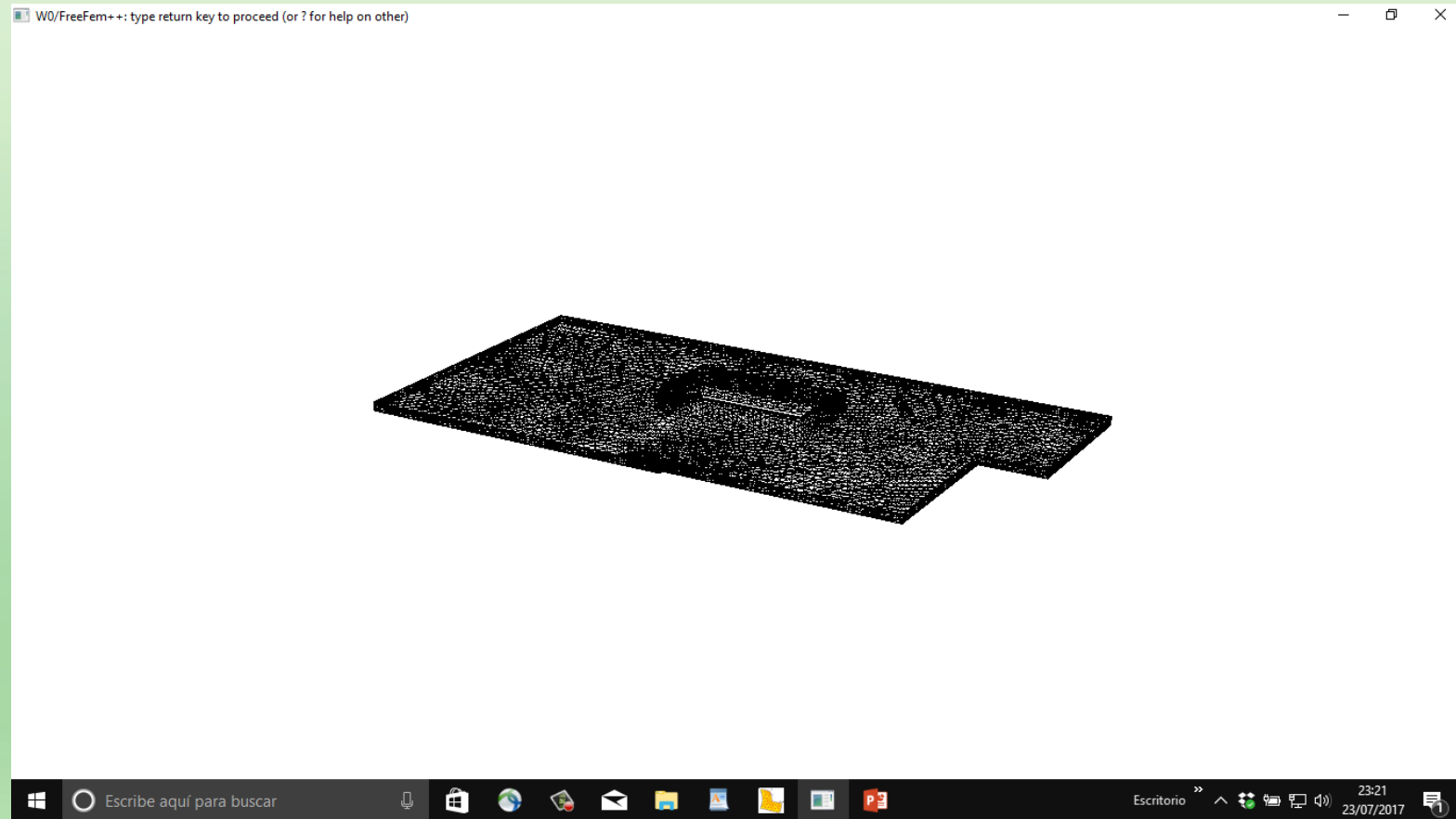
# SIDE COURTYARD WALL



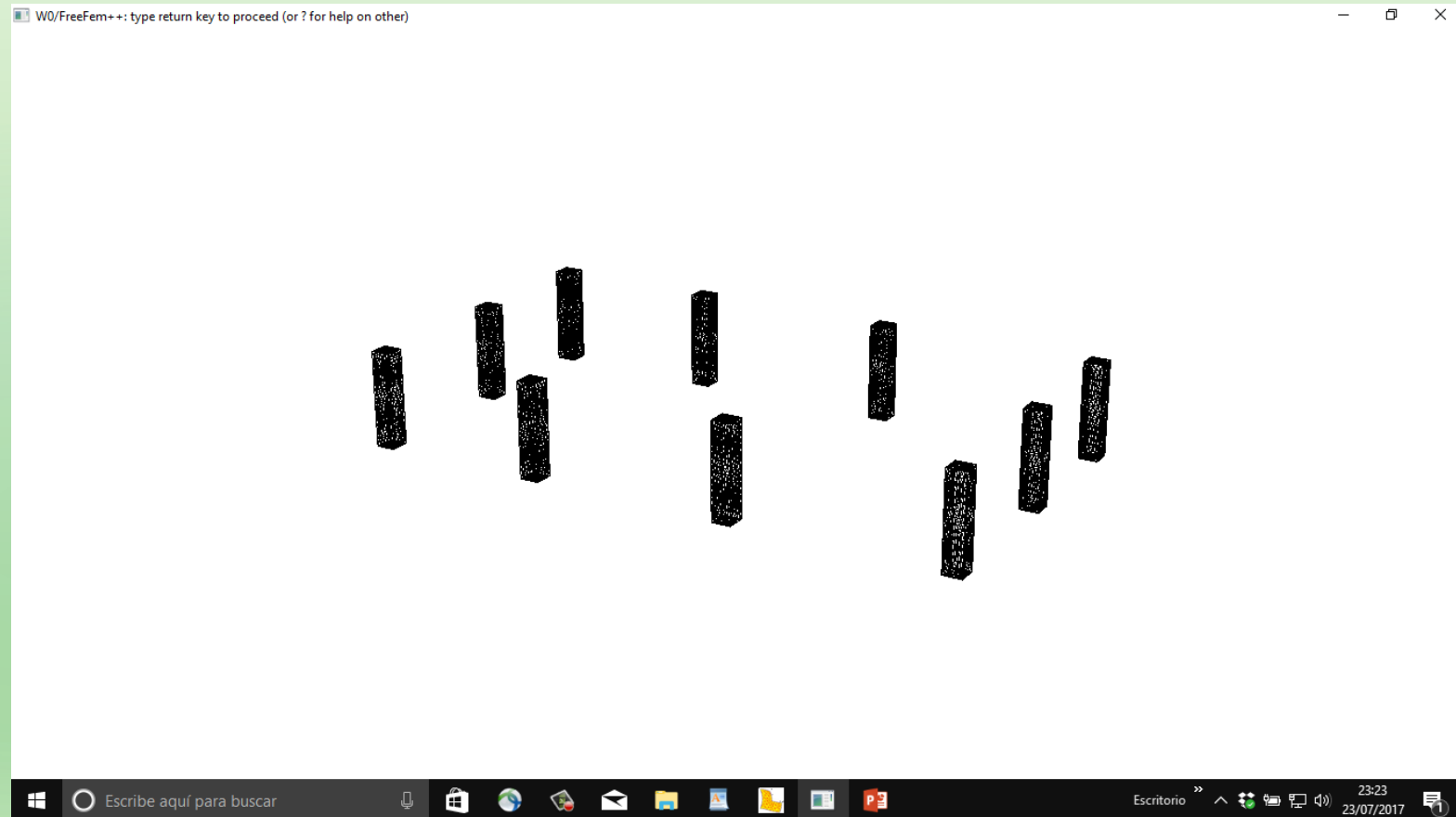
# GLAZED WALL (CENTER COURTYARD)



# ROOF

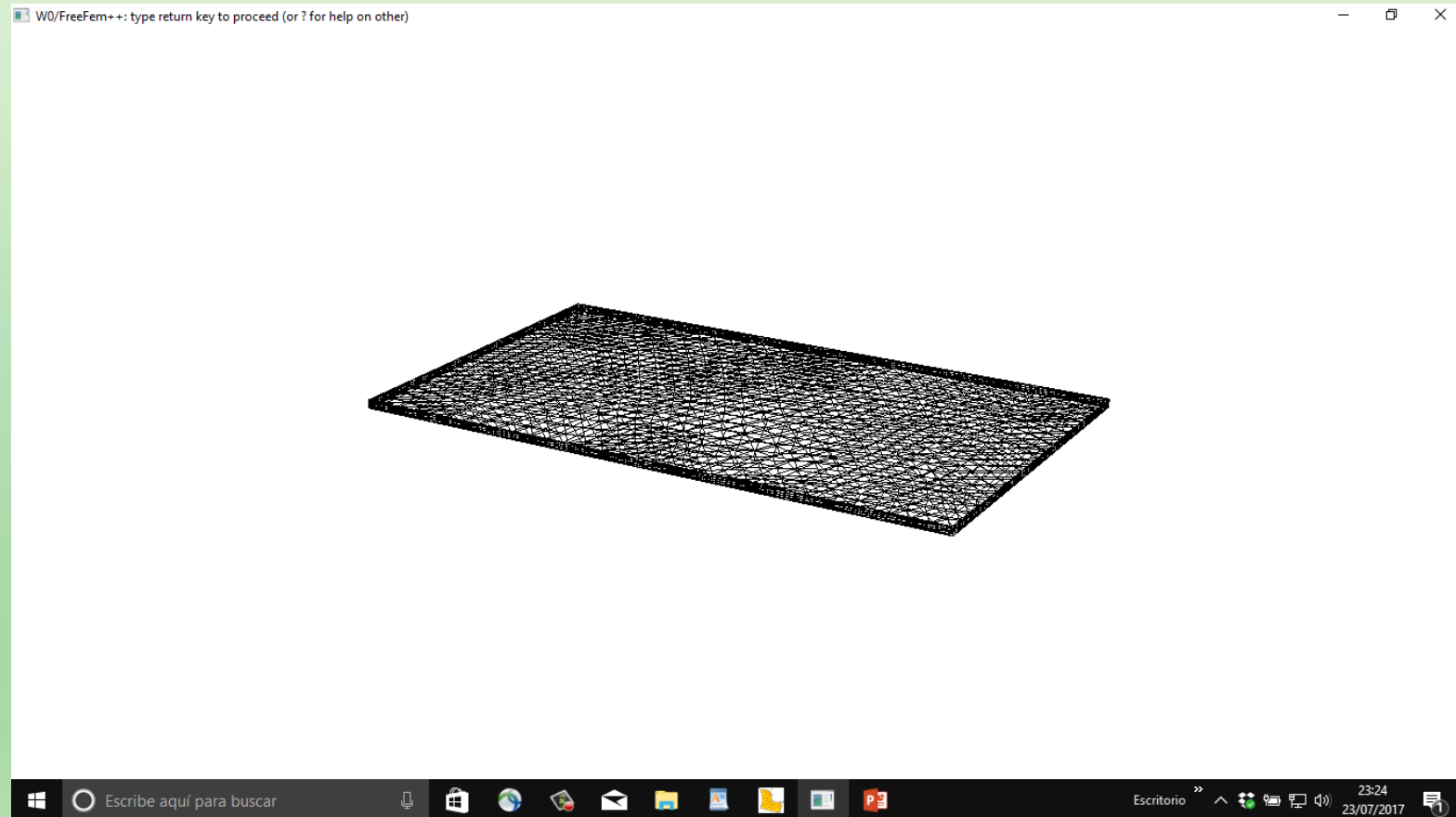


# CENTRAL COURTYARDS COLUMNS

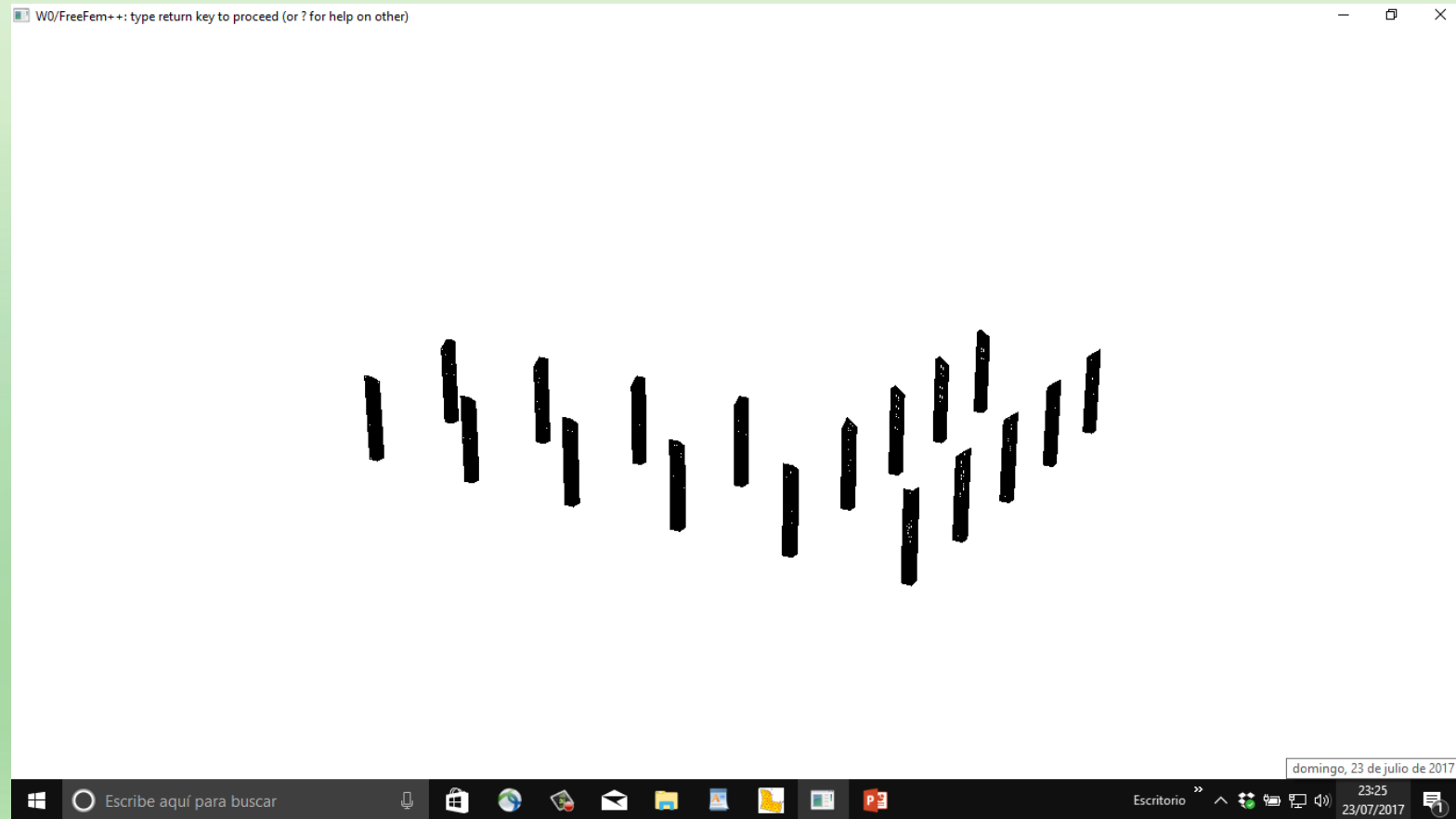




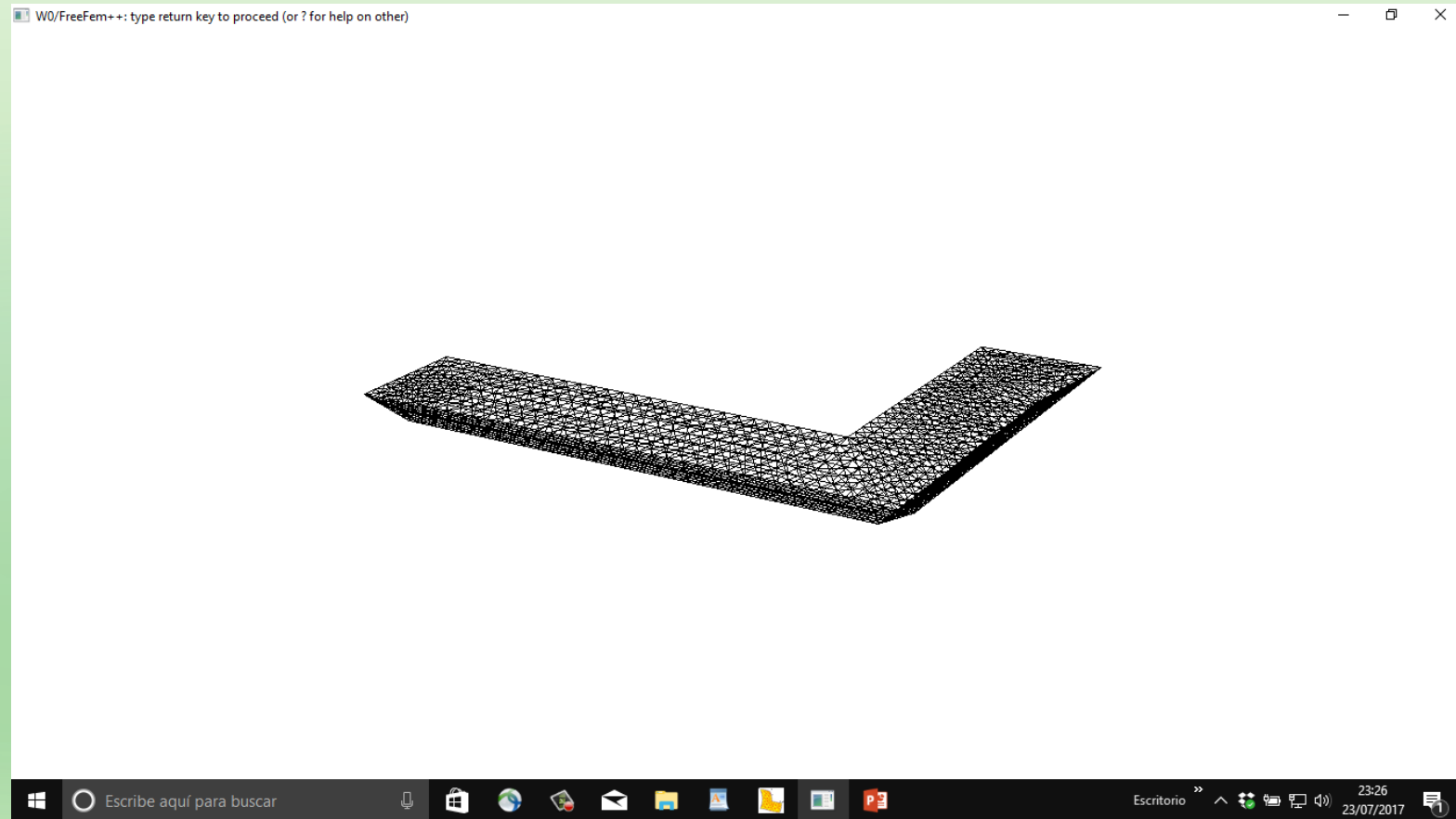
# CENTRAL COURTYARD ROOF



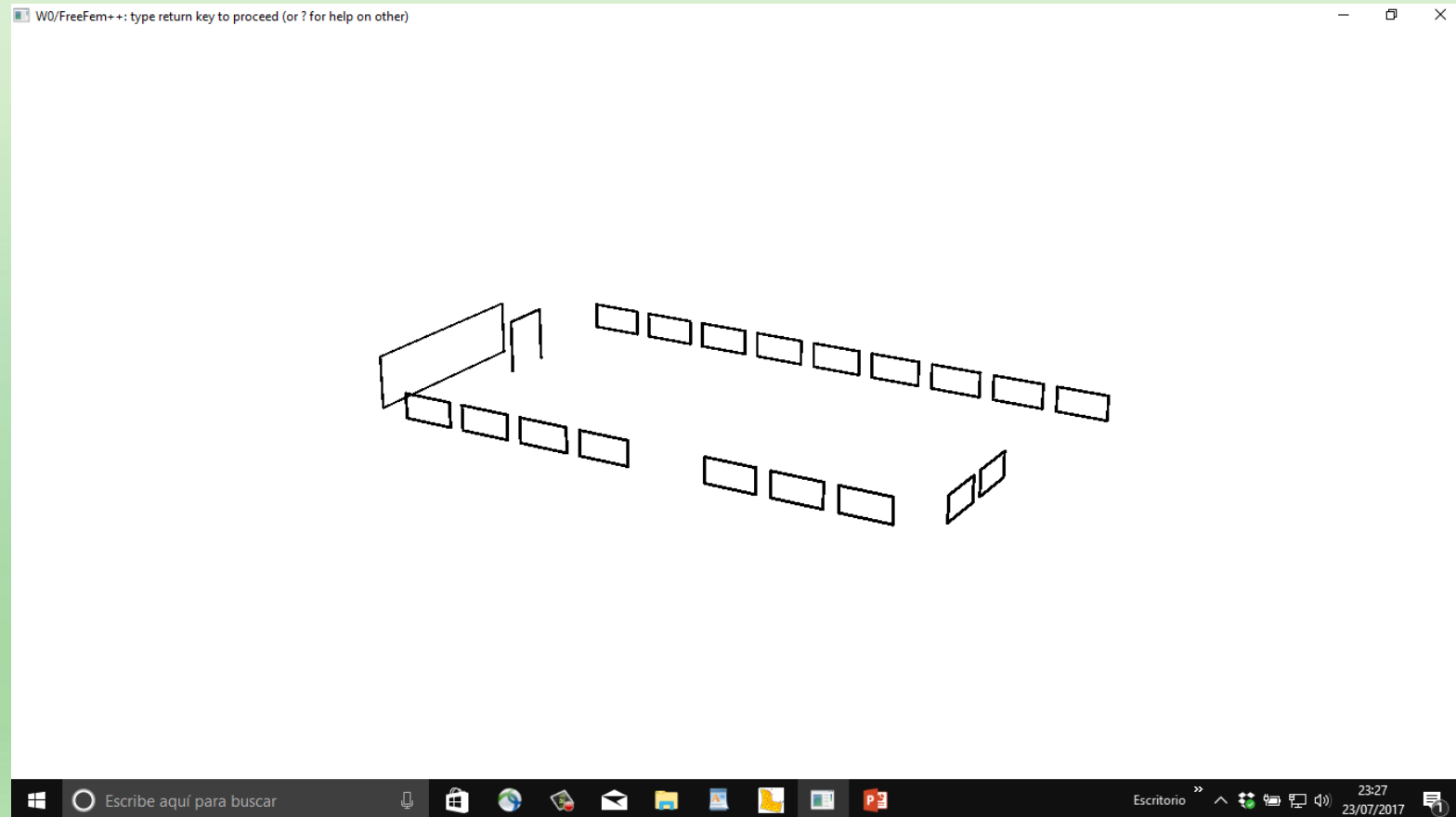
# SIDE COLUMNS



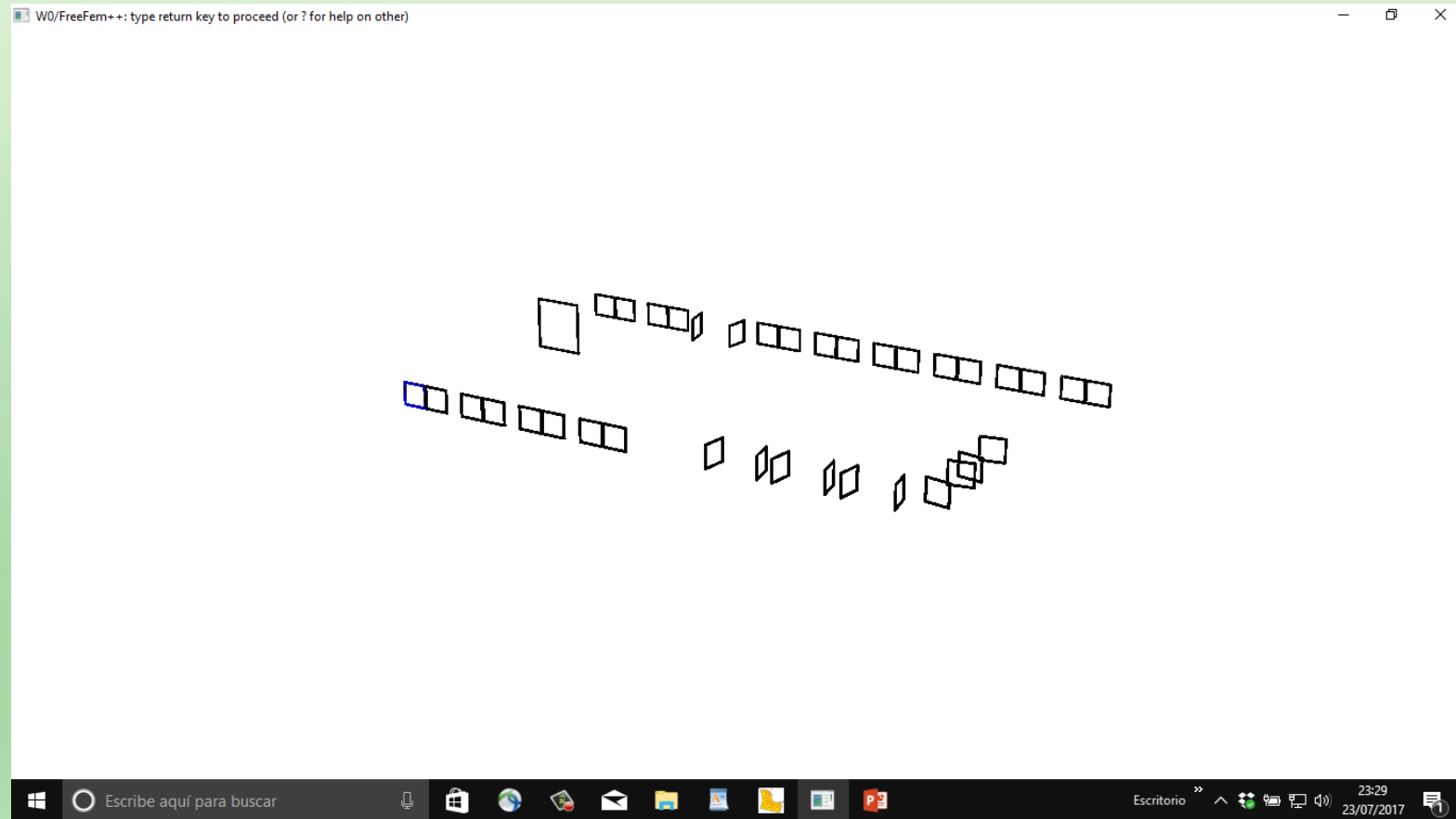
# SIDE COURTYARD ROOF



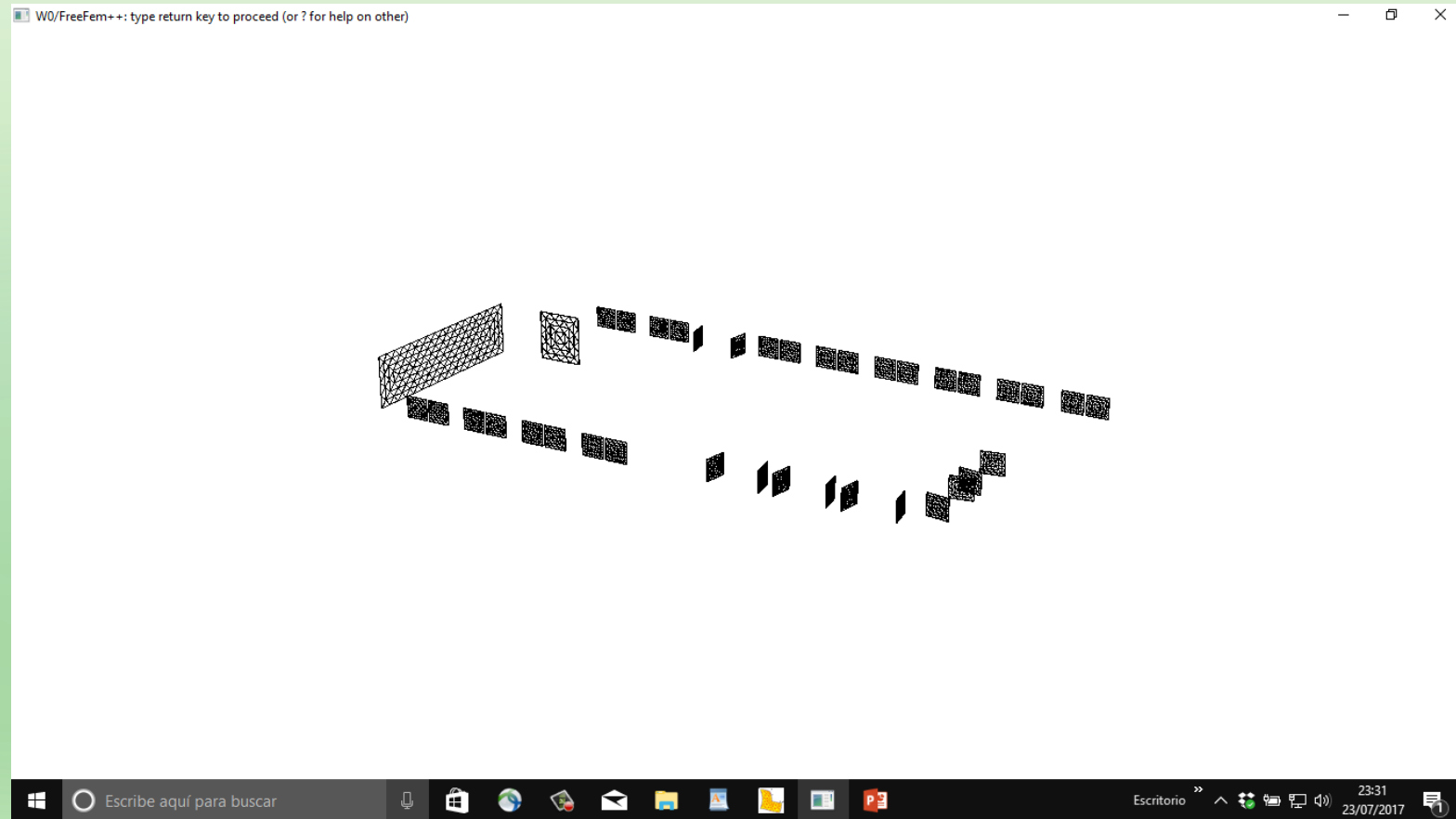
# EXTERNAL FRAMES



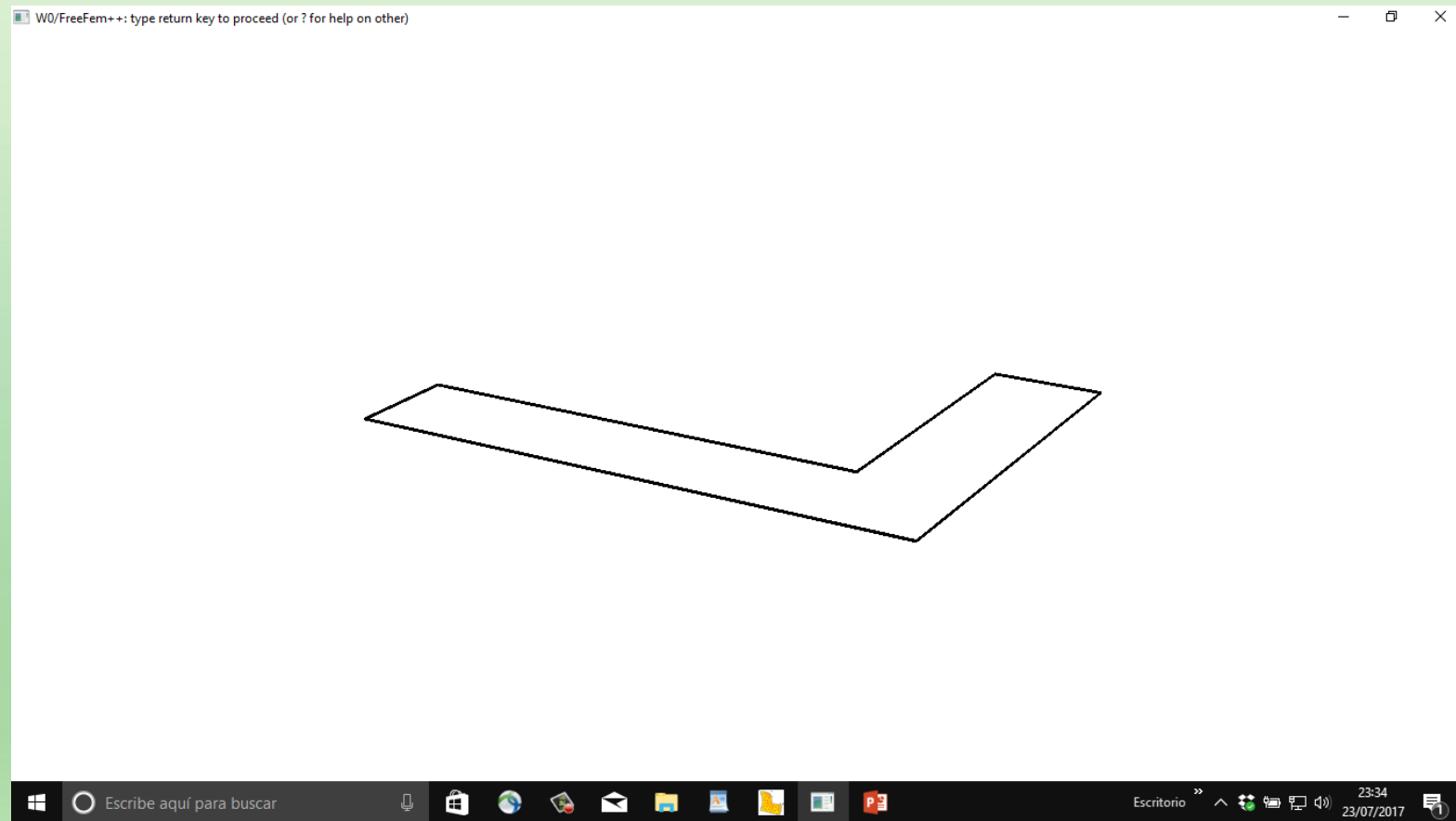
# Internal Frames



# GLASSES



# SILL

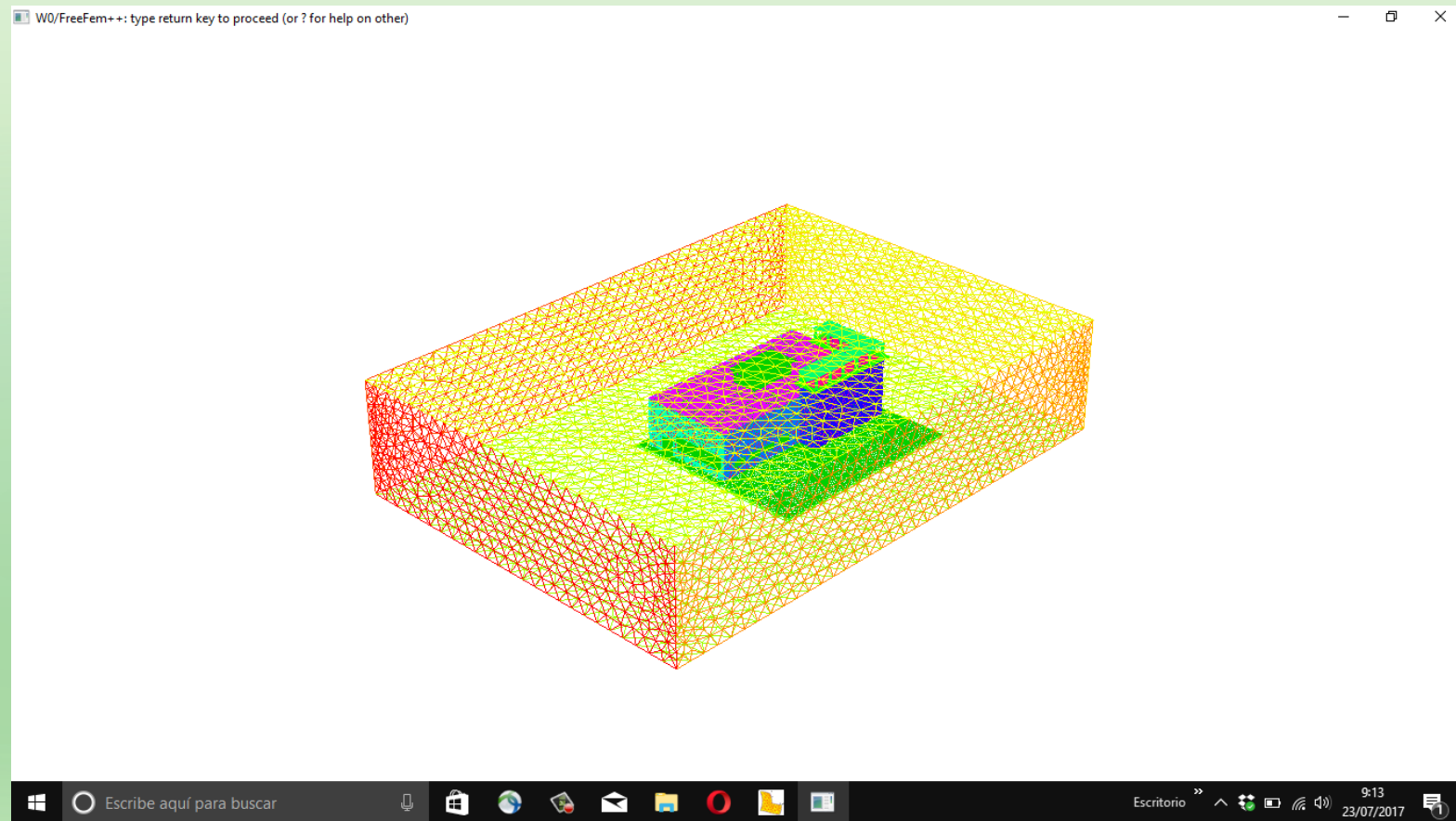


# solidmesh3d

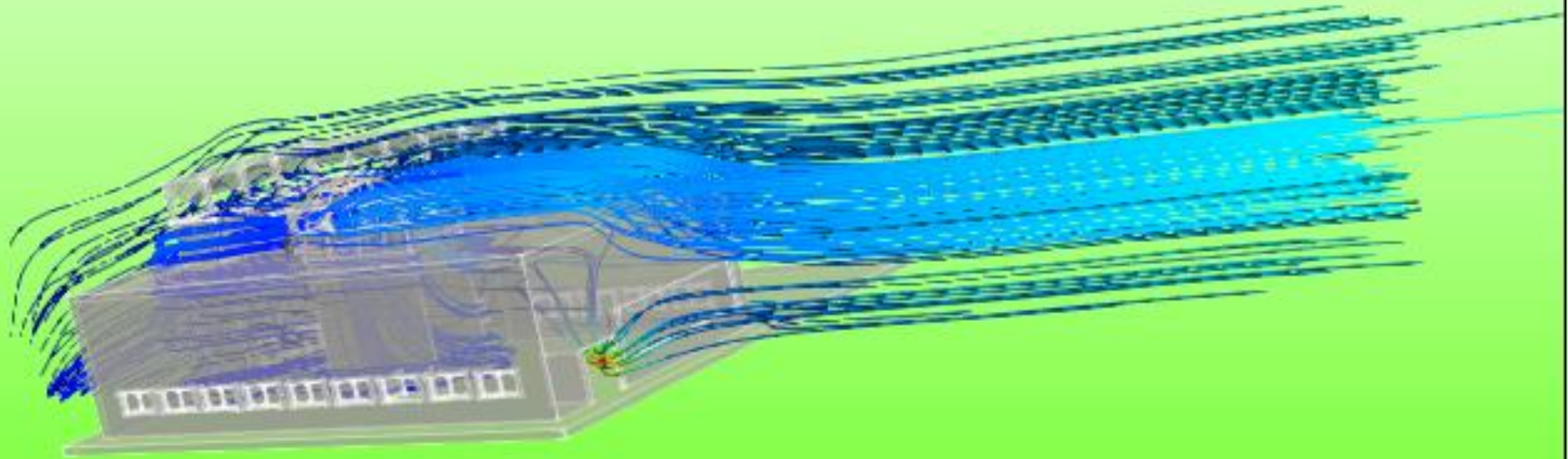
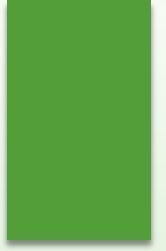




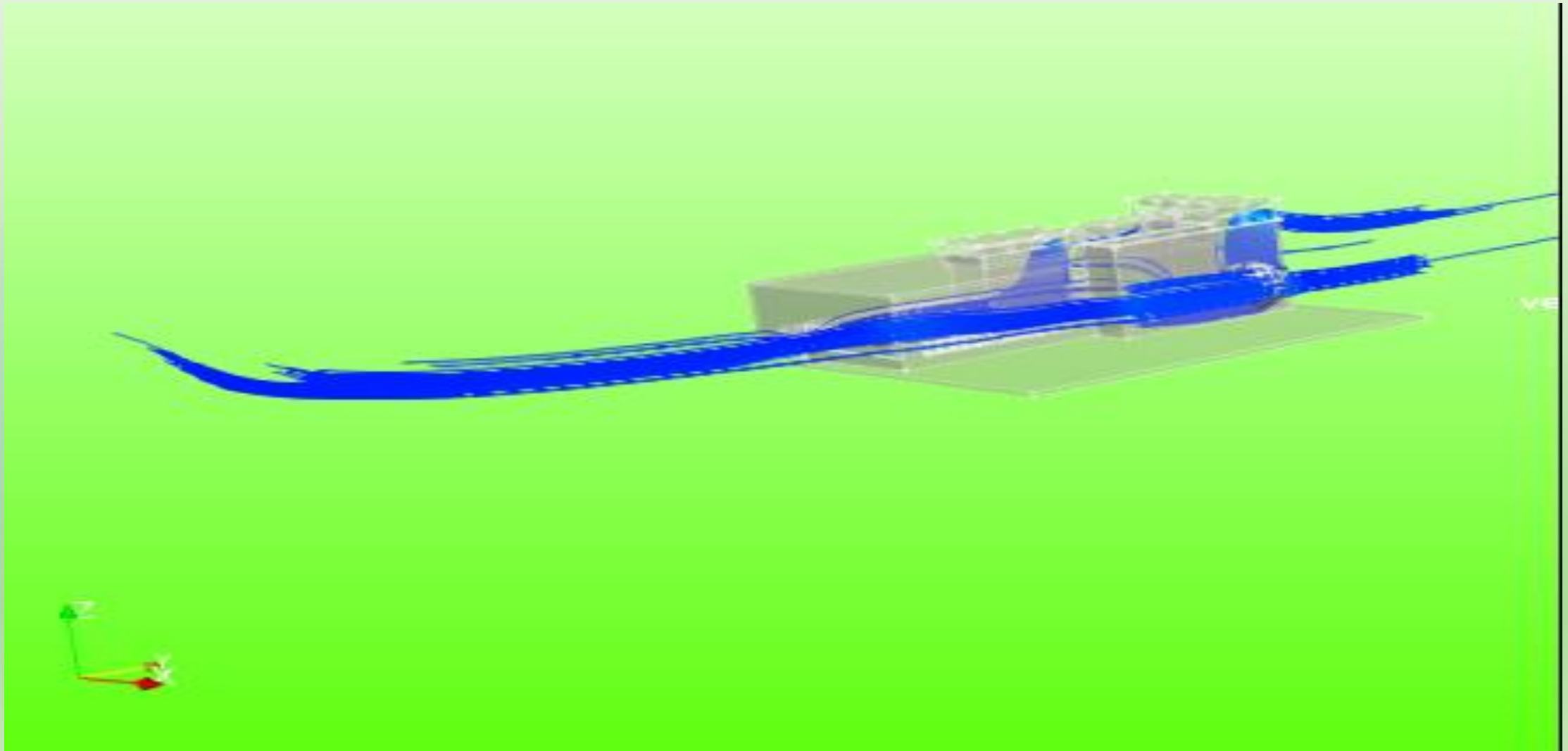
# Air Domain



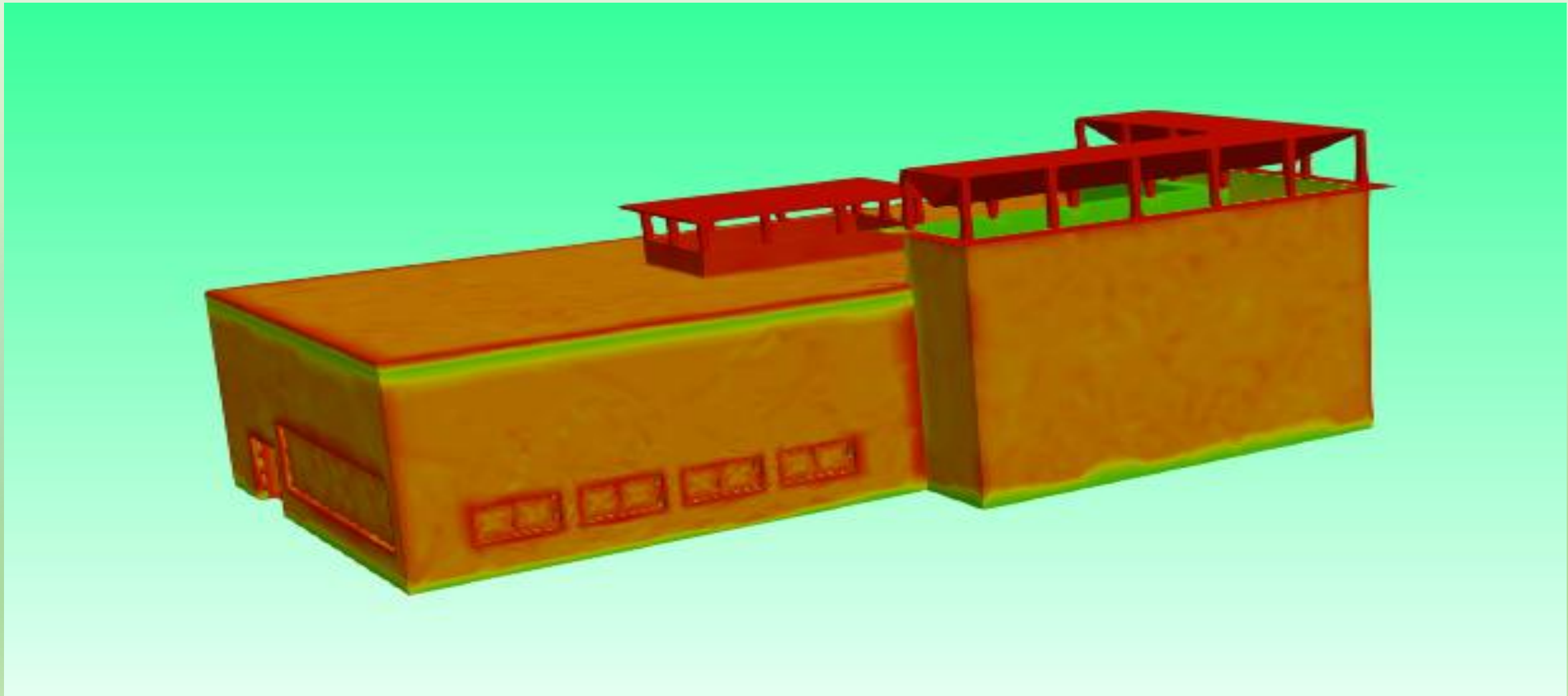
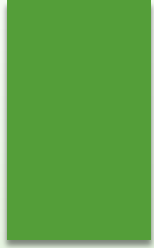
# Velocity



# VELOCITY

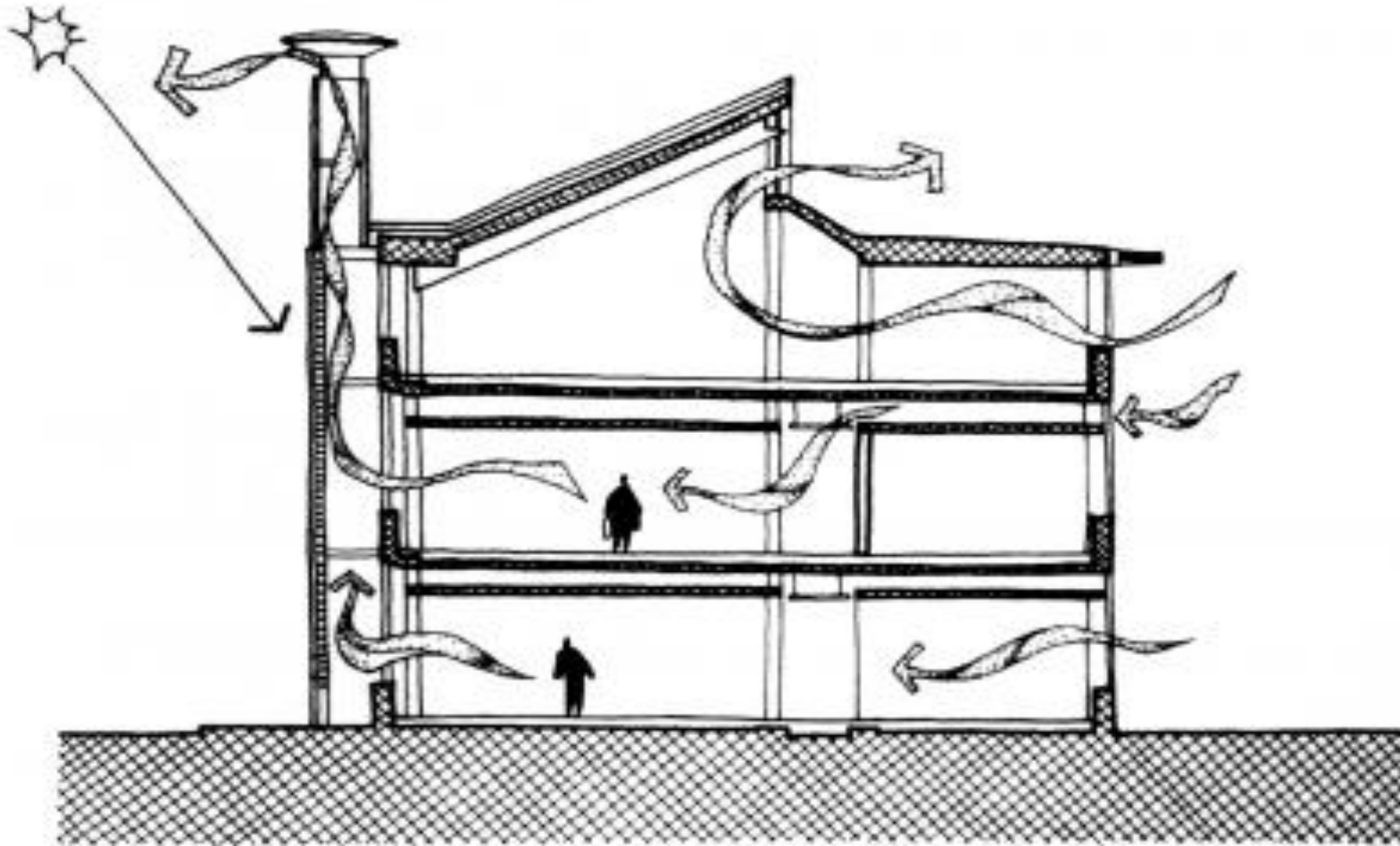


# TEMPERATURE



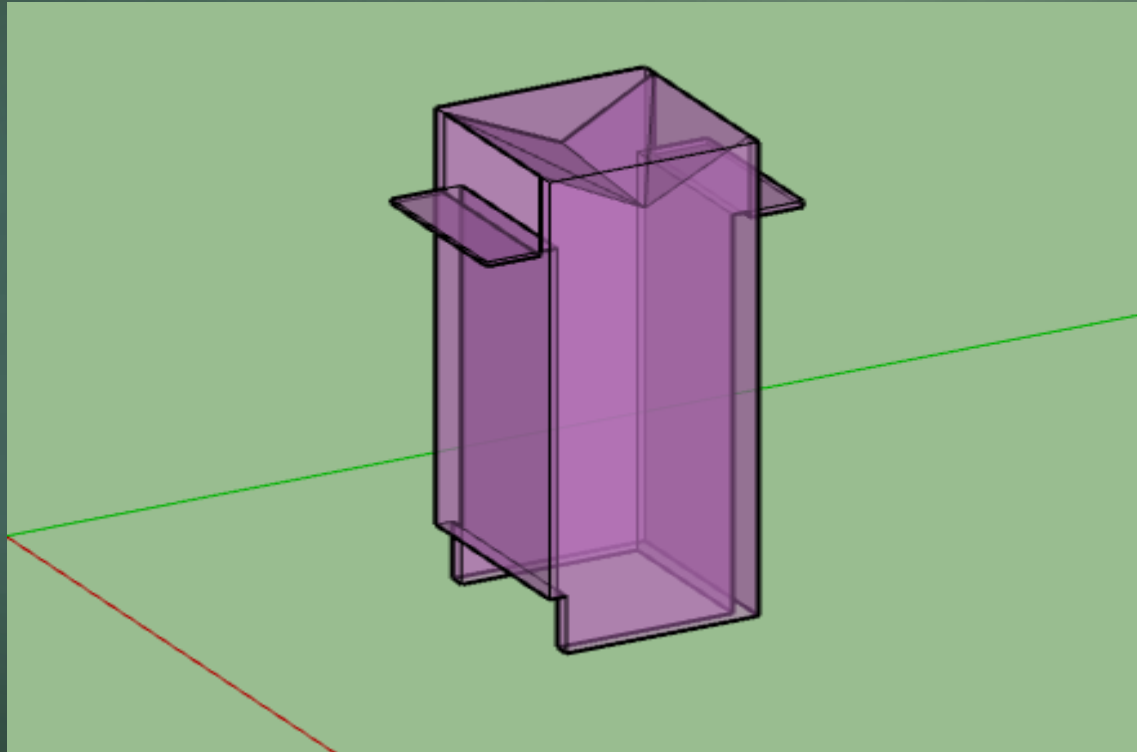
# PROPUESTA DE EDIFICIO PARA SIMULACIONES CON VENTILACIÓN NATURAL

- ▶ LA DIFERENCIA DE TEMPERATURAS MUEVE EL AIRE CALIENTE QUE SUBE DEBIDO A QUE TIENE UNA MENOR DENSIDAD Y PRESIÓN.



# PROPUESTA DE EDIFICIO PARA SIMULACIONES CON VENTILACIÓN NATURAL

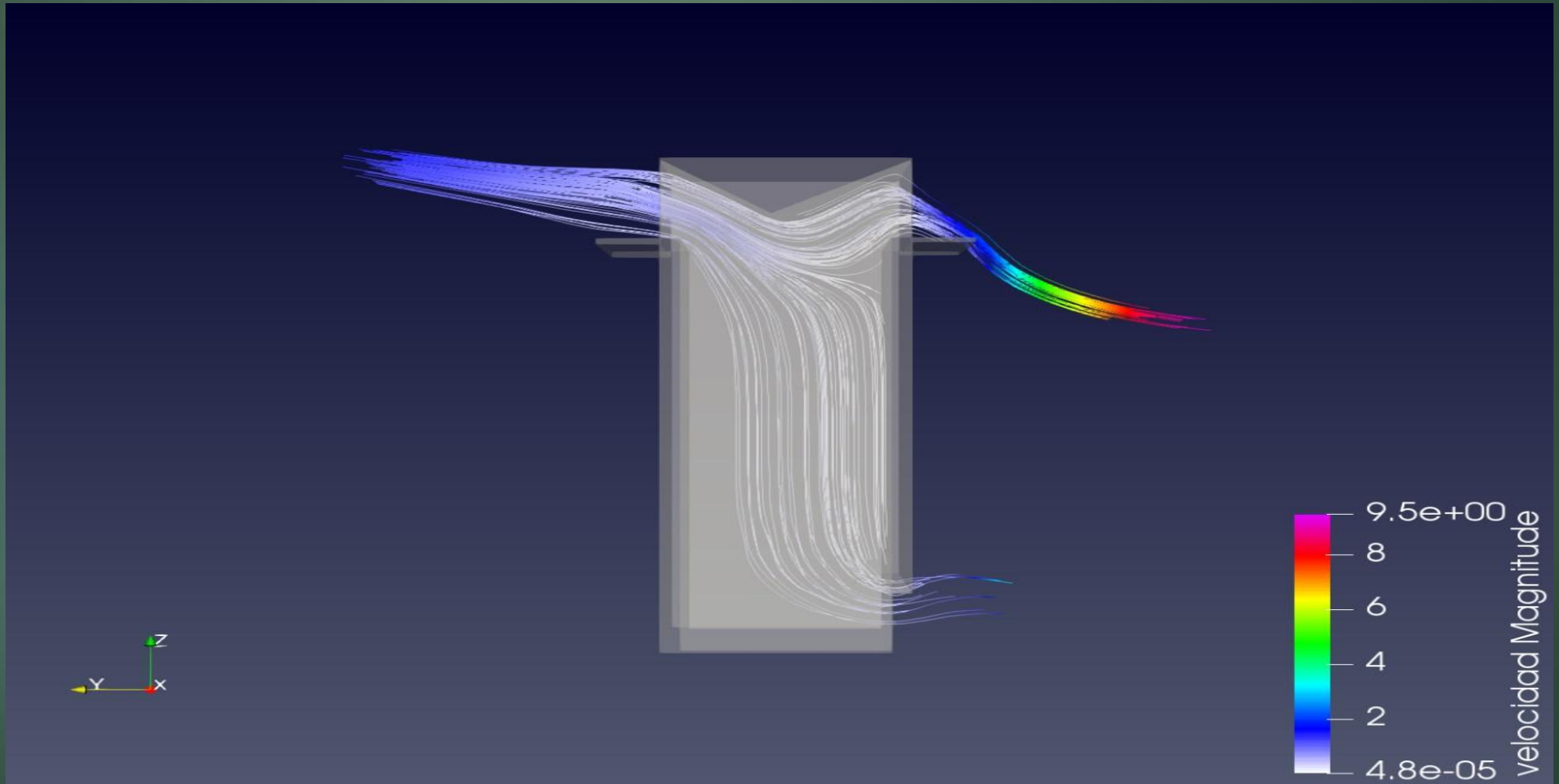
- ▶ UN ENSAYO EN UN EDIFICIO BÁSICO EN EL QUE SE REPRODUCE EL EFECTO DE LA VENTILACIÓN



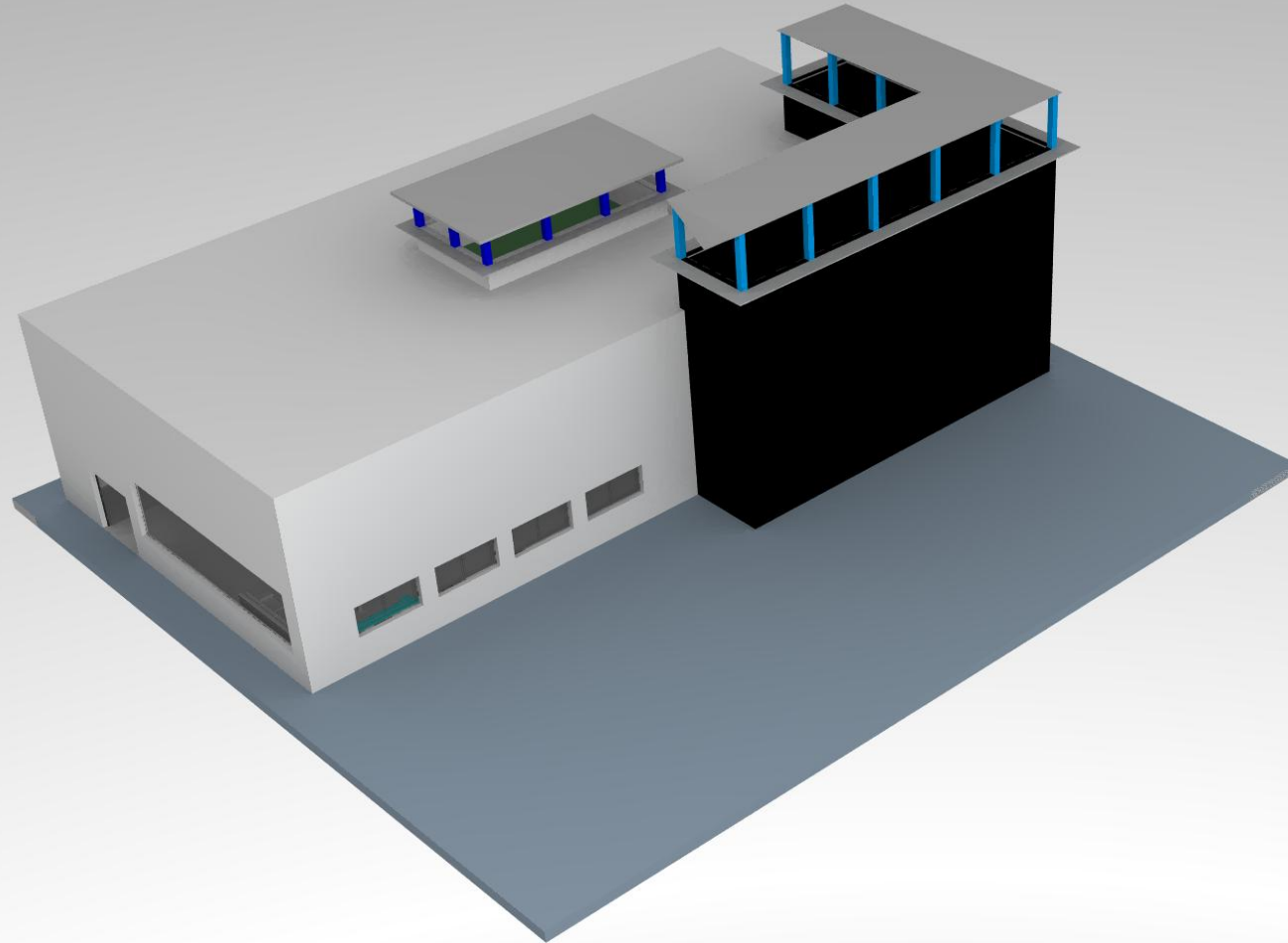
EL DOMINIO DEL AIRE ES EL QUE RESTE DE UN CUBO EL DOMINIO DE AIRE EN EL LOCAL.

# PROPUESTA DE EDIFICIO PARA SIMULACIONES CON VENTILACIÓN NATURAL

## ▶ LÍNEAS DE FLUJO

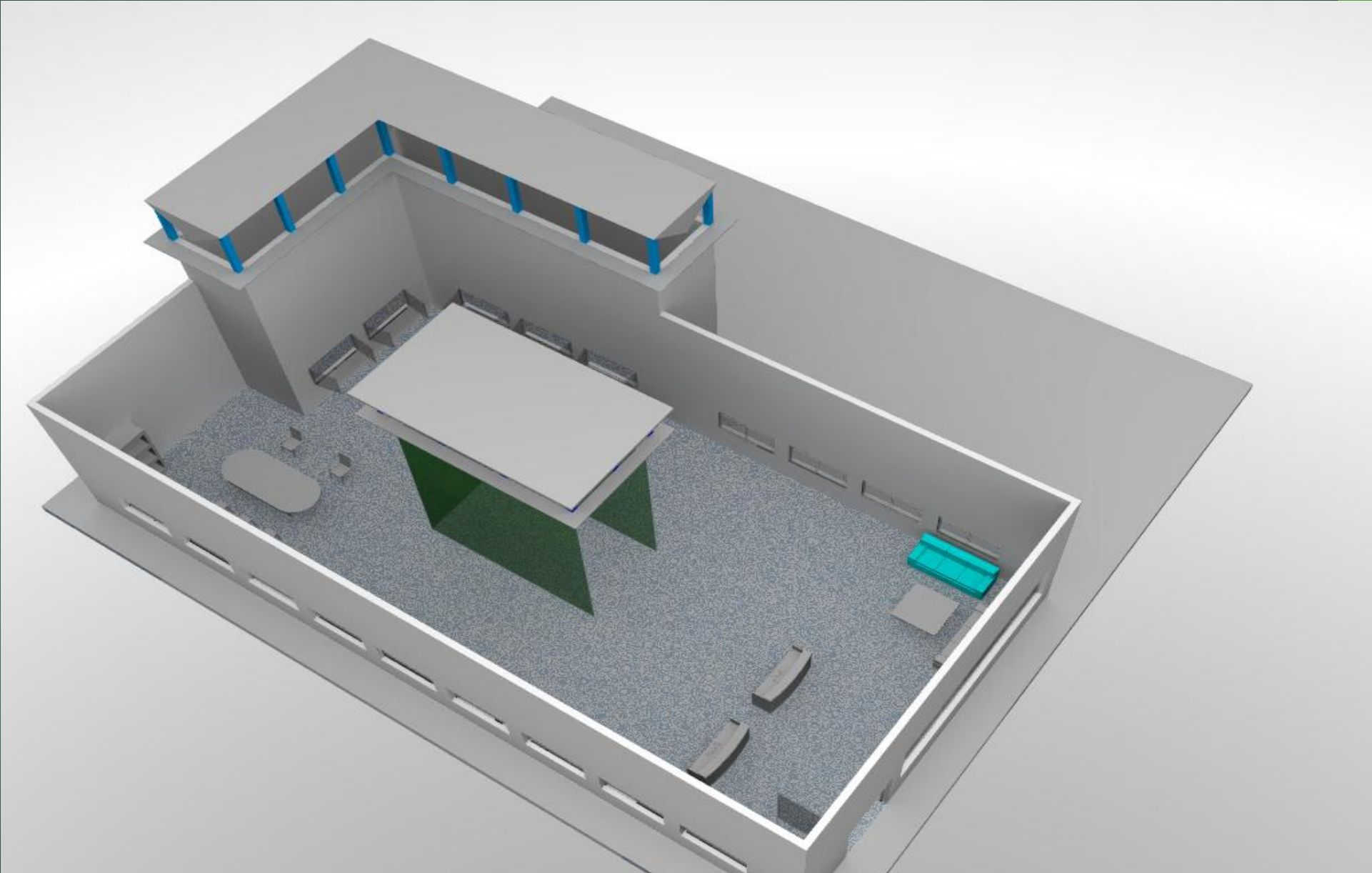


# SIMULACIONES EN UN EDIFICIO





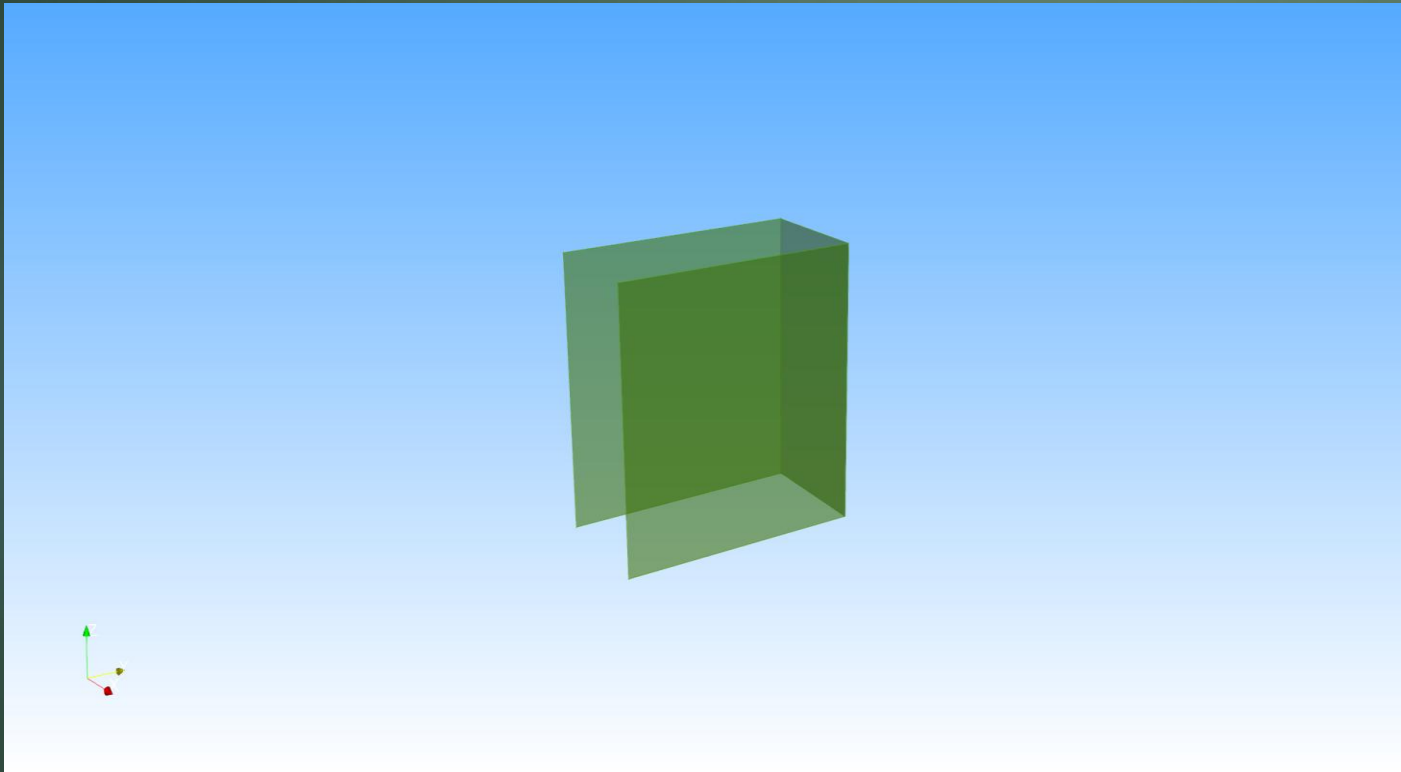
# SIMULACIONES CON VENTILACIÓN NATURAL



# PROPUESTA DE EDIFICIO PARA SIMULACIONES CON VENTILACIÓN NATURAL

## DISEÑO DEL EDIFICIO DEFINITIVO

### PANEL PATIO CENTRAL

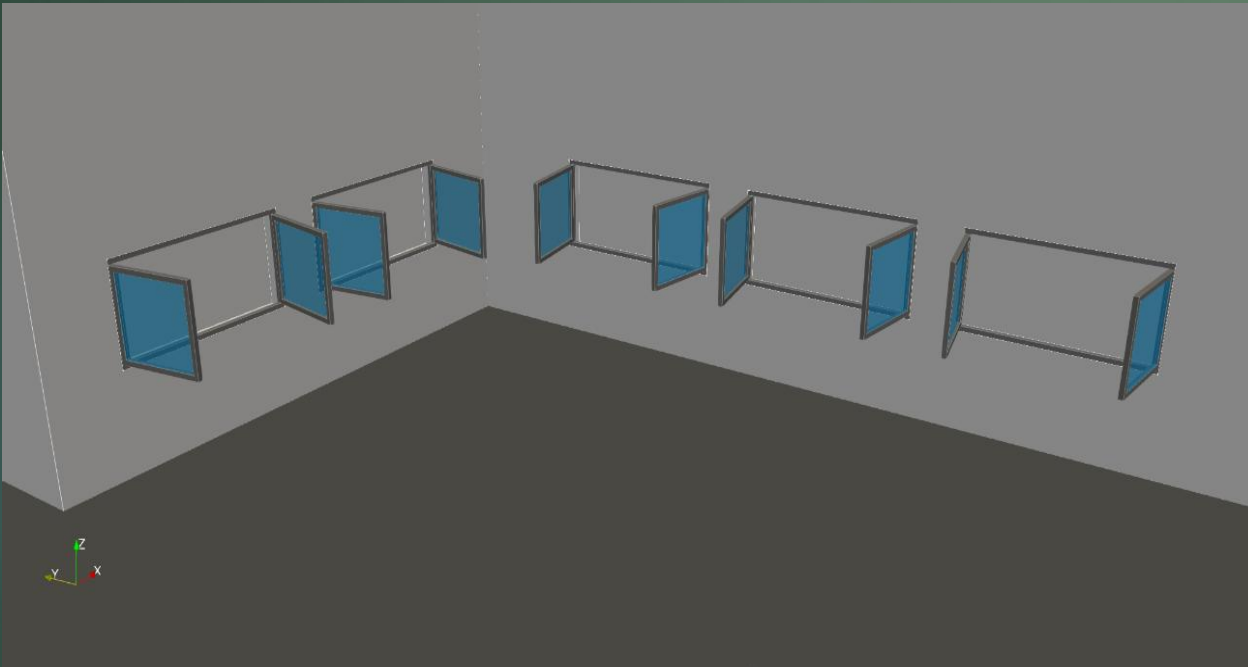


- EL ESPACIO CENTRAL TIENE UN PANEL ACRISTALADO QUE ACTUARÁ COMO CANALIZADOR DEL FLUJO AL EXTERIOR, DE ACUERDO AL PRINCIPIO DE BERNOUILLI.
- LA ENTRADA DEL FLUJO VENDRÁ DE LA PUERTA PRINCIPAL, ASÍ LA ABERTURA DEL PANEL ESTARÁ ORIENTADA HACIA LA PUERTA.

# PROPUESTA DE EDIFICIO PARA SIMULACIONES CON VENTILACIÓN NATURAL

## DISEÑO DEL EDIFICIO DEFINITIVO

### PATIO LATERAL

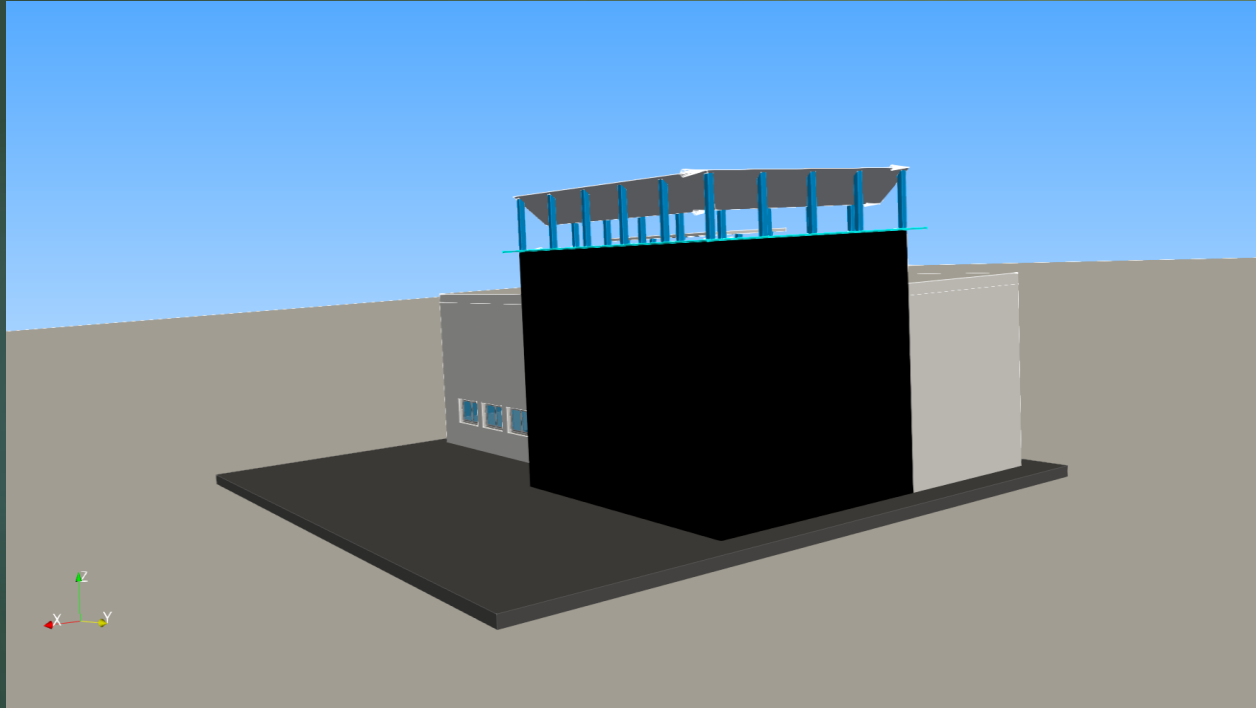


- EL PATIO LATERAL DISPONDRÁ DE UNAS VENTANAS, QUE ESTARÁN SIEMPRE ABIERTAS.

# PROPUESTA DE EDIFICIO PARA SIMULACIONES CON VENTILACIÓN NATURAL

## DISEÑO DEL EDIFICIO DEFINITIVO

### PATIO LATERAL

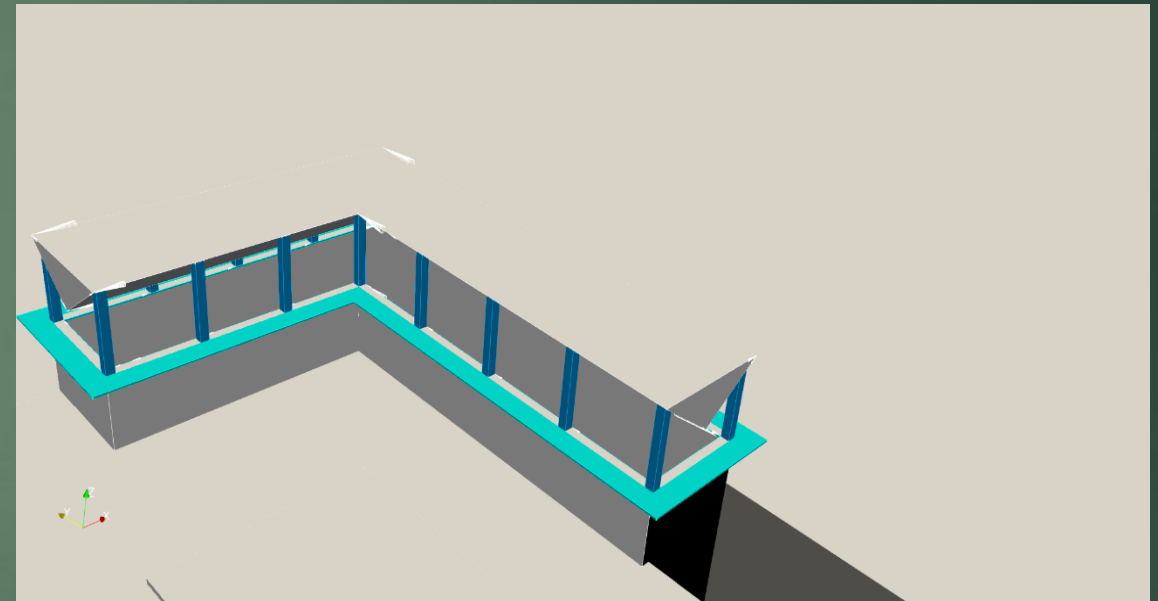
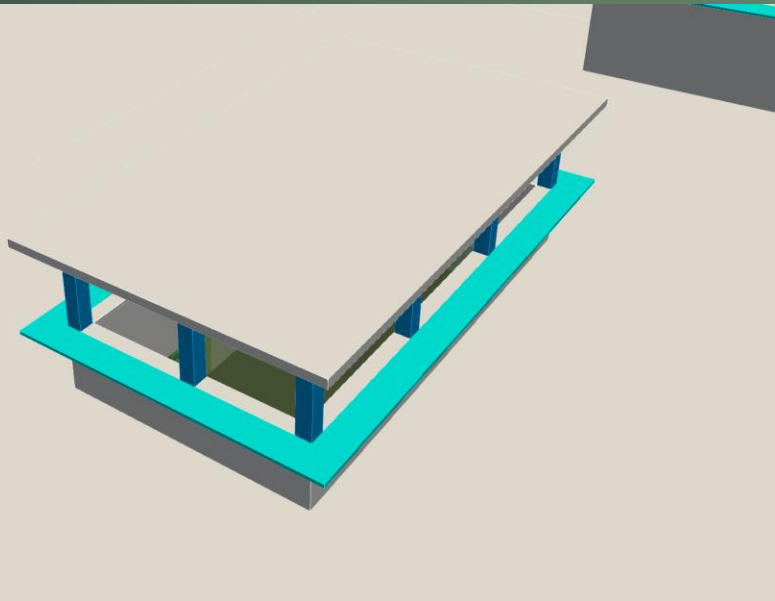


- EL PATIO LATERAL DISPONDRÁ DE UNAS VENTANAS, QUE ESTARÁN SIEMPRE ABIERTAS
- ESTE EFECTO SE ACRECENTARÁ PINTANDO DE NEGRO LAS SUPERFICIES EXTERIORES DE LA FACHADA

# PROPUESTA DE EDIFICIO PARA SIMULACIONES CON VENTILACIÓN NATURAL

## DISEÑO DEL EDIFICIO DEFINITIVO

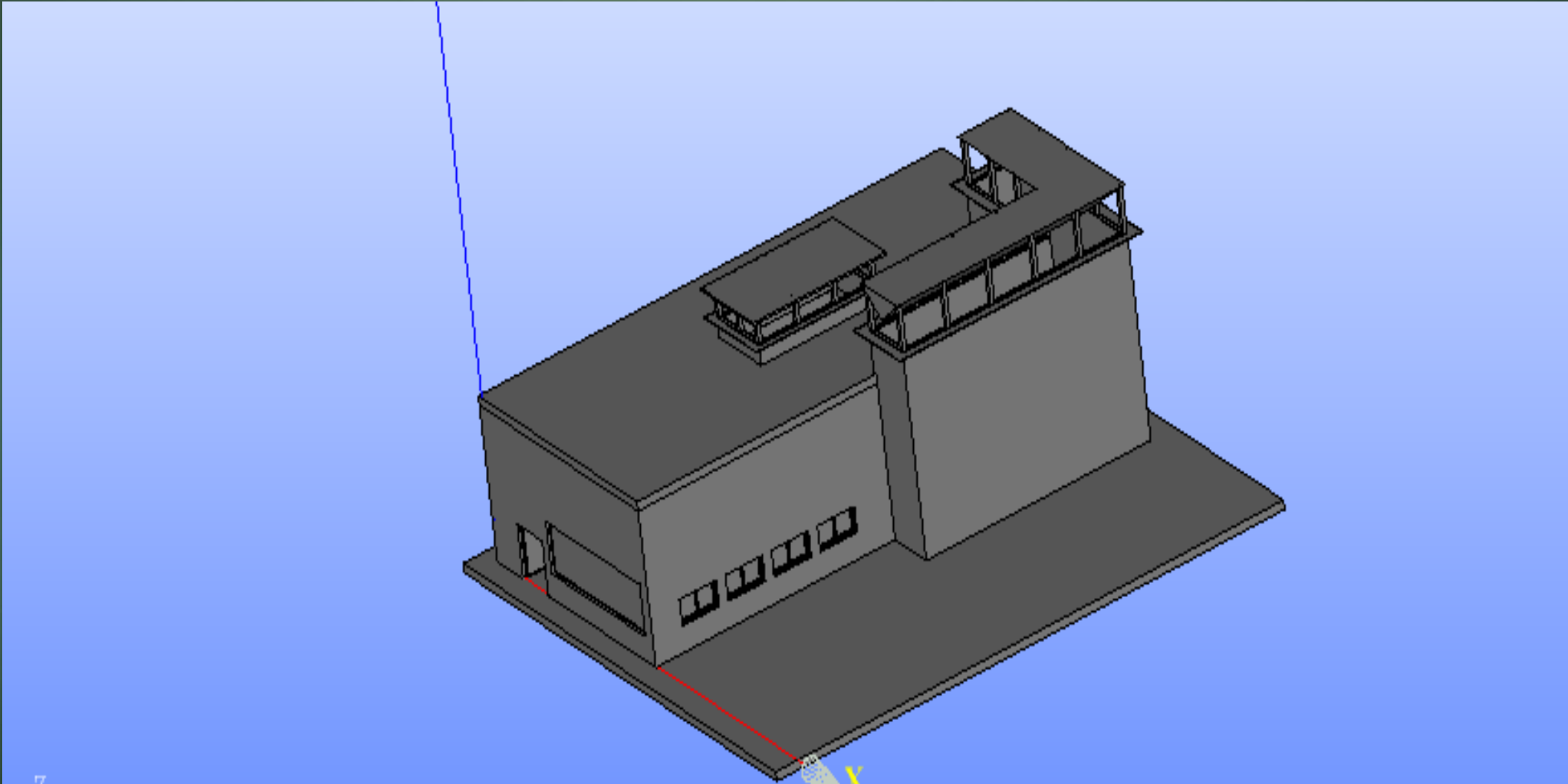
### CORNISAS PATIO LATERAL



- SE HAN INTRODUCIDO UNAS CORNISAS PARA REDUCIR LOS EFECTOS DE VORTICIDAD DEL FLUJO AL ENCONTRARSE CON LAS ESQUINAS.

# METODOLOGÍA

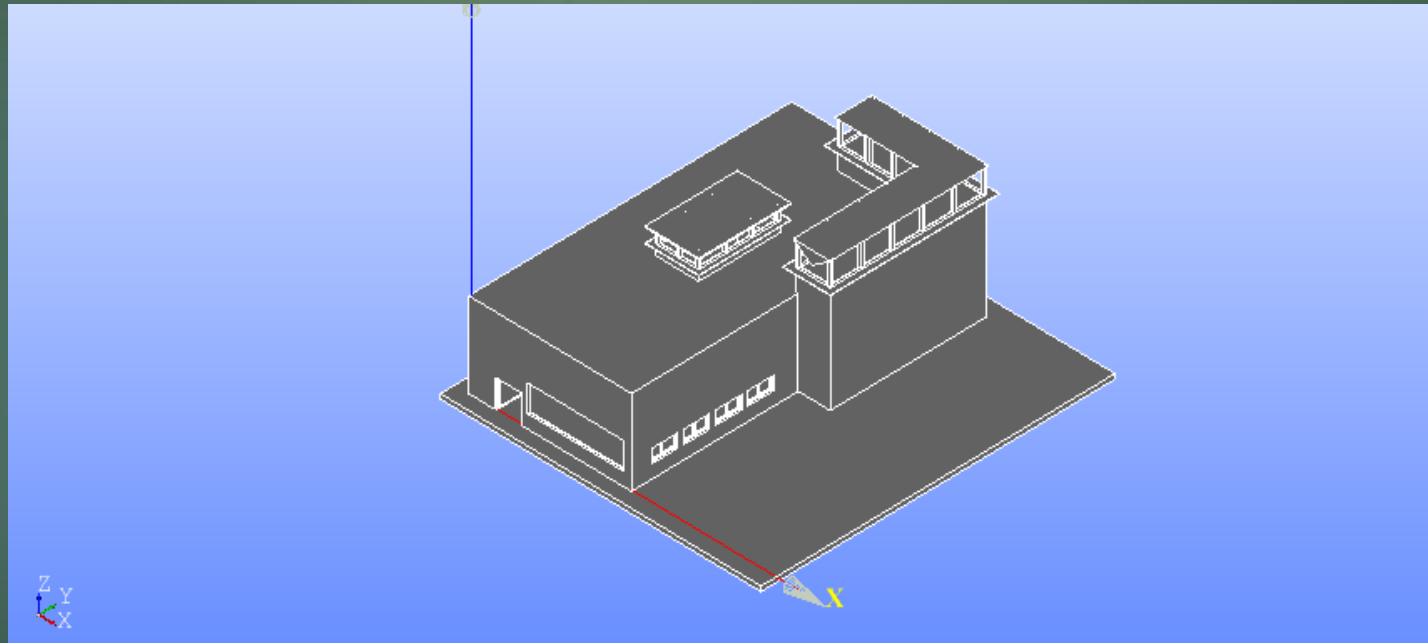
PREPARACIÓN DE LA GEOMETRÍA DE ESTUDIO PARA LA SIMULACIÓN. UNA POSIBILIDAD EXPORTAR LA GEOMETRÍA DE ESTUDIO EN FORMATO .STEP O .STP DESDE FREECAD



# METODOLOGÍA

## PREPARACIÓN DE LA GEOMETRÍA DE ESTUDIO PARA LA SIMULACIÓN.

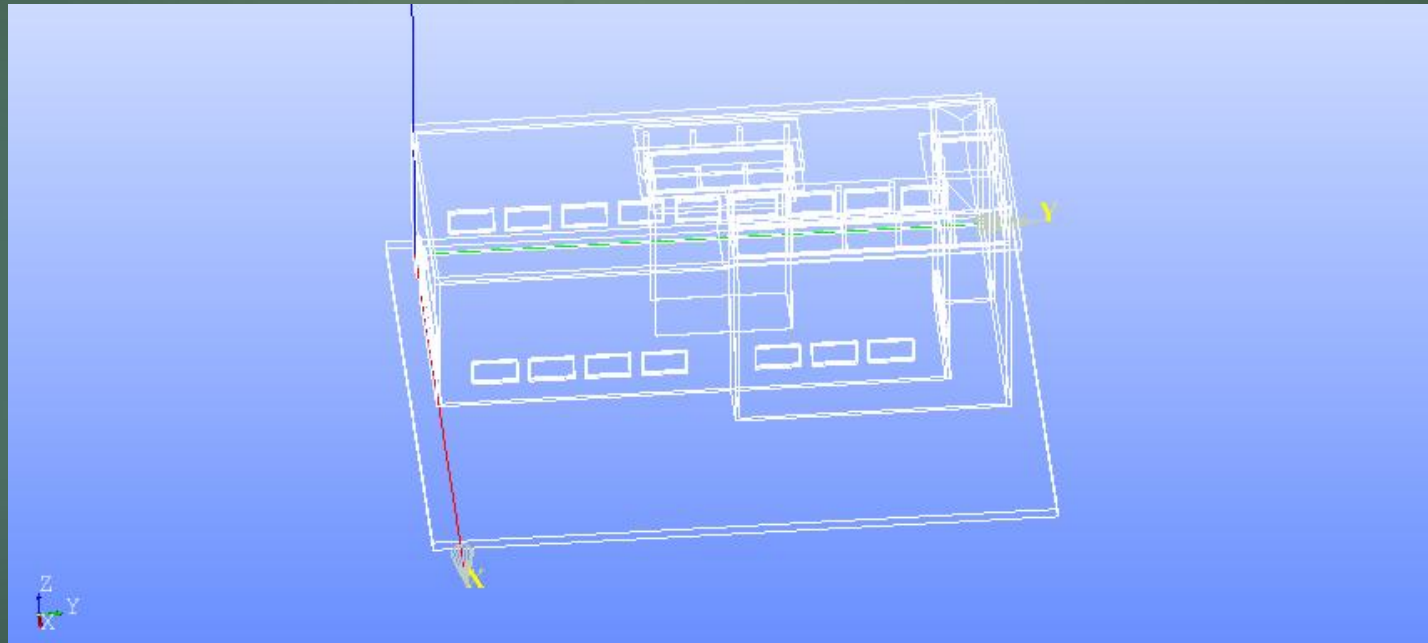
- ▶ APLICAREMOS LA UNIÓN BOOLEANA A TODAS LAS PARTES DEL EDIFICIO PARA CONVERTIRLA EN UN VOLUMEN CERRADO.



# METODOLOGÍA

PREPARACIÓN DE LA GEOMETRÍA DE ESTUDIO PARA LA SIMULACIÓN.

- ▶ EXPLOSIONAREMOS LA GEOMETRÍA ORIGINAL EN LÍNEAS

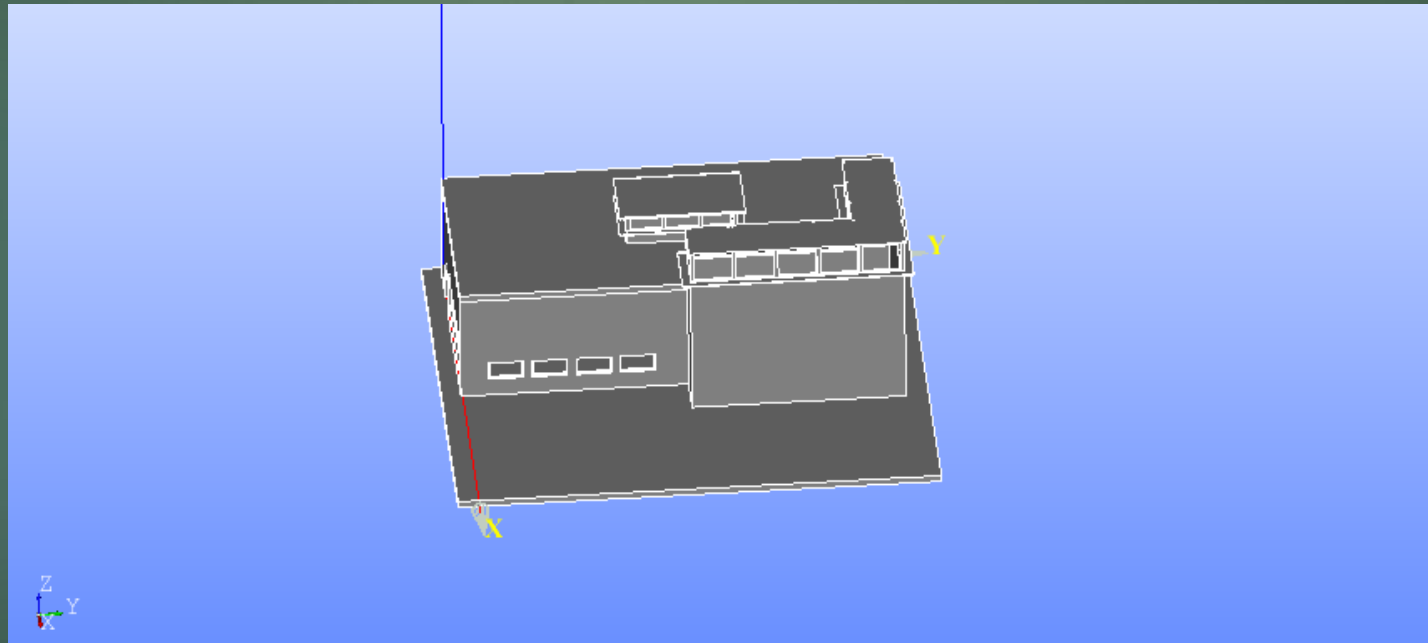




# METODOLOGÍA

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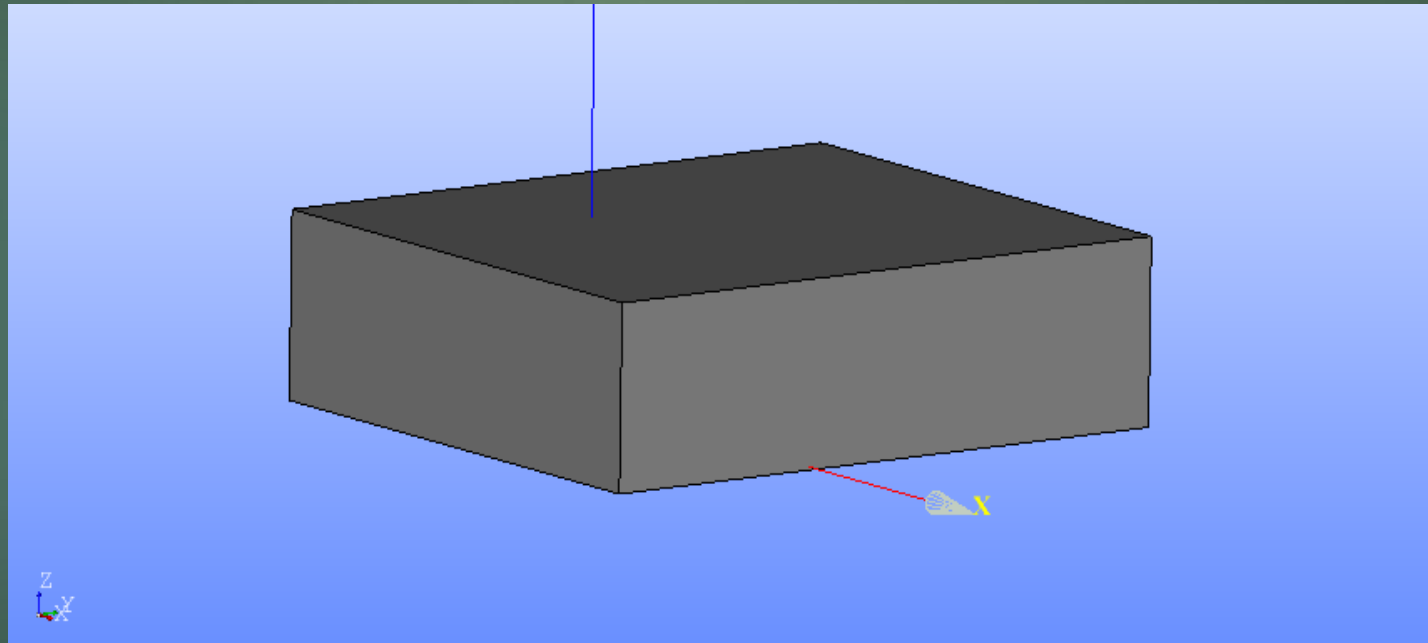
- ▶ DIVIDIMOS LAS CARAS DE LA GEOMETRÍA CERRADA PARA OBTENER LAS DIFERENTES INTERFASES DE INTERCAMBIO DE CALOR.



# METODOLOGÍA

## PREPARACIÓN DE LA GEOMETRÍA DE ESTUDIO PARA LA SIMULACIÓN.

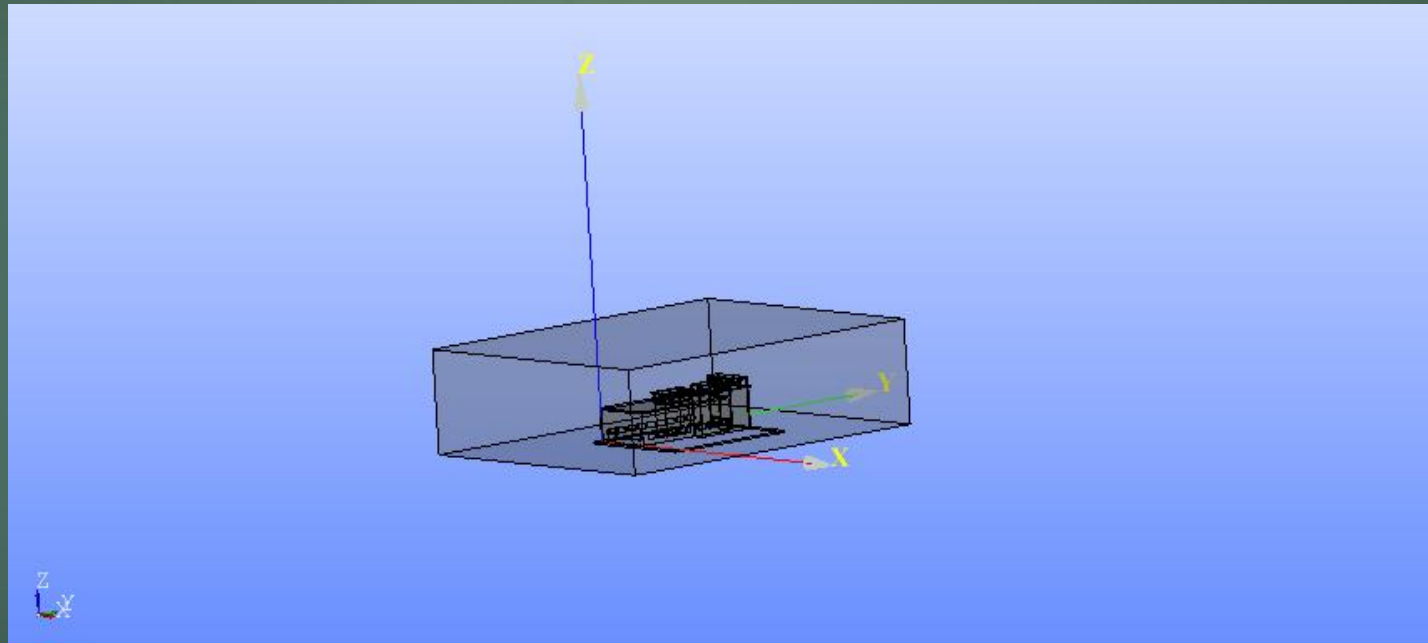
- ▶ DEFINIREMOS UN CUBO DE 60 M DE ANCHO, 70 DE LARGO Y 20 DE ALTO.



# METODOLOGÍA

PREPARACIÓN DE LA GEOMETRÍA DE ESTUDIO PARA LA SIMULACIÓN.

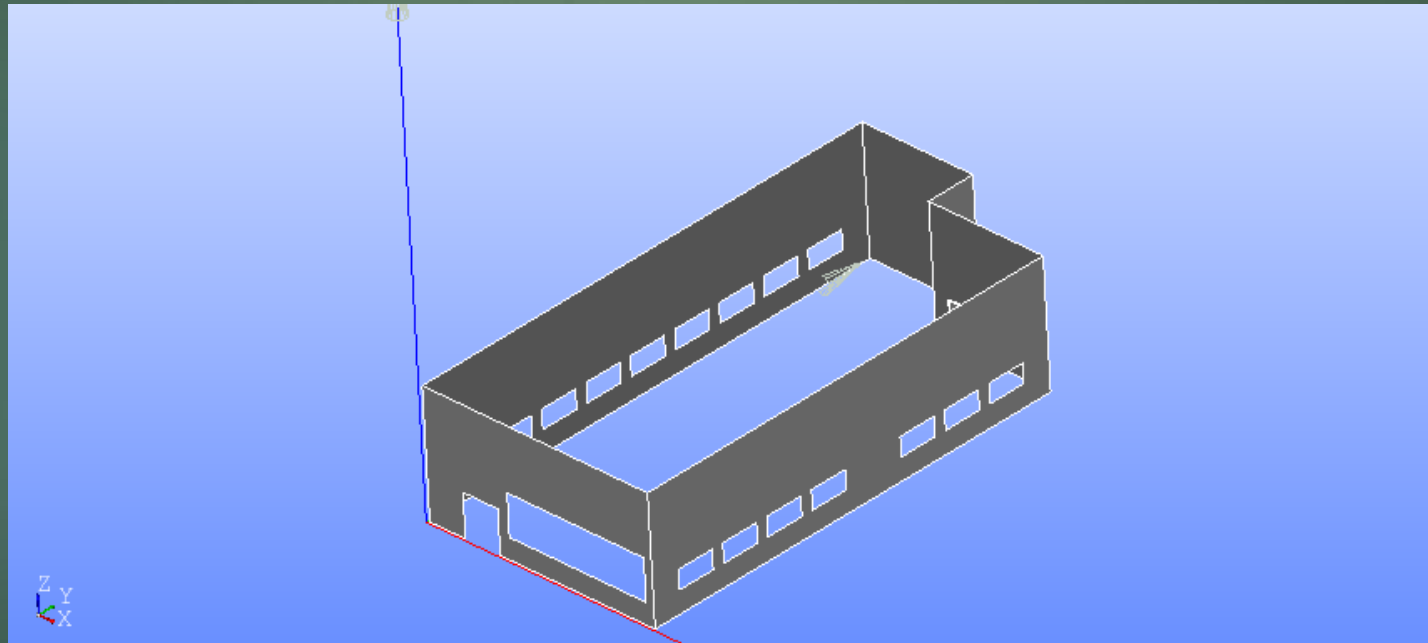
- ▶ LA **GEOMETRÍA RESULTANTE** SE OBTENDRÁ APLICANDO EL OPERADOR BOOLEANO "CUT".



# METODOLOGÍA

## PREPARACIÓN DE LA GEOMETRÍA DE ESTUDIO PARA LA SIMULACIÓN.

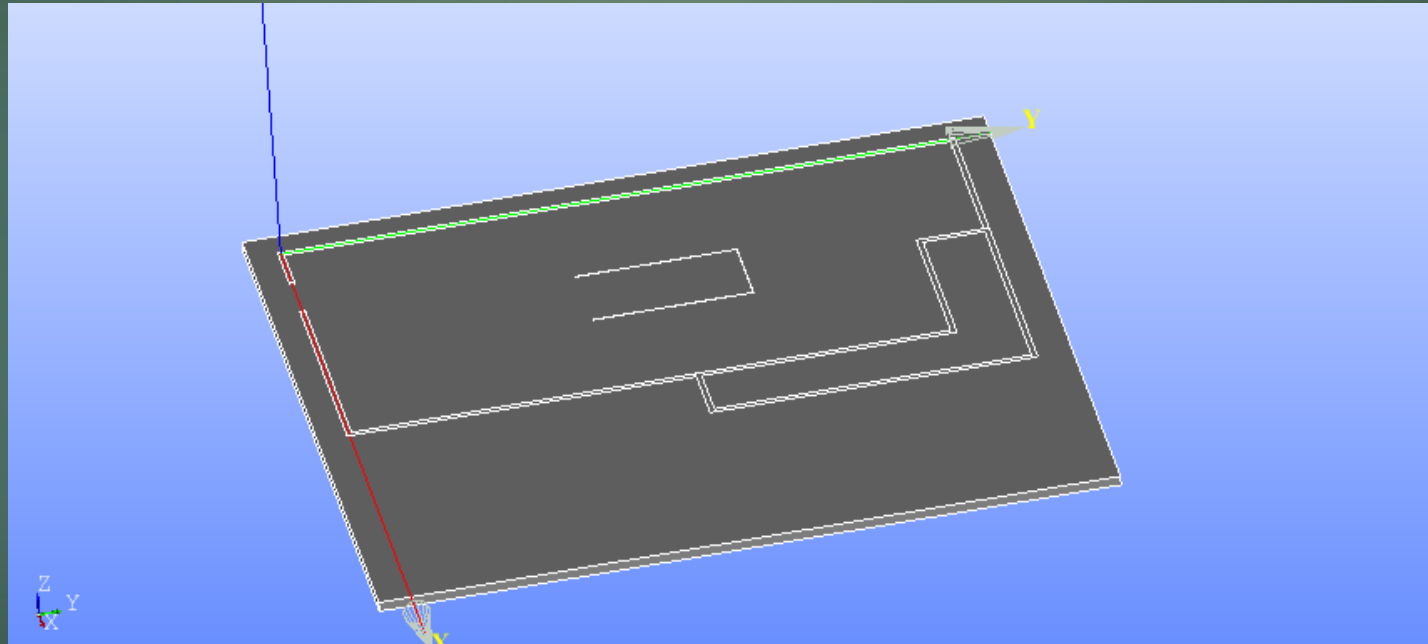
- ▶ AGRUPAREMOS LAS CARAS SEGÚN SEGÚN EL TIPO DE INTERCAMBIO DE FLUJO DE CALOR QUE SE PRESENTE



# METODOLOGÍA

## PREPARACIÓN DE LA GEOMETRÍA DE ESTUDIO PARA LA SIMULACIÓN.

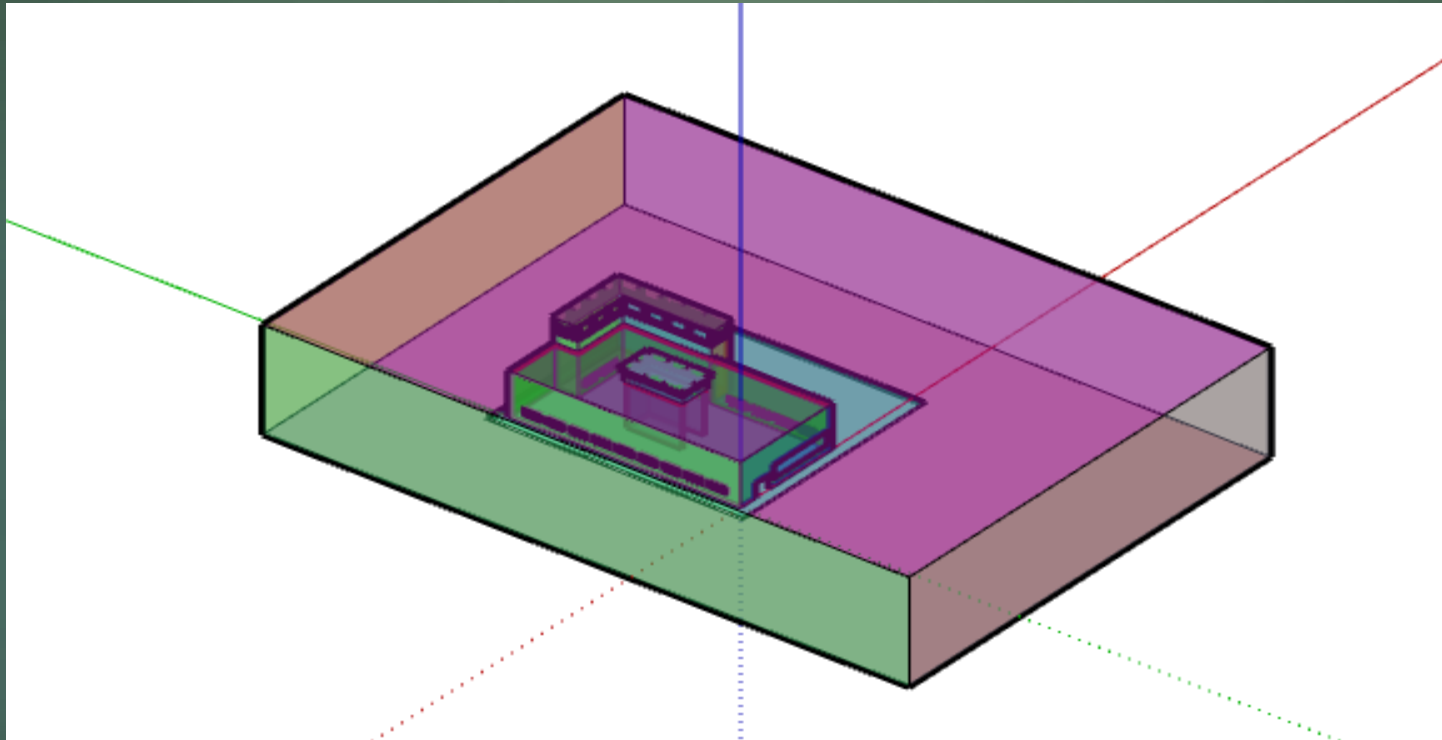
- ▶ EL PROCESO DESCRITO ANTERIORMENTE SE REPETIRÁ PARA LAS DIFERENTES PARTES DEL EDIFICIO.



# METODOLOGÍA

## DEFINICION DE ETIQUETAS

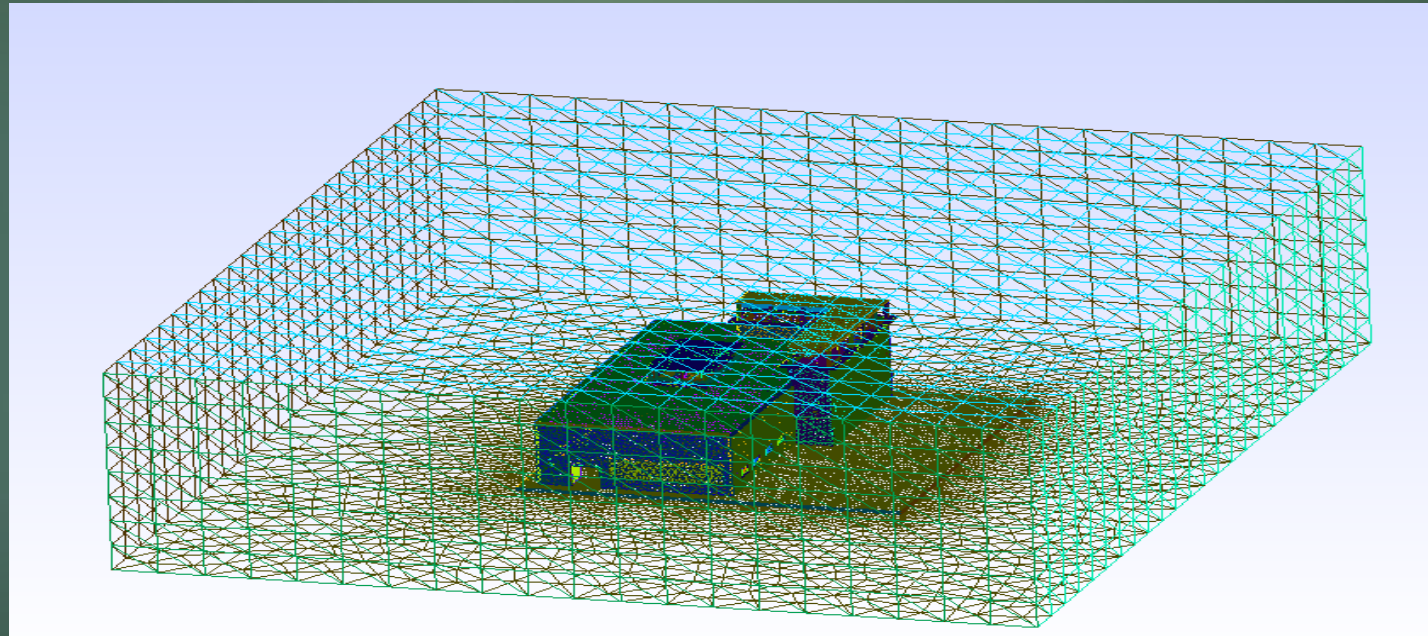
### ► SOFTWARE UTILIZADO



# METODOLOGÍA

## EXPORTACION DE LA GEOMETRIA PARA REALIZAR LA MALLA

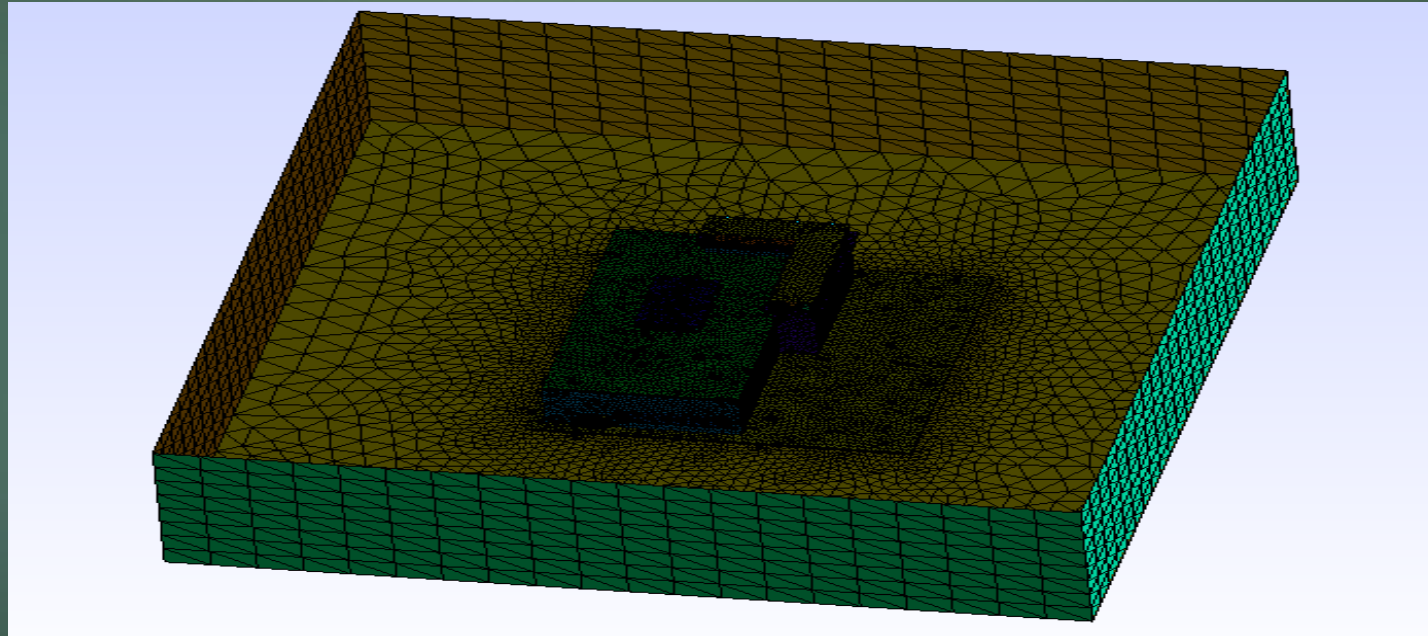
- ▶ LOS RESULTADOS DE LA MALLA PARA LAS DIFERENTES PARTES SON:



# METODOLOGÍA

## EXPORTACION DE LA GEOMETRIA PARA REALIZAR LA MALLA

- ▶ LOS RESULTADOS DE LA MALLA PARA LAS DIFERENTES PARTES SON:

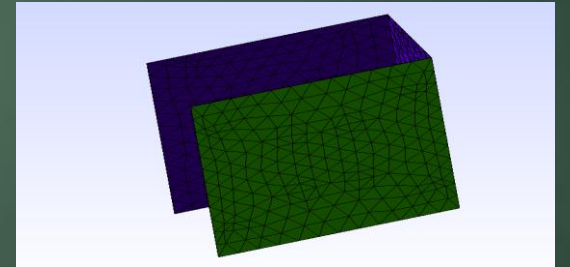
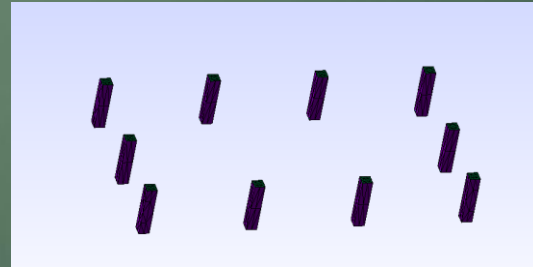
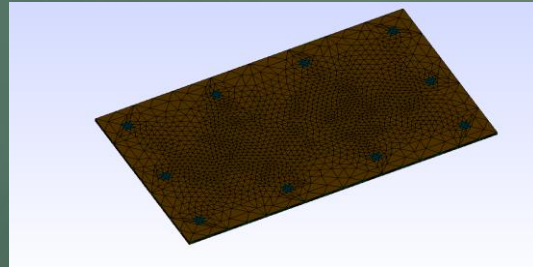
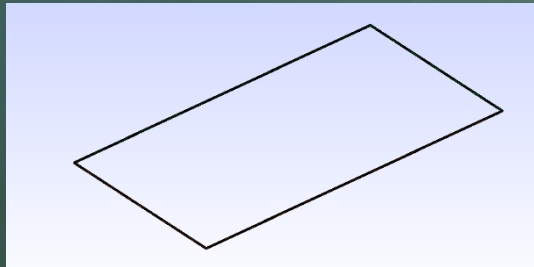
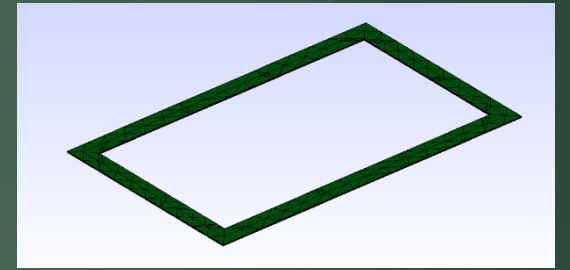
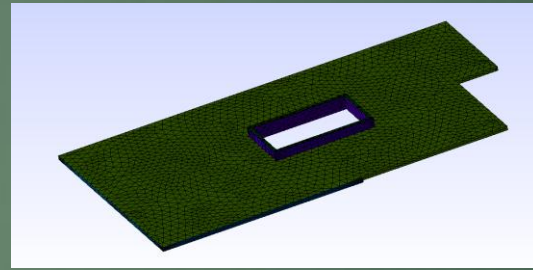
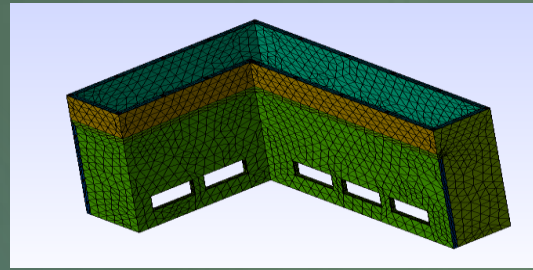
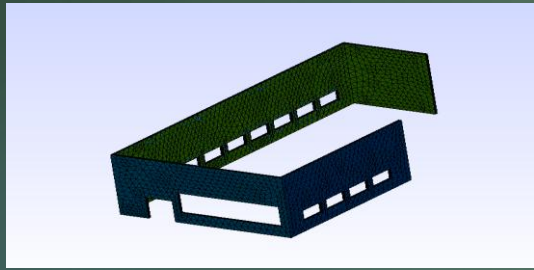




# METODOLOGÍA

## EXPORTACION DE LA GEOMETRIA PARA REALIZAR LA MALLA

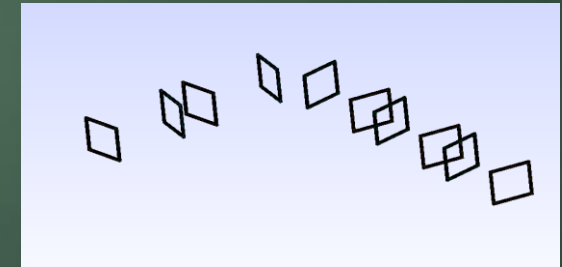
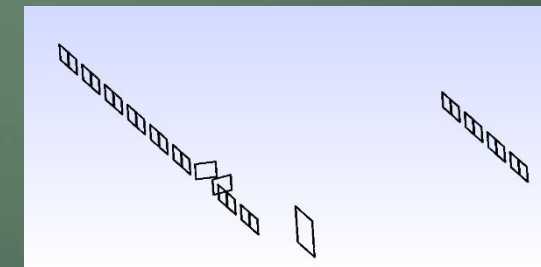
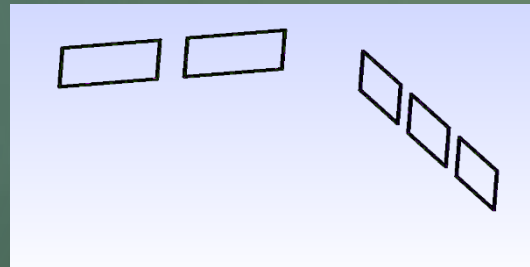
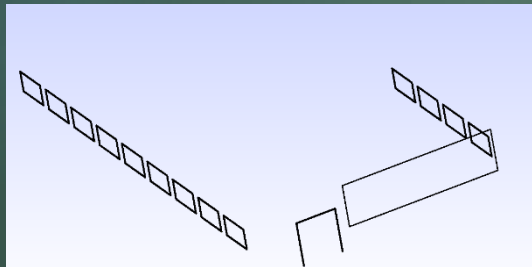
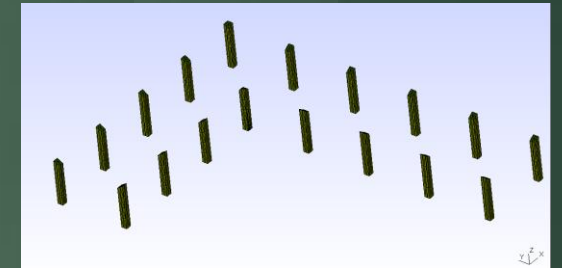
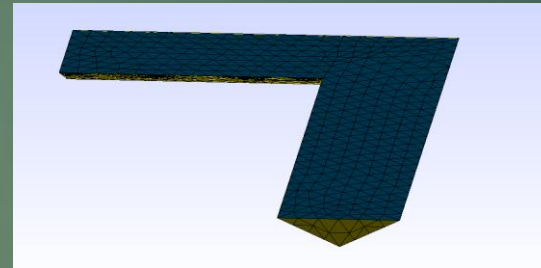
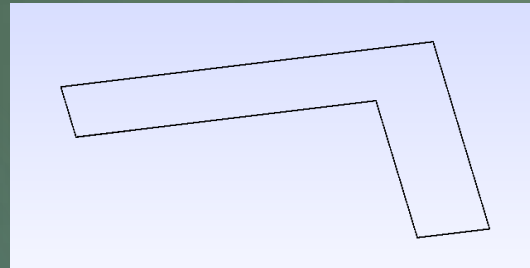
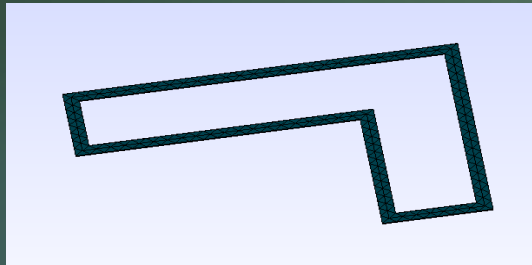
▶ LAS MALLAS SOLIDAS SON:



# METODOLOGÍA

## EXPORTACION DE LA GEOMETRIA PARA REALIZAR LA MALLA

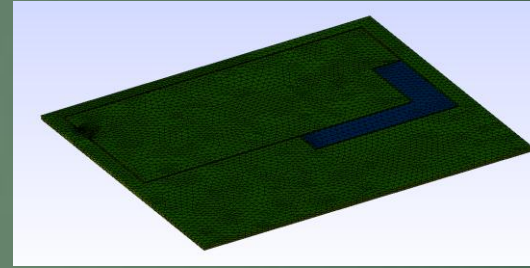
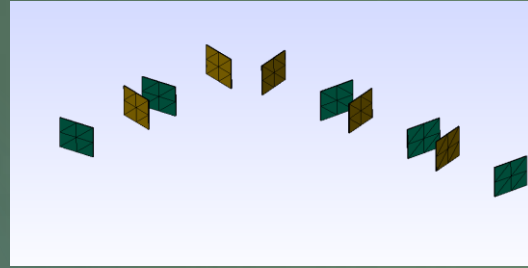
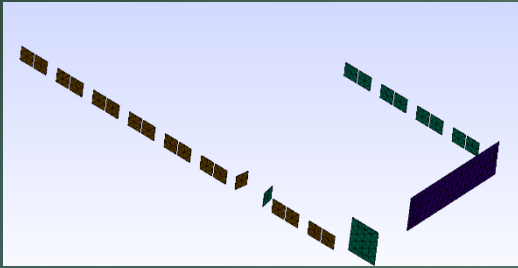
- ▶ LAS MALLAS SOLIDAS SON:



# METODOLOGÍA

## EXPORTACION DE LA GEOMETRIA PARA REALIZAR LA MALLA

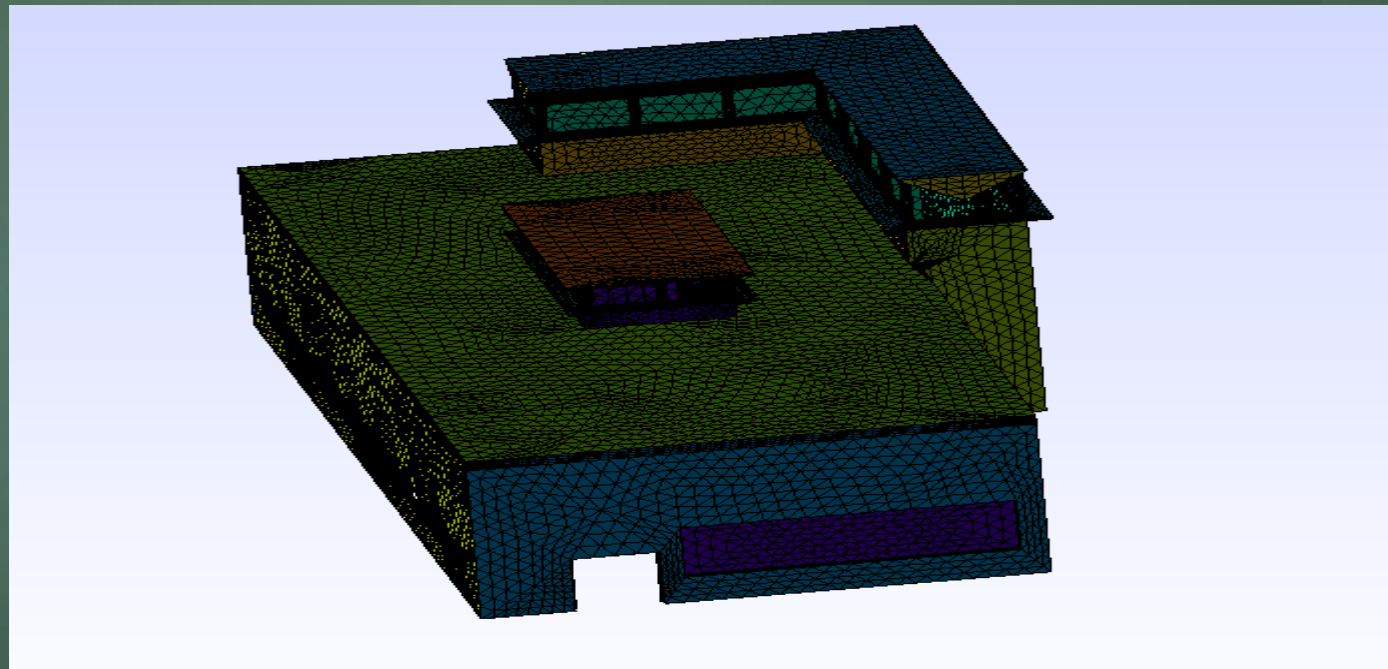
- ▶ LAS MALLAS SOLIDAS SON:



# METODOLOGÍA

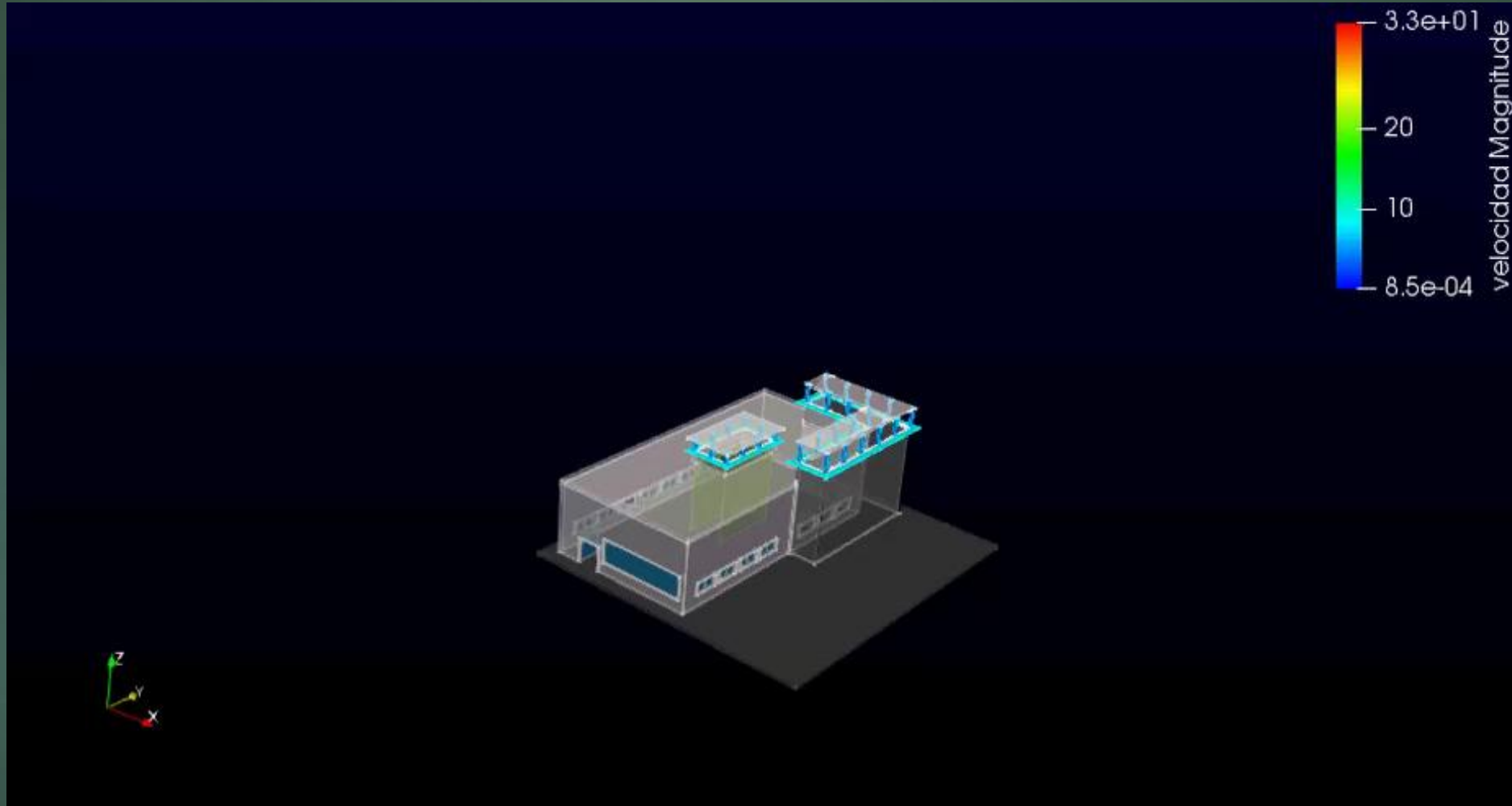
## EXPORTACION DE LA GEOMETRIA PARA REALIZAR LA MALLA

- ▶ LAS MALLAS SOLIDAS SON:



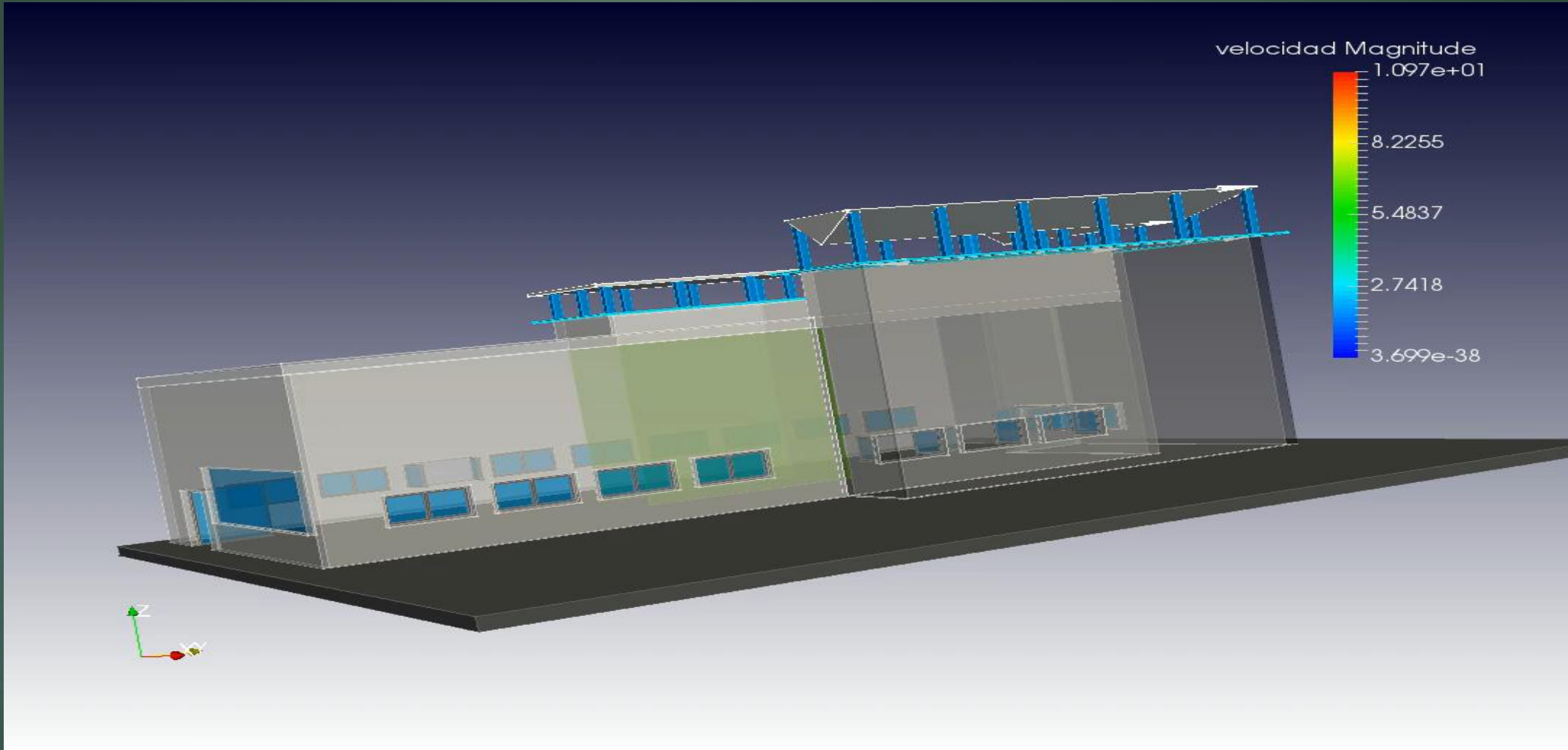
# RESULTADOS

## VELOCIDAD



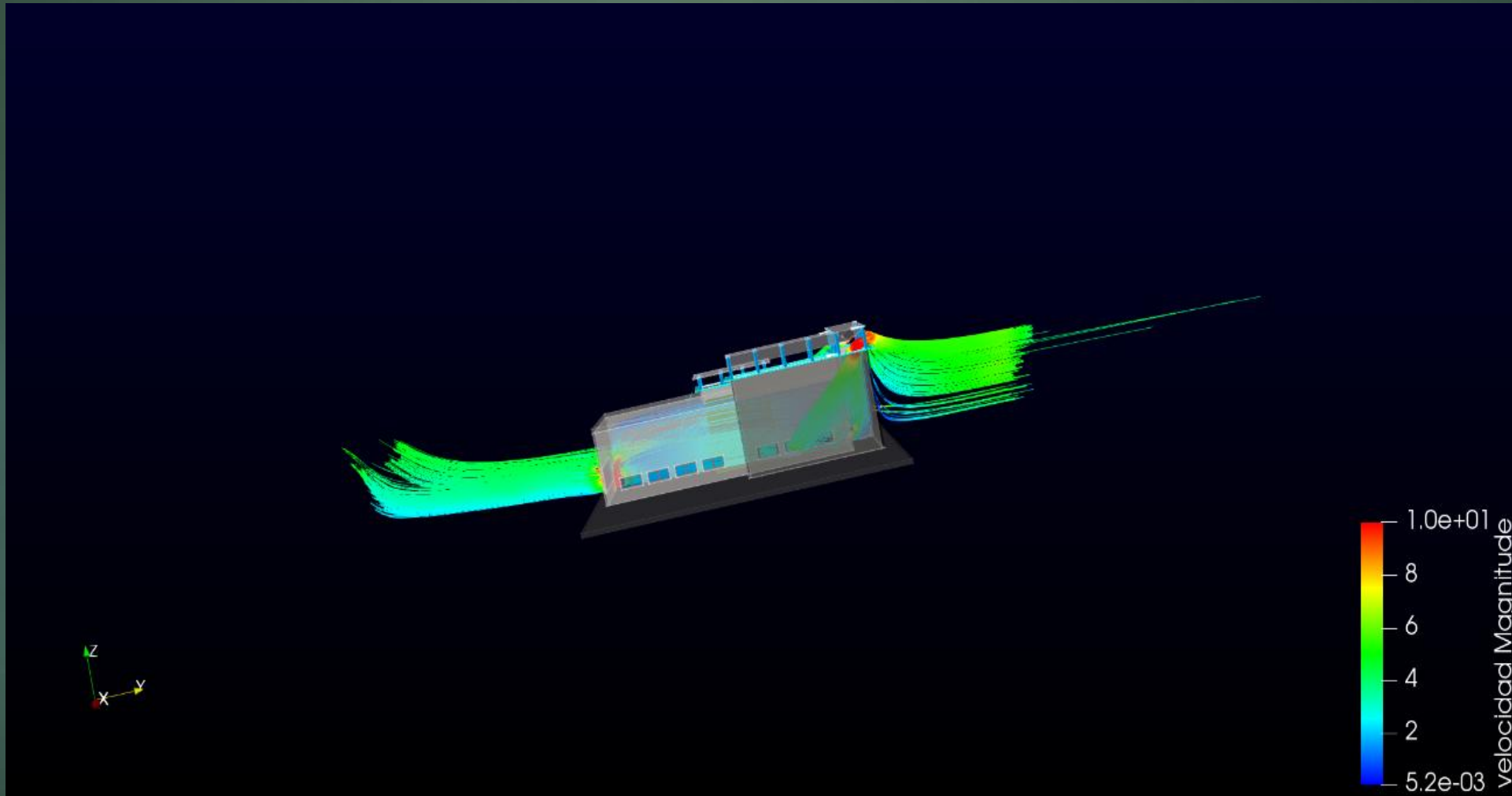
# RESULTADOS

## VELOCIDAD



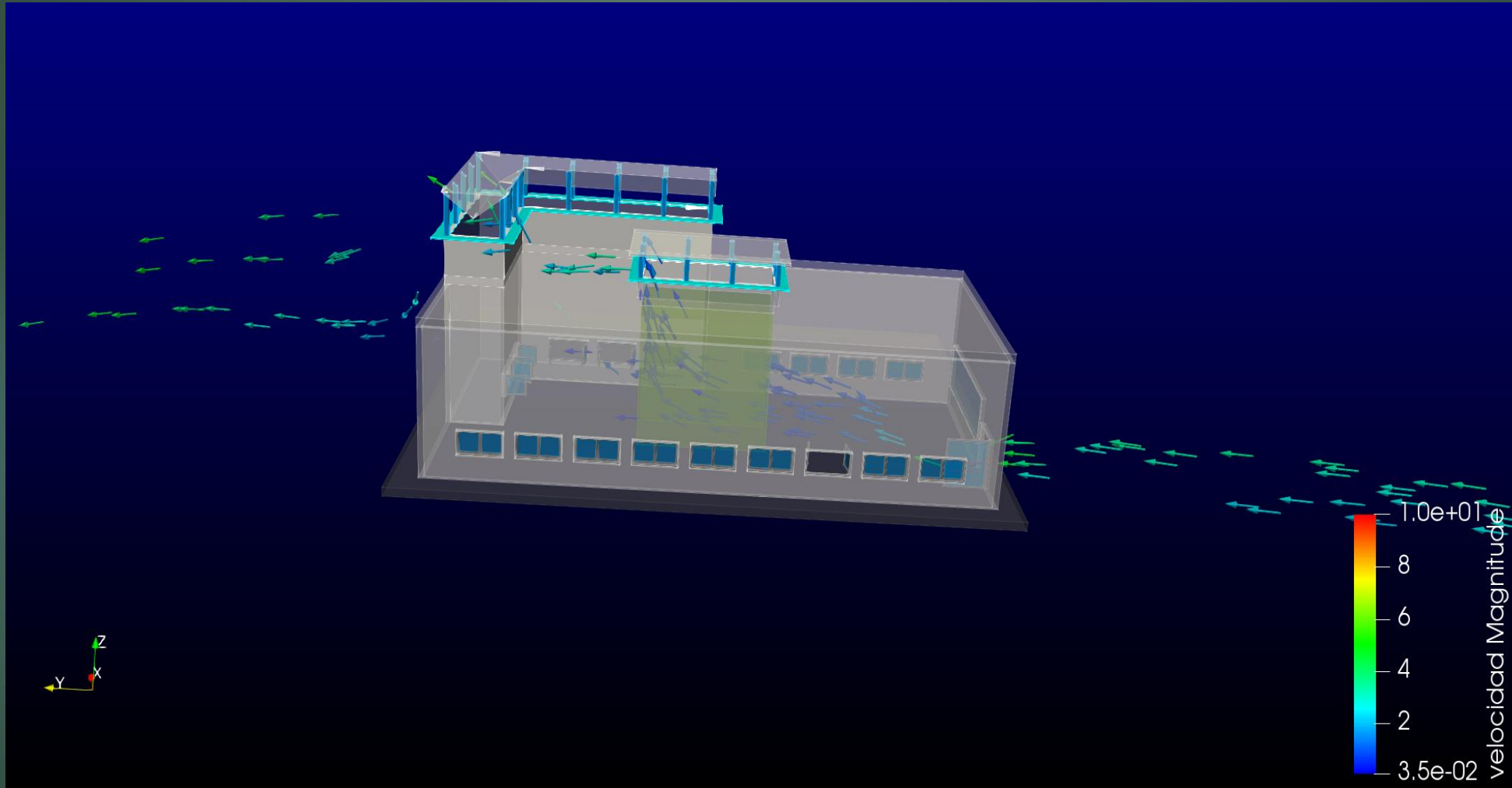
# RESULTADOS

## VELOCIDAD



# RESULTADOS

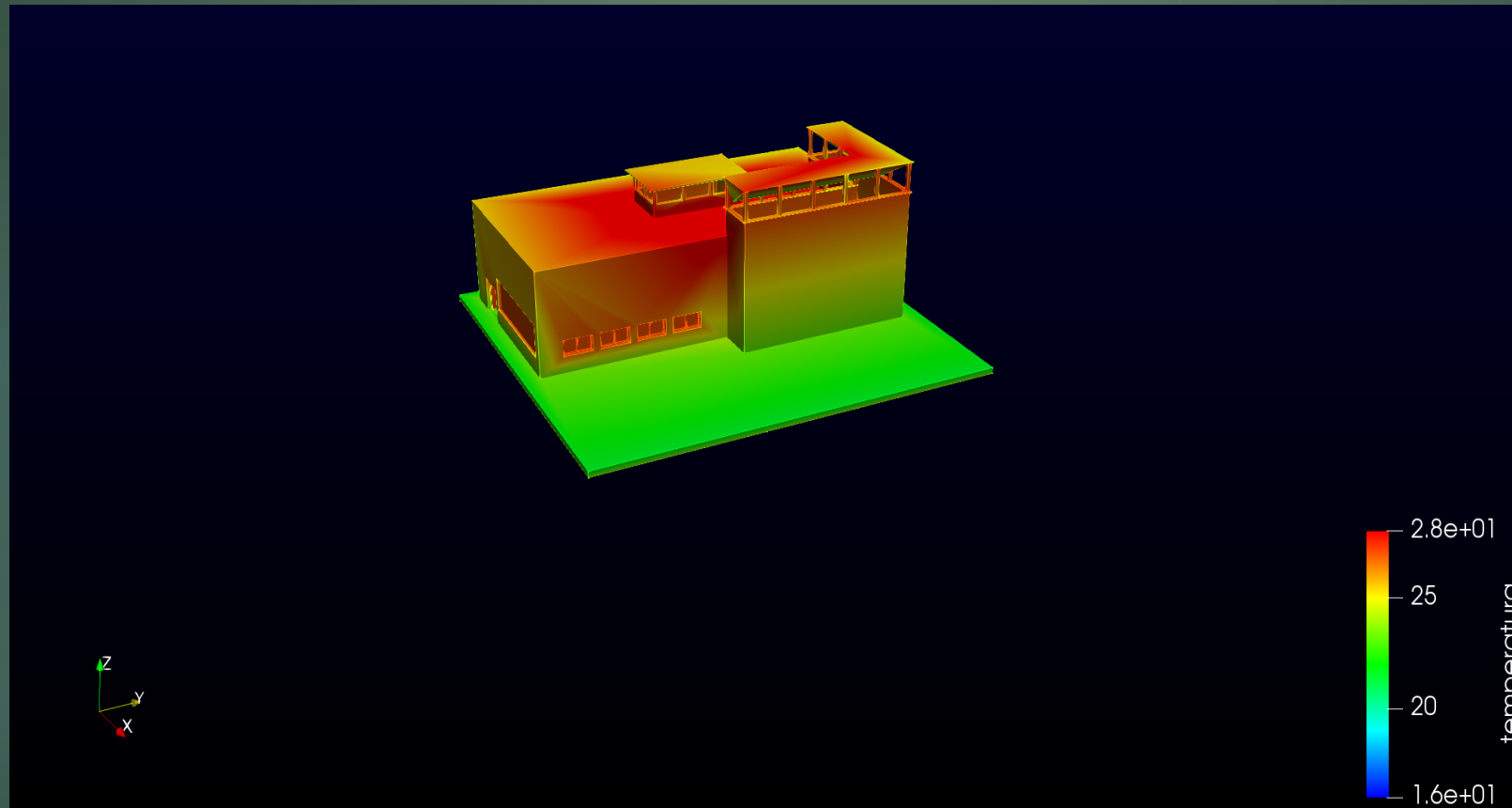
## VELOCIDAD





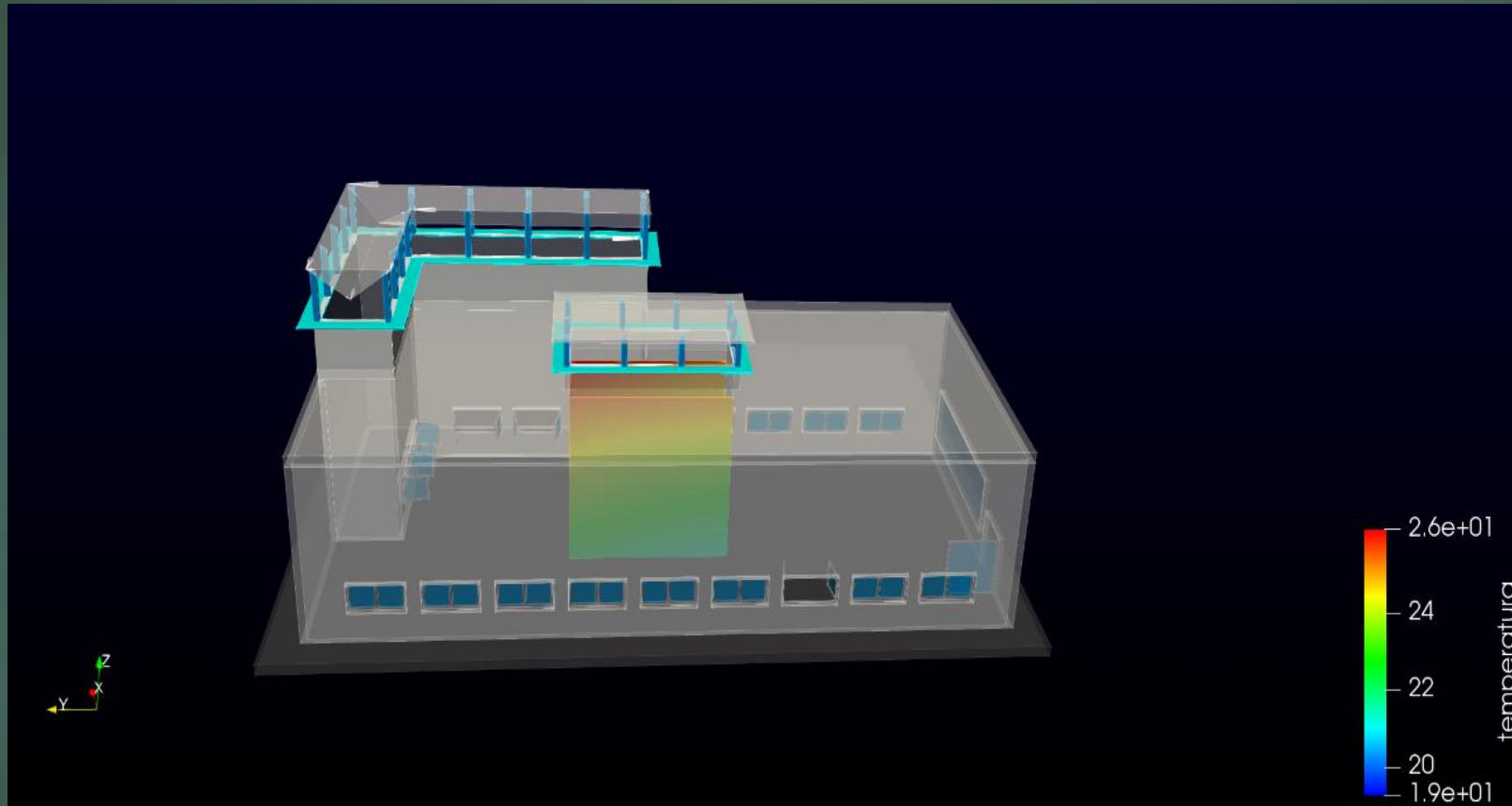
# RESULTADOS

## TEMPERATURA



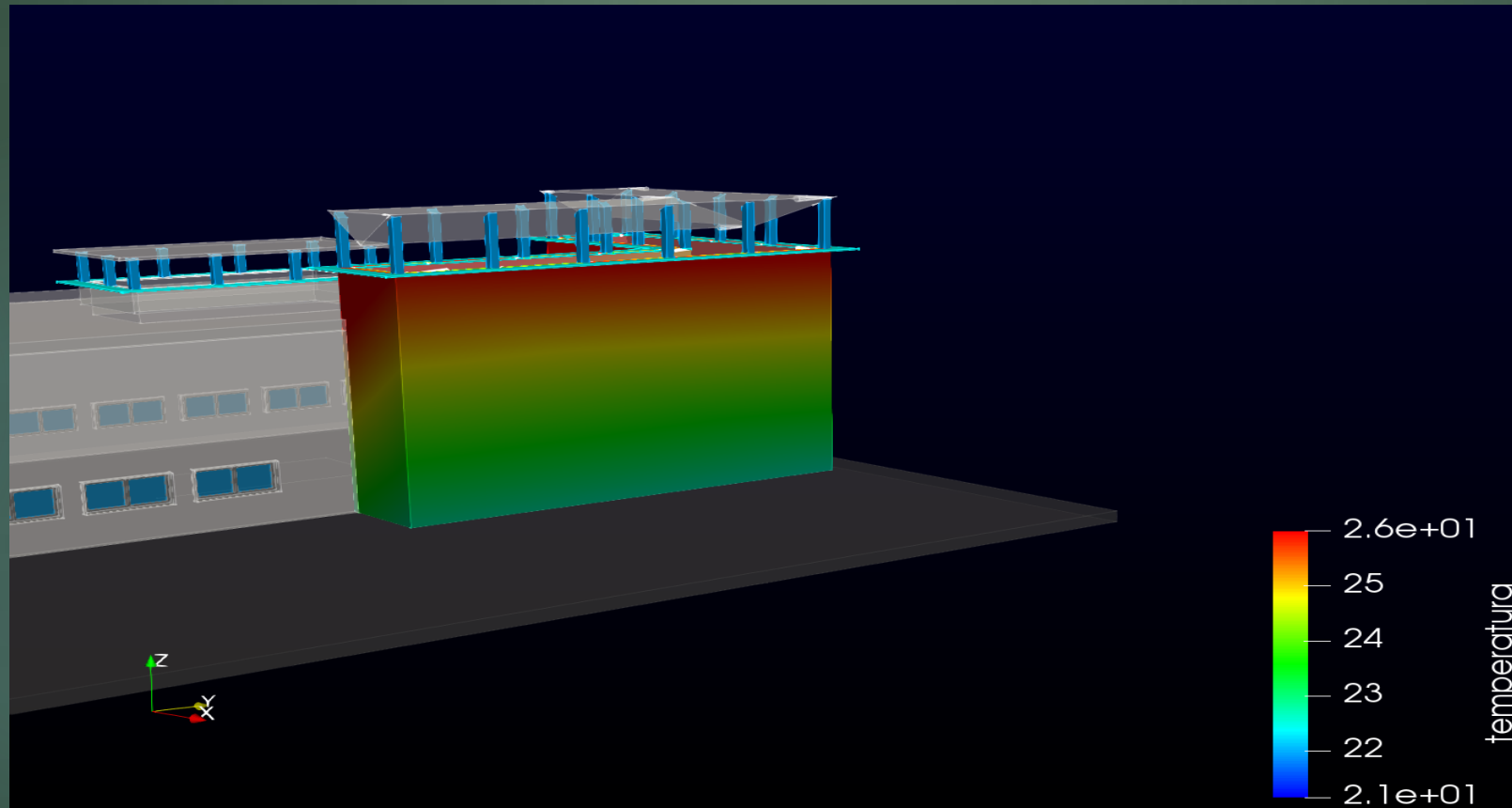
# RESULTADOS

## TEMPERATURA



# RESULTADOS

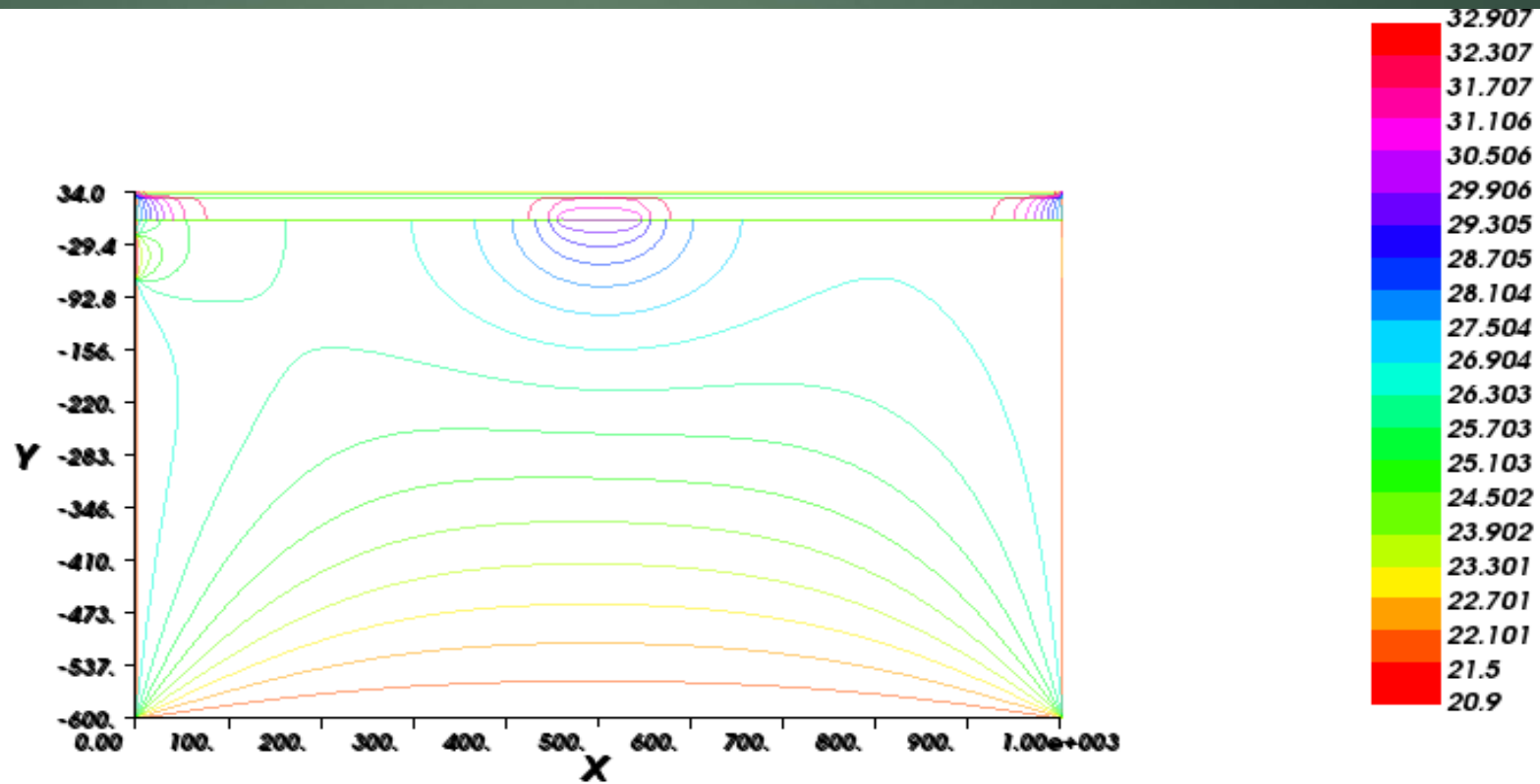
## TEMPERATURA



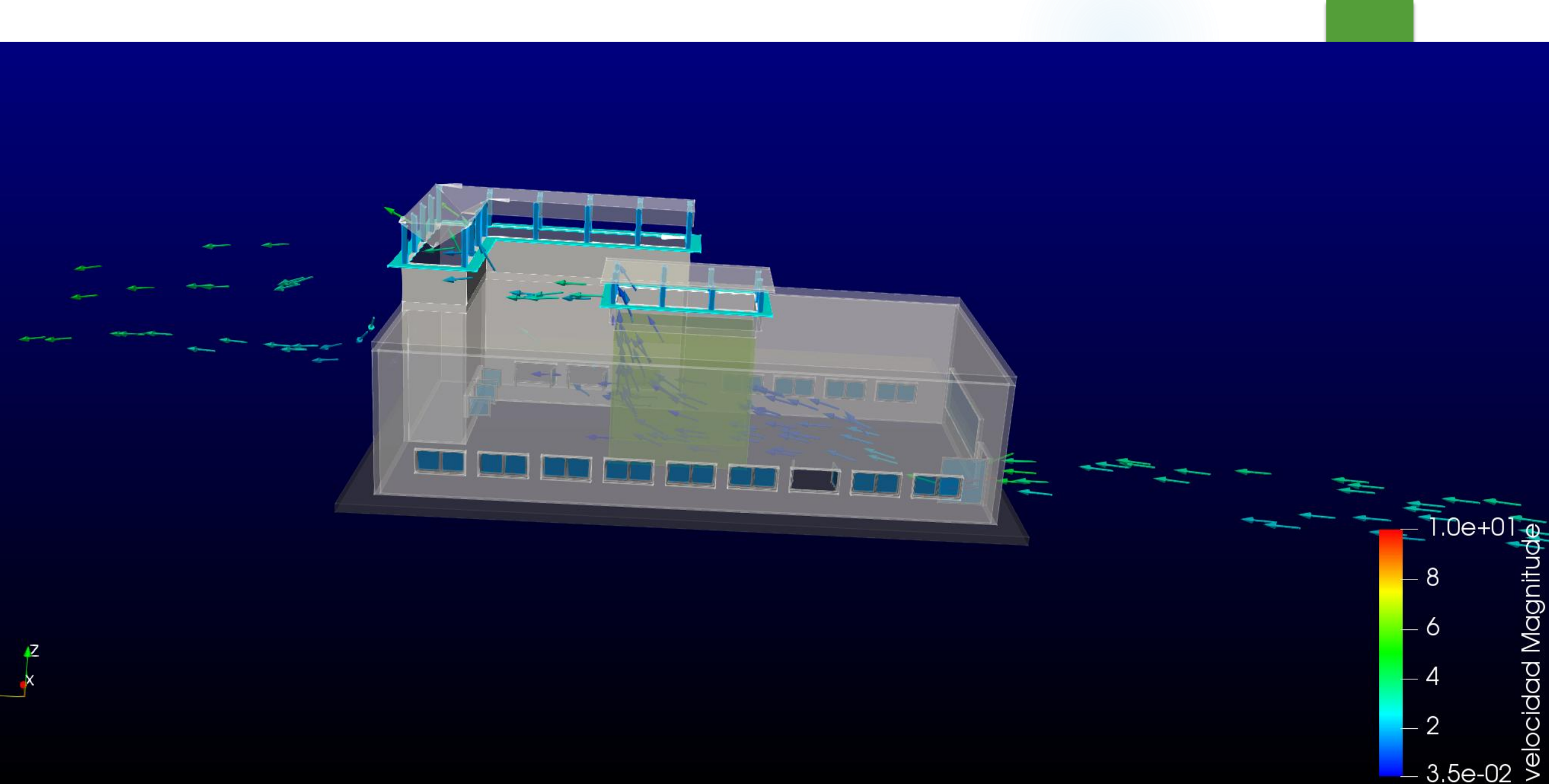
# CONSIDERACIONES DE CÁLCULO

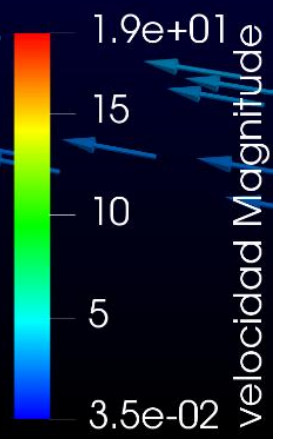
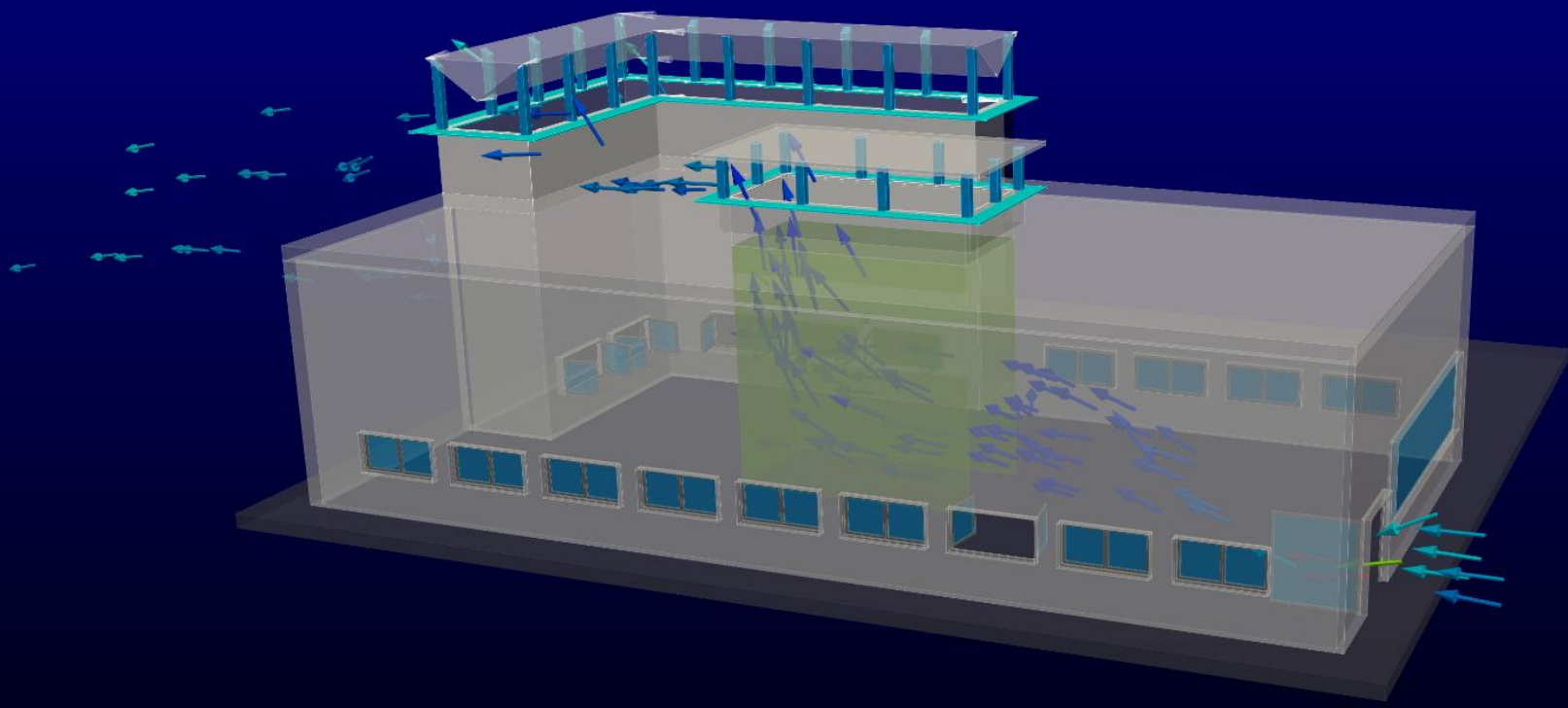
## CÁLCULO DE LA TEMPERATURA DE LA CUBIERTA

RESULTADOS FINALES

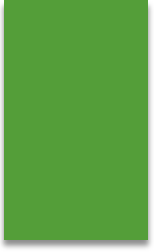


temperatura





velocidad Magnitude

- 
- ▶ WE PROPOSE A NUMERICAL MODEL IMPLEMENTATION WHICH IT INCLUDES COUPLED NAVIER-STOKES EQUATIONS WITH ENERGY EQUATION AND RADIATION.
  - ▶ CONSIDERING BOUYANCY AND ALL HEAT TRANSFER PROCESSES: CONDUCTION, CONVECTION AND RADIATION.
  - ▶ WE APPLY THE MODEL IN A REAL GEOMETRY.
  - ▶ THE INLET AIRFLOW IN THE BUILDING IS A BOUNDARY CONDITION WHICH IS ESTABLISHED FROM DATA OF PREDOMINANT WIND ( TRADE WIND) AND FROM THE CORRESPONDING ATMOSPHERIC STABILITY. WE USE AN ADJUST MODEL NAMED MMC (MATRIX MASS CONSISTENT) (WINTER, 1995)
  - ▶ FOR INSIDE BUILDING WE CONSIDER A DNS (DIRECT NUMERICAL SIMULATION) METHOD (THUS AVOIDING PARAMETRISATIONS AND CALIBRATIONS).



UNIVERSIDAD POLITECNICA DE LAS PALMAS  
ESCUELA TECNICA SUPERIOR DE INGENIEROS INDUSTRIALES

## TESIS DOCTORAL

APLICACION DE LOS METODOS DE QUASI-NEWTON A PROBLEMAS  
NO LINEALES DE TRANSFERENCIA DE CALOR.

Autor: Gabriel Winter Althaus

Director: Luis Ferragut Canals

Las Palmas de Gran Canaria, Octubre 1984



# EDIFICIO PRELIMINAR Y DISEÑO DEL SISTEMA DE CLIMATIZACIÓN

SOFTWARE UTILIZADO PARA EL DISEÑO DEL EDIFICIO



**FreeCAD**

# METODOLOGÍA

PREPARACIÓN DE LA GEOMETRÍA DE ESTUDIO PARA LA SIMULACIÓN.

SOFTWARE UTILIZADO

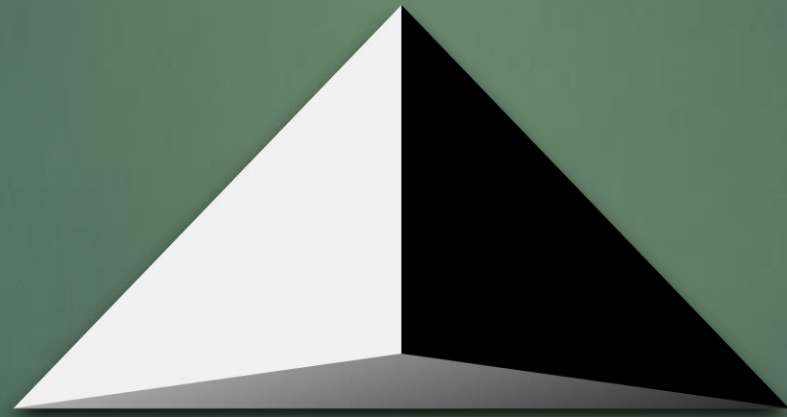


# METODOLOGÍA

EXPORTACION DE LA GEOMETRIA PARA REALIZAR LA MALLA

► SOFTWARE UTILIZADO

**GMSH**



# METODOLOGÍA

SOFTWARE UTILIZADO PARA LA VISUALIZACIÓN DE RESULTADOS



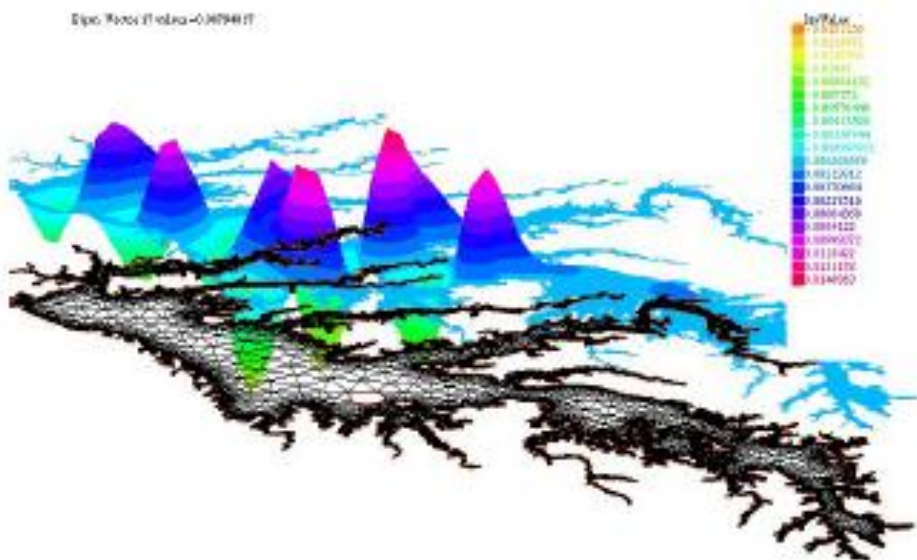
# Freefem++

Third Edition, Version 3.58-1

<http://www.freefem.org/ff++>

F. Hecht

Exo: Poiseuille - 0.009817



S. Auliac, A. Le Hyaric, J. Morice, F. Hecht, K. Ohtsuka, O. Pironneau, *FreeFem++*. Third Edition, Version 3.31-2, 2014.

<http://www.freefem.org/ff++/ftp/freefem++doc.pdf>

F. Hecht, *New development in FreeFem++*. *J. Numer. Math.* **20** (2012), no. 3-4, 251–265, 65Y15.

