Diseño y Optimización de una Cámara de Simulación de Atmósfera Espacial

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Máster Propio Universitario en Simulación Numérica en Ciencia e Ingeniería con COMSOL Multiphysics

Contenido

- Descripción general
- Fundamento teórico
- Posibles soluciones
- Geometría
- Interfaces físicas y condiciones de contorno
- Malla

Contenido

- Estudios
- Resultados
- Elección en base a los resultados
- Simplificación del Modelo
- App

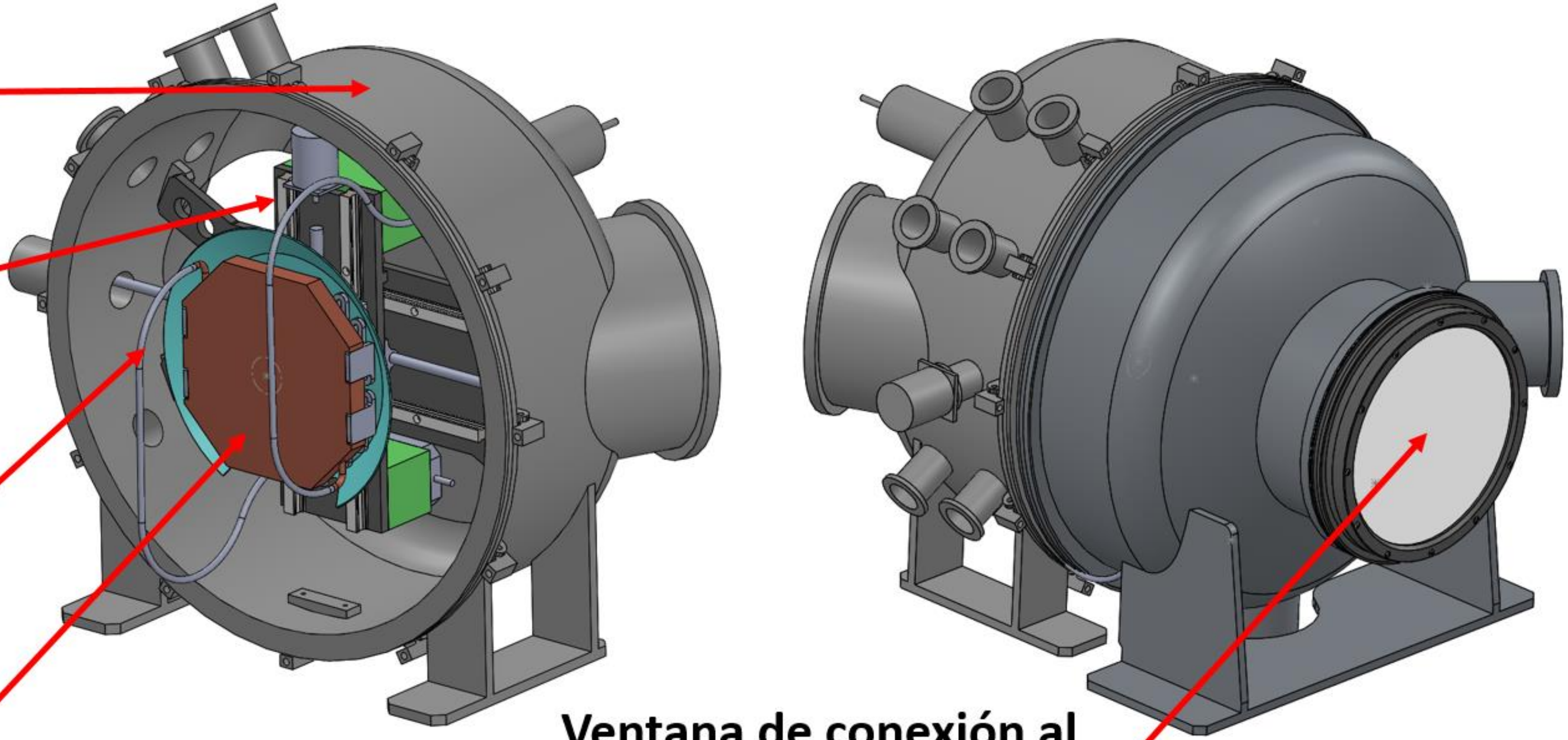
Descripción general

- Simulación de condiciones espaciales
- Temperaturas
- Presión
- Radiación Solar

PROACTIVE R&D

Ejemplo de Cámara de Simulación desarrollada por **PROACTIVE R&D**

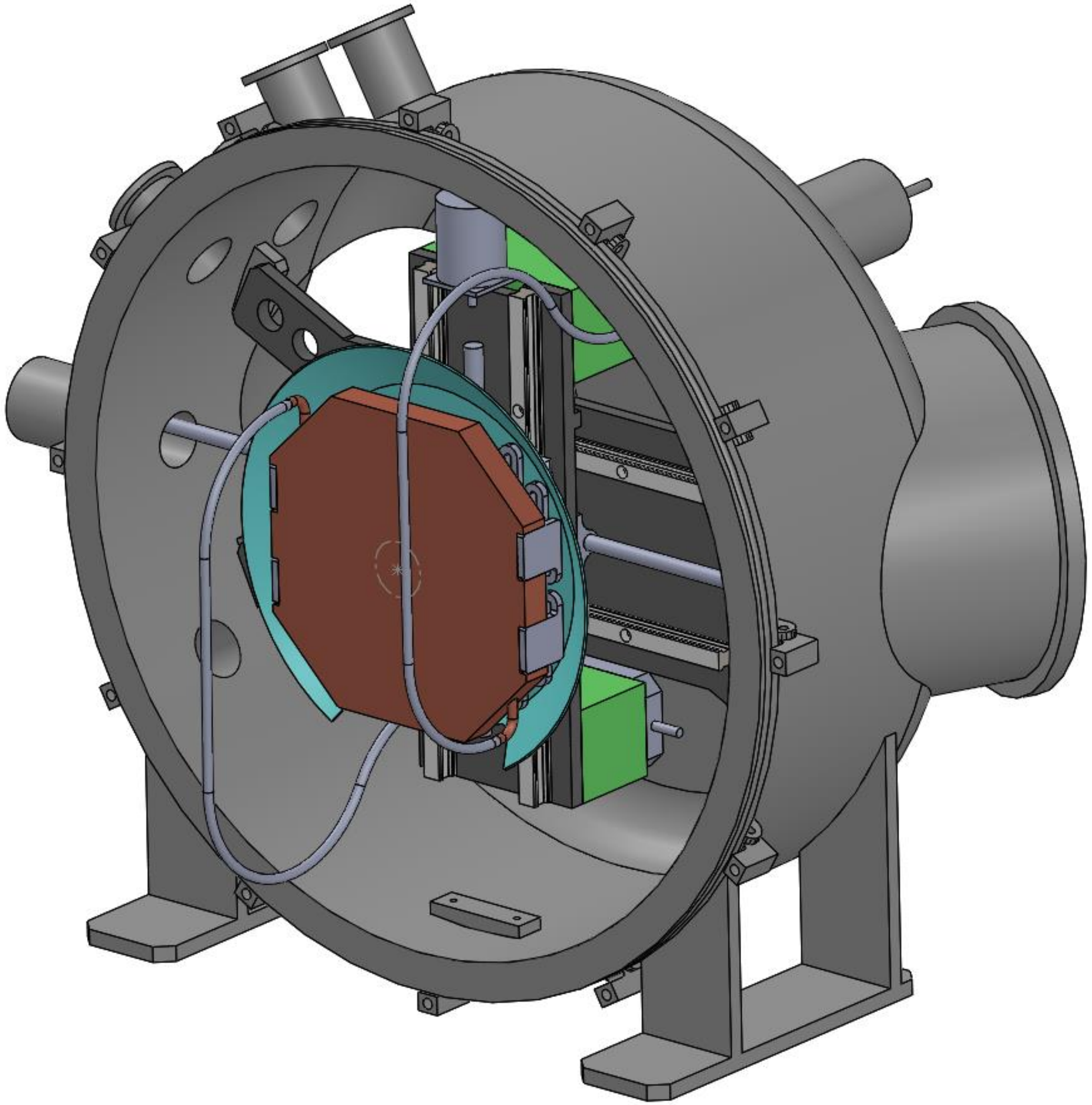
Descripción general



Descripción general

- Alto Vacío **(~10e-6 mbar)**
- Rango de temperaturas controlable entre -150 y 200 ºC
- Sistema de traslación XY del porta muestras, con un rango de movimiento de 200 mm por eje.

El presente trabajo se centra en el estudio del Rango frio de temperaturas.



Fundamento teórico – Transferencia de Calor

- **Convección - Ley de Newton:**

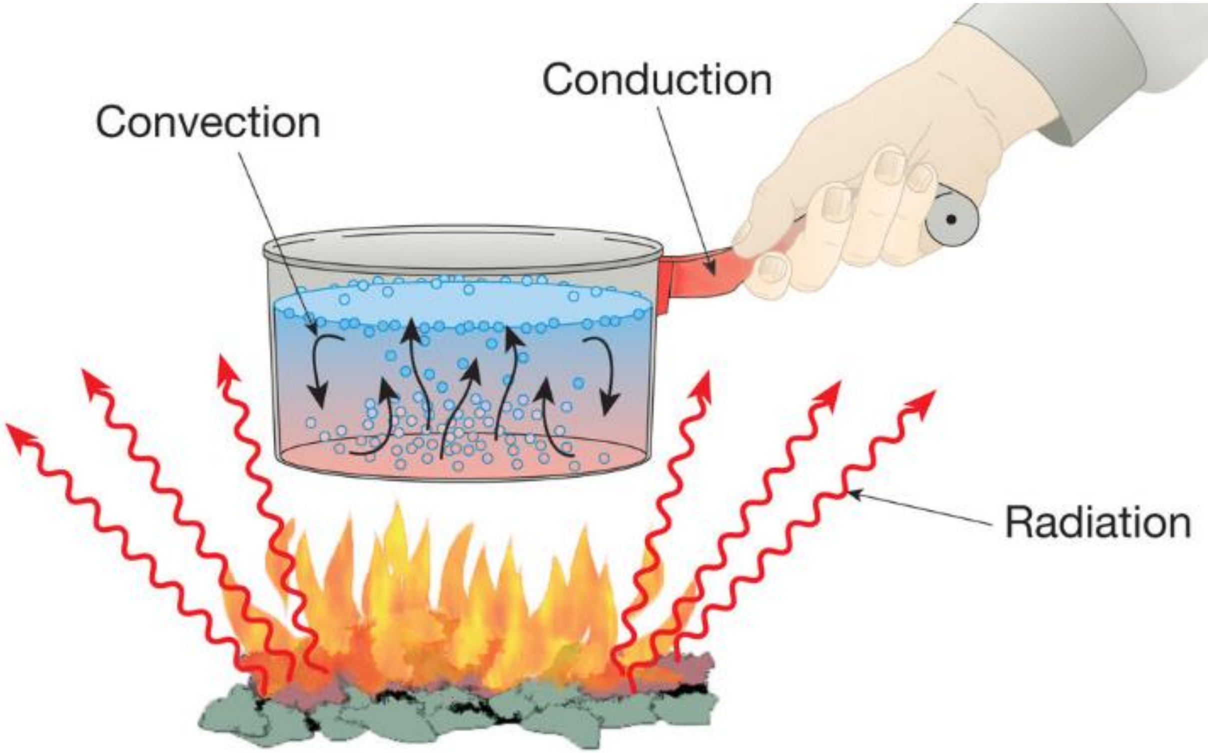
$$\dot{Q} = A \cdot h \cdot (T_w - T_\infty)$$

- **Conducción – Ley de Fourier:**

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{G}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

- **Radiación – Ley de Stefan-Boltzmann:**

$$E_b(T) = \sigma T^4$$



Fundamento teórico – Dinámica de Fluidos

- Número de Reynolds

$$Re = \frac{Vs \cdot Dh}{v} \qquad v = \frac{u}{rho}$$

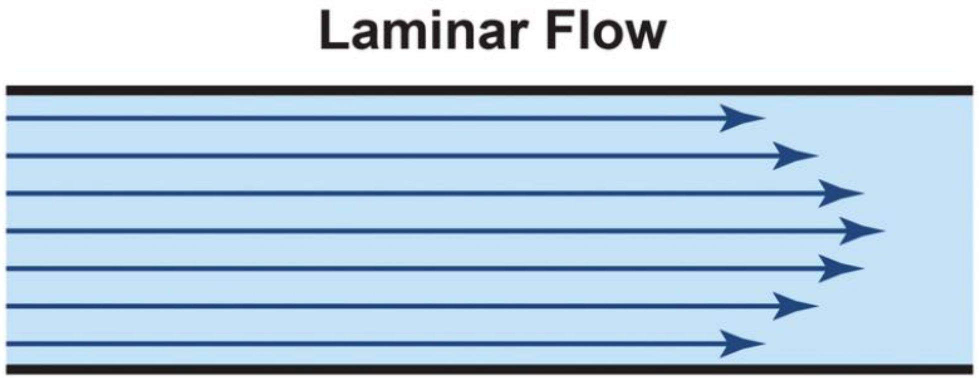
Vs - Velocidad del fluido

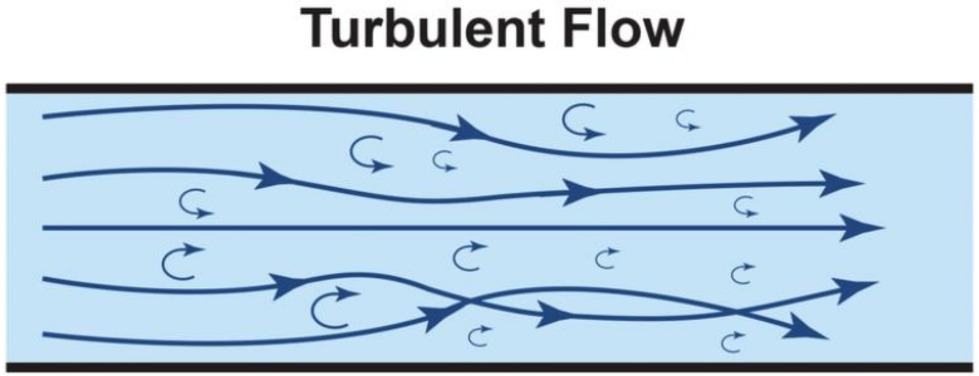
Dh - Diámetro hidráulico del circuito de refrigeración

v - Viscosidad cinemática

u - Viscosidad dinámica

rho - Densidad.

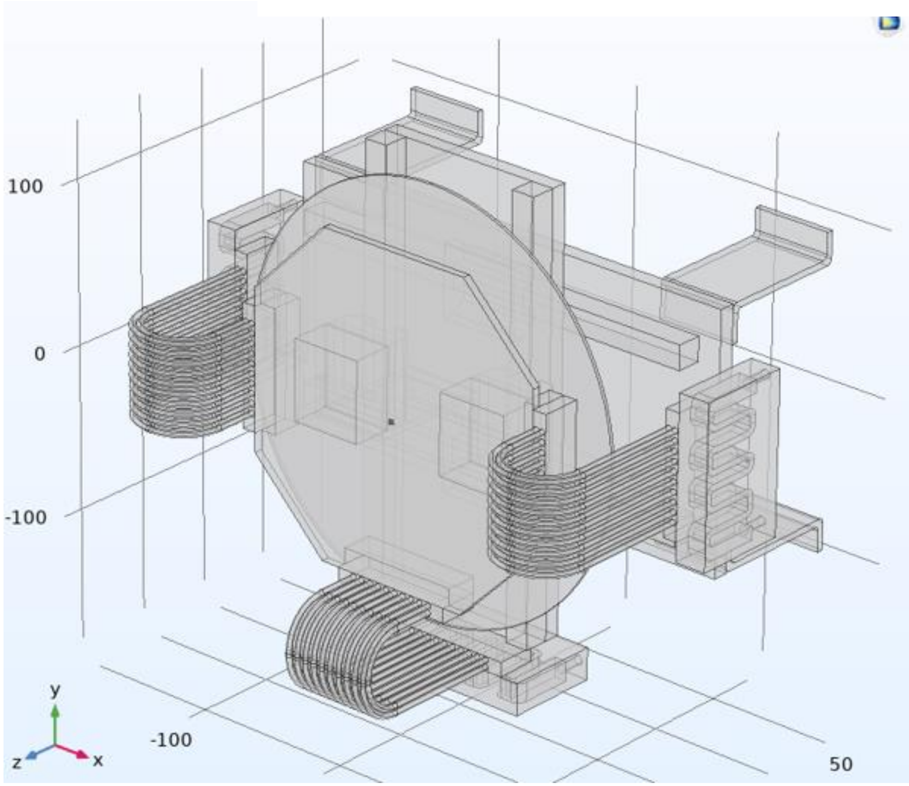




Posibles soluciones – Thermal Links

Ventajas:

- Muy buena conductividad térmica.
- Elementos muy flexibles, ideales para integrarlos junto con el sistema de traslación.
- El circuito de refrigeración permanece fijo, con uniones soldadas entre elementos, ideal para entornos de Alto Vacío.



Desventajas:

- Enfriamientos más lentos.

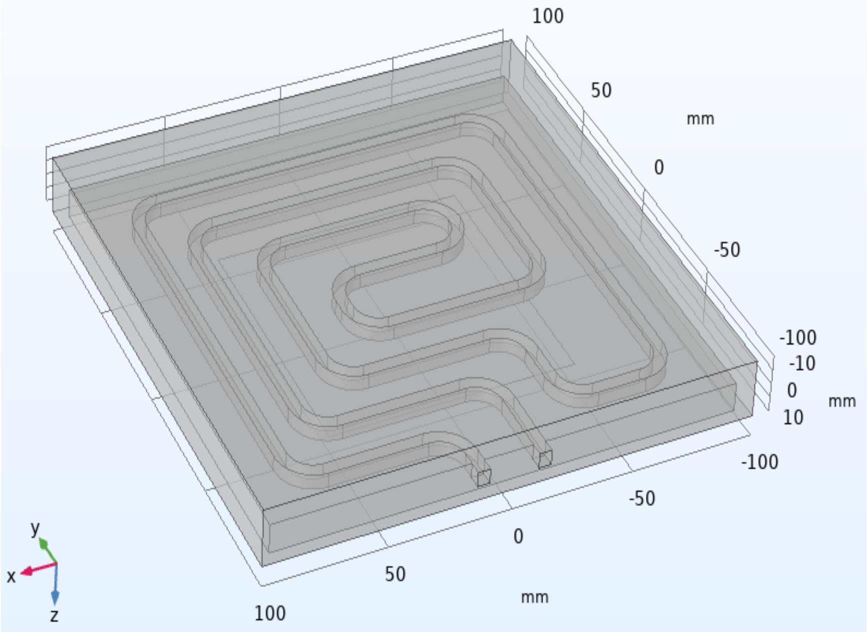
Posibles soluciones – Refrigeración directa

Ventajas:

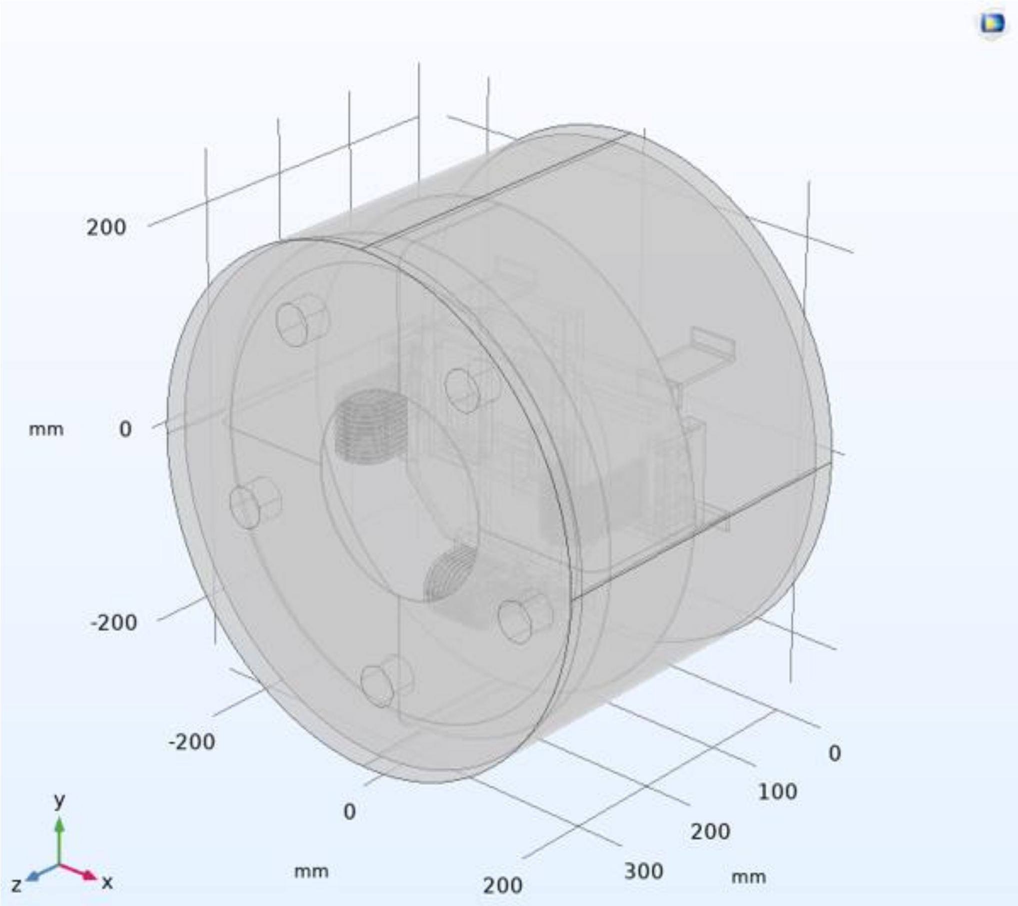
- Enfriamientos más rápidos.

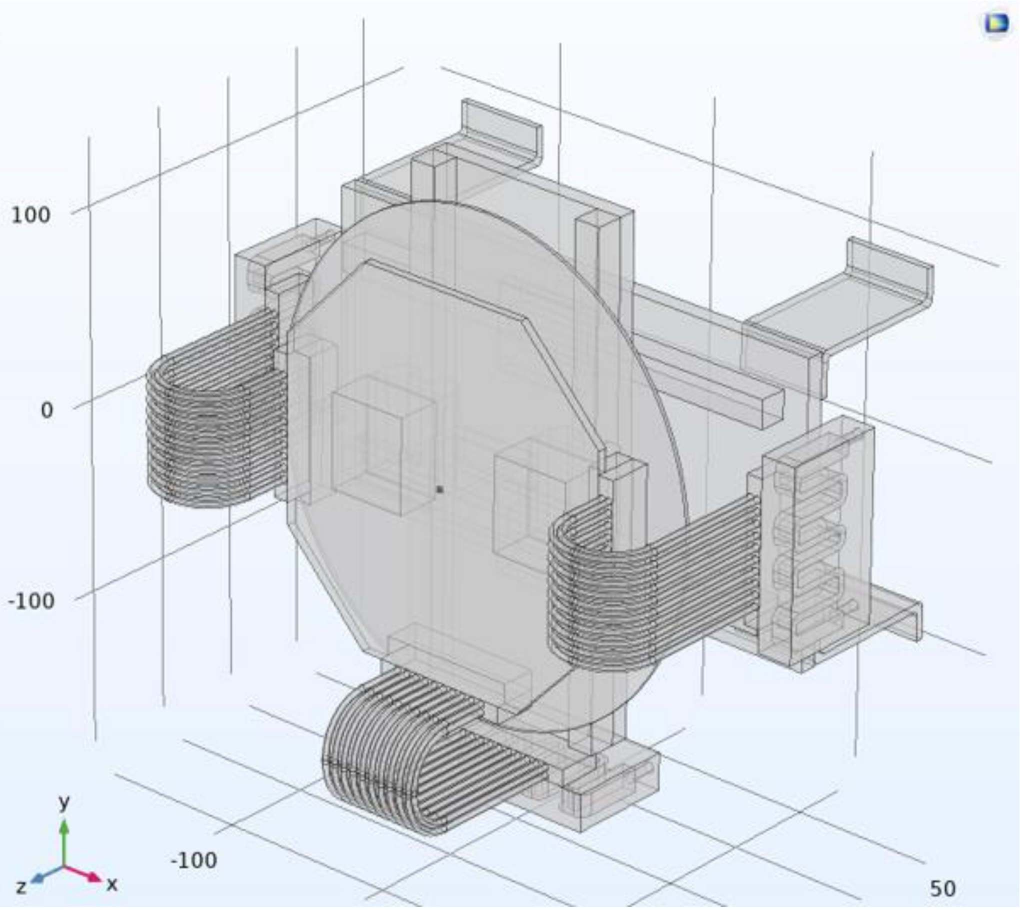
Desventajas:

- Suelen ser más rígidas que los Thermal Links.
- Mayor número de conexiones en el circuito de refrigeración, por lo tanto mayor riesgo de fugas y pérdida de vacío.

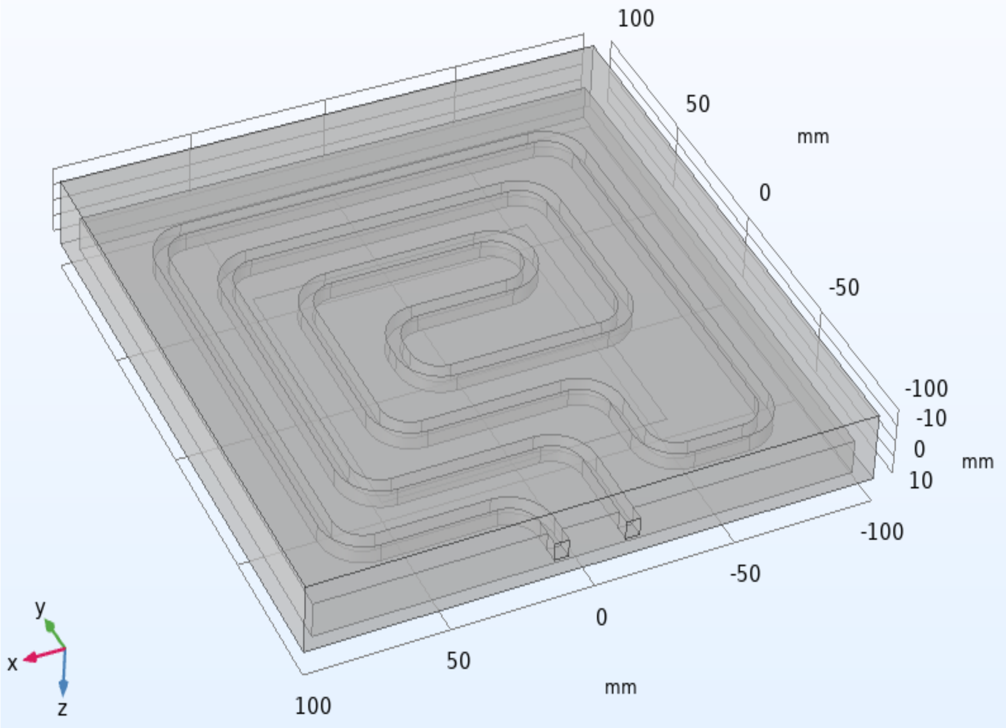


Geometría – Thermal Links

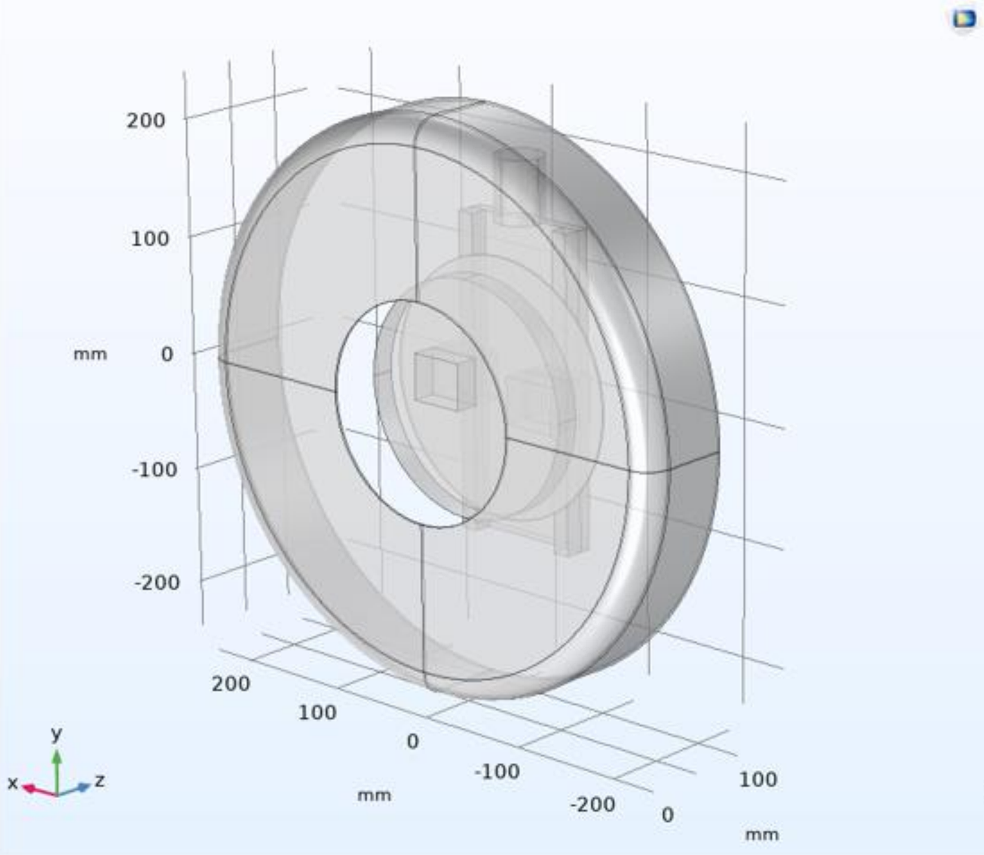


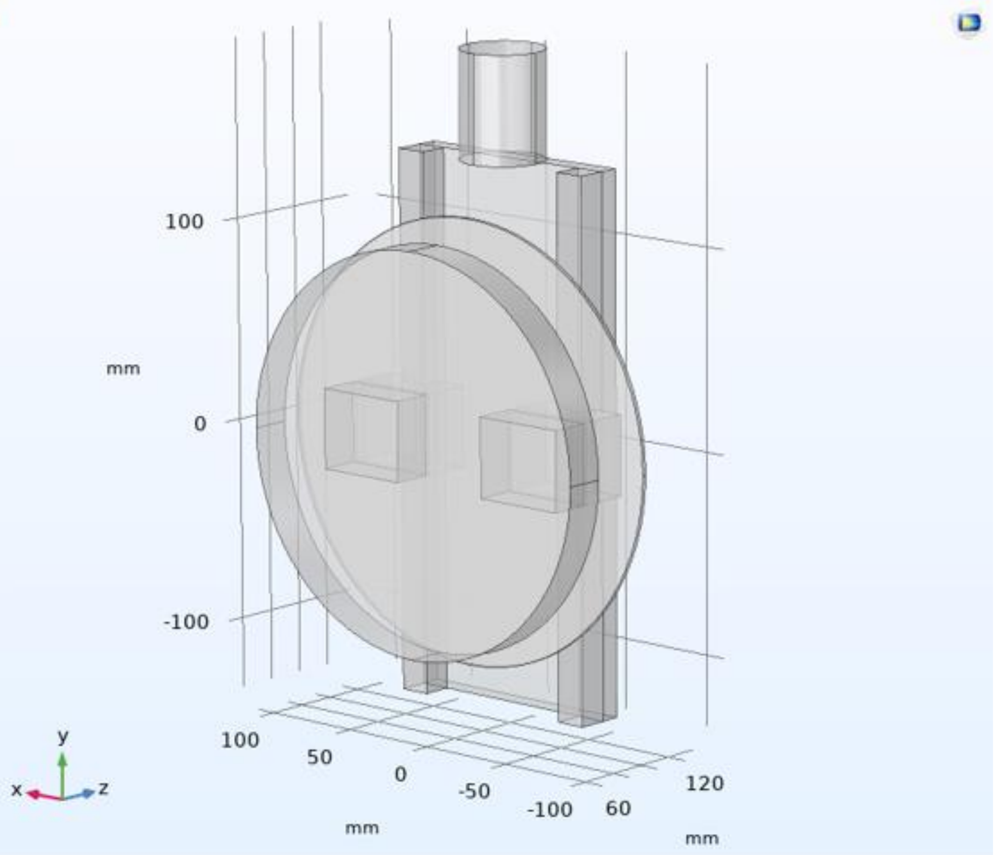


Geometría – Refrigeración directa



Geometría – Estimación de la Radiación Térmica





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Interfaz física – Thermal Links

- Turbulent Flow, k-ε 2 *(spf2)*
  - Fluid Properties 1
  - Initial Values 1
  - Wall 1
  - Inlet 1
  - Outlet 1
  - Equation View
- Heat Transfer in Solids and Fluids *(ht)*
  - Solid 1
  - Fluid 1
  - Initial Values 1
  - Thermal Insulation 1
  - Inflow - Inferior
  - Inflow - Derecha
  - Inflow - Izquierda
  - Inflow 2
  - Outflow 1
  - Vessel Heat Flux
  - Equation View
- Surface-to-Surface Radiation *(rad)*
  - Diffuse Surface 1
  - Initial Values 1
  - Equation View
- Multiphysics
  - Nonisothermal Flow 1 *(nitf1)*
  - Heat Transfer with Surface-to-Surface Radiation 1 *(htrad1)*

Turbulent Flow Settings

Physical Model

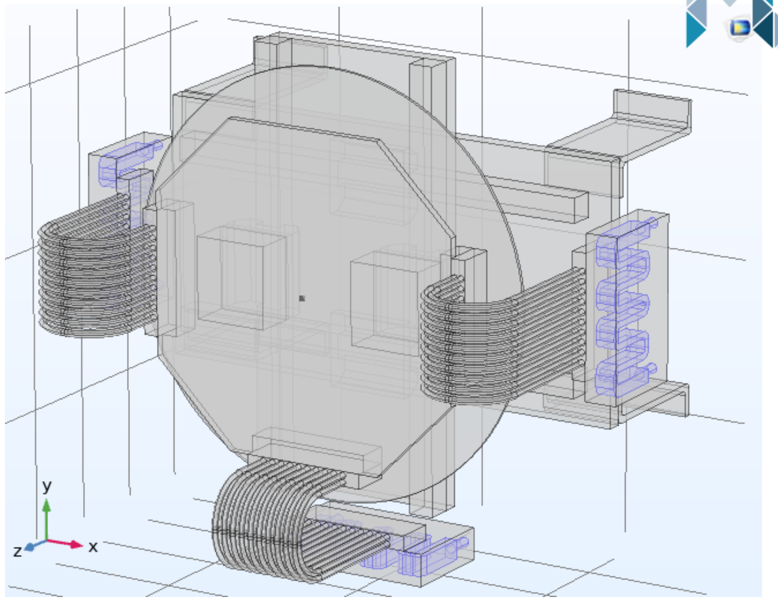
Compressibility: Weakly compressible flow

Turbulence

Turbulence model type: RANS

Turbulence model: k-ε

Wall treatment: Wall functions



Inlet Settings

Boundary Condition

Fully developed flow

Fully Developed Flow

- (●) Average velocity
- ( ) Flow rate
- ( ) Average pressure

Average velocity:

U_{av} V_in m/s

V_in = 75 m/s

Interfaz física – Thermal Links

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  - Inflow - Inferior
  - Inflow - Derecha
  - Inflow - Izquierda
  - Inflow 2
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  - Equation View
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  - Diffuse Surface 1
  - Initial Values 1
  - Equation View
- Multiphysics
  - Nonisothermal Flow 1 *(nitf1)*
  - Heat Transfer with Surface-to-Surface Radiation 1 *(htrad1)*

Inflow Inferior Settings

Upstream Properties

Upstream temperature:

T_{ustr} User defined

T_Fluid K

Inflow Derecha Settings

Upstream Properties

Upstream temperature:

T_{ustr} User defined

T_Fluid + T_Lost_Refr K

Inflow Izquierda Settings

Upstream Properties

Upstream temperature:

T_{ustr} User defined

T_Fluid + 2*T_Lost_Refr K

Vessel Heat Flux Settings

Heat Flux

○ General inward heat flux

◉ Convective heat flux

$q_0 = h \cdot (T_{ext} - T)$

Heat transfer coefficient:

External natural convection

Vertical wall

Wall height:

L 0.5 m

Fluid:

Air

Absolute pressure:

p_A User defined

1[atm] Pa

External temperature:

T_{ext} User defined

293.15[K] K

○ Heat rate

$q_0 = \frac{P_0}{A}$

Interfaz física – Thermal Links

- Turbulent Flow, k-ε 2 *(spf2)*
  - Fluid Properties 1
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- Heat Transfer in Solids and Fluids *(ht)*
  - Solid 1
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  - Equation View
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  - Diffuse Surface 1
  - Initial Values 1
  - Equation View
- Multiphysics
  - Nonisothermal Flow 1 *(nitf1)*
  - Heat Transfer with Surface-to-Surface Radiation 1 *(htrad1)*

Diffuse Surface Settings

Ambient

Ambient temperature

☐ Define ambient temperature on each side

Ambient temperature:

T_{amb} User defined

293.15[K] K

Ambient emissivity

☐ Define ambient emissivity on each side

Ambient emissivity:

Blackbody

Surface Emissivity

☑ Define surface emissivity on each side

Surface emissivity, upside:

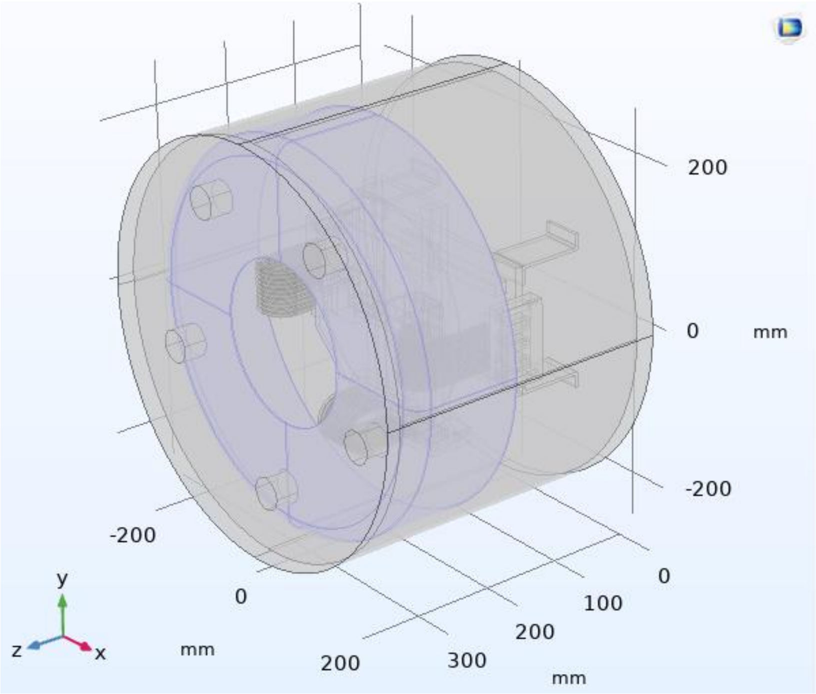
Boundary material

ε_u From material

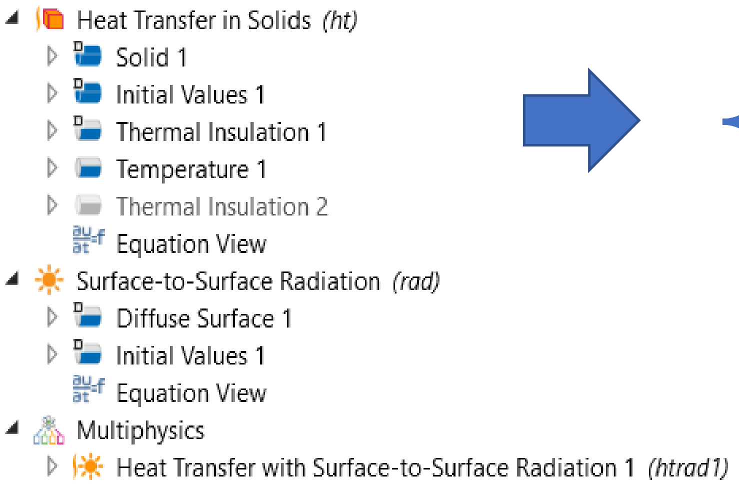
Surface emissivity, downside:

Boundary material

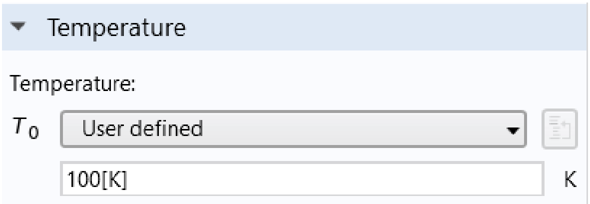
ε_d From material

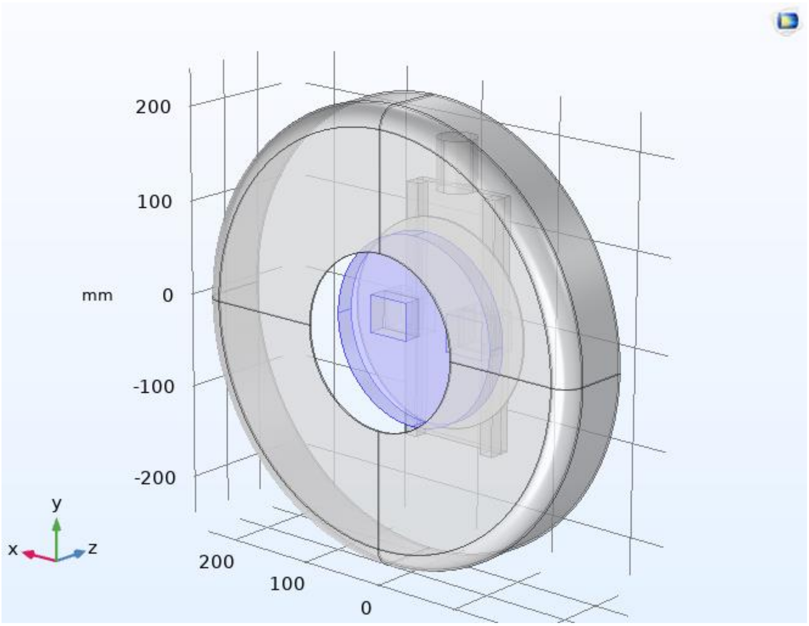


Interfaz física – Estimación de la Radiación Térmica



Temperature Settings





Interfaz física – Estimación de la Radiación Térmica

- Heat Transfer in Solids *(ht)*
  - Solid 1
  - Initial Values 1
  - Thermal Insulation 1
  - Temperature 1
  - Thermal Insulation 2
  - Equation View
- Surface-to-Surface Radiation *(rad)*
  - Diffuse Surface 1
  - Initial Values 1
  - Equation View
- Multiphysics
  - Heat Transfer with Surface-to-Surface Radiation 1 *(htrad1)*

Difuse Surface Settings

Ambient

Ambient temperature

☐ Define ambient temperature on each side

Ambient temperature:

T_{amb} User defined

293.15[K] K

Ambient emissivity

☐ Define ambient emissivity on each side

Ambient emissivity:

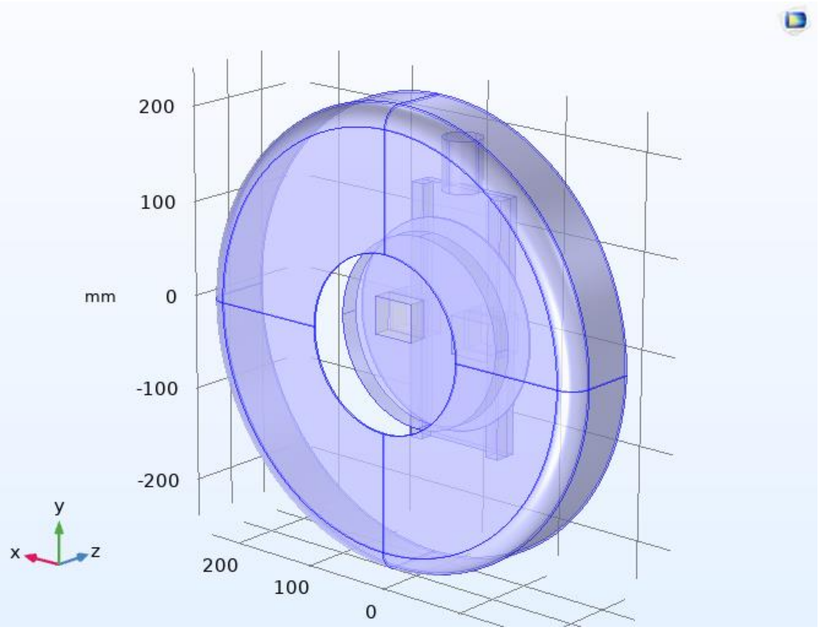
Blackbody

Surface Emissivity

☐ Define surface emissivity on each side

Surface emissivity:

ε From material



Interfaz física – Refrigeración directa

- Turbulent Flow, k-ω *(spf)*
  - Fluid Properties 1
  - Initial Values 1
  - Wall 1
  - Inlet 1
  - Outlet 1
  - Equation View
- Heat Transfer in Solids and Fluids *(ht)*
  - Solid 1
  - Fluid 1
  - Initial Values 1
  - Thermal Insulation 1
  - Inflow - Initial Conditions
  - Inflow - T input
  - Outflow 1
  - Resistors - Heat Flux
  - Radiation - Heat Flux
  - Thermal Insulation 2
  - PCB - Heat Flux
  - Equation View
- Heat Transfer in Solids 2 *(ht2)*
  - Solid 1
  - Initial Values 1
  - Thermal Insulation 1
  - Resistors - Heat Flux
  - Radiation - Heat Flux
  - Thermal Insulation 2
  - Convective Heat Flux - Ref Power 35 m/s
  - Convective Heat Flux - Ref Power 55 m/s
  - PCB Heat Flux
  - Equation View
- Multiphysics
  - Nonisothermal Flow 1 *(nitf1)*

Turbulent Flow Settings

Physical Model

Compressibility:

Weakly compressible flow

Turbulence

Turbulence model type:

RANS

Turbulence model:

k-ω

Wall treatment:

Wall functions

Wall Settings

Boundary Condition

Wall condition:

No slip

☑ Apply wall roughness

Roughness model:

Sand roughness

Equivalent sand roughness height:

k_{seq} 0.0015[mm] m

Inlet Settings

Boundary Condition

Fully developed flow

Fully Developed Flow

◉ Average velocity

○ Flow rate

○ Average pressure

Average velocity:

U_{av} V_in m/s

V_in = 15 – 75 m/s

Interfaz física – Refrigeración directa

- Turbulent Flow, k-ω *(spf)*
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  - Wall 1
  - Inlet 1
  - Outlet 1
  - Equation View
- Heat Transfer in Solids and Fluids *(ht)*
  - Solid 1
  - Fluid 1
  - Initial Values 1
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  - Inflow - Initial Conditions
  - Inflow - T input
  - Outflow 1
  - Resistors - Heat Flux
  - Radiation - Heat Flux
  - Thermal Insulation 2
  - PCB - Heat Flux
  - Equation View
- Heat Transfer in Solids 2 *(ht2)*
  - Solid 1
  - Initial Values 1
  - Thermal Insulation 1
  - Resistors - Heat Flux
  - Radiation - Heat Flux
  - Thermal Insulation 2
  - Convective Heat Flux - Ref Power 35 m/s
  - Convective Heat Flux - Ref Power 55 m/s
  - PCB Heat Flux
  - Equation View
- Multiphysics
  - Nonisothermal Flow 1 *(nitf1)*

Inflow Settings

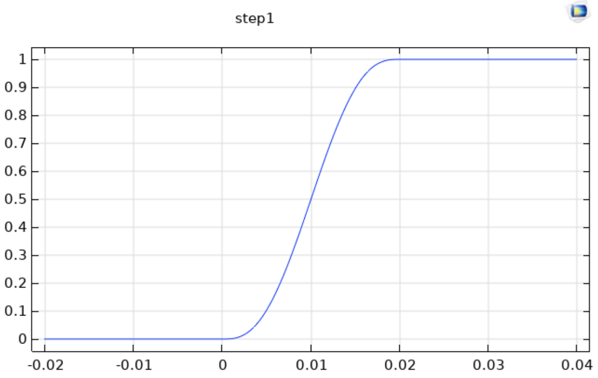
Upstream Properties

Upstream temperature:

T_{ustr} User defined

T_in*step1(t[1/h])+T_amb*(1-step1(t[1/h])) K

☐ Specify upstream absolute pressure



Resistors - Heat Flux Settings

Heat Flux

○ General inward heat flux

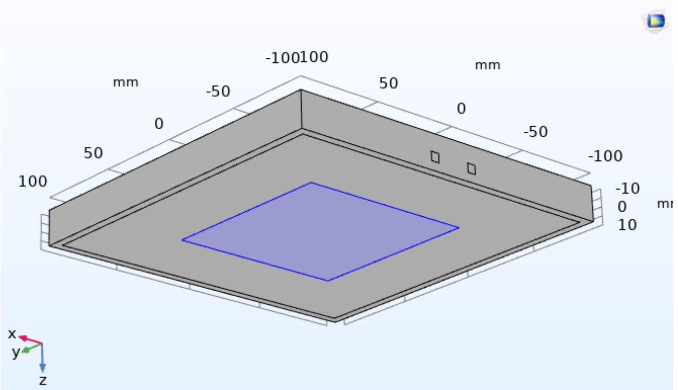
○ Convective heat flux

$q_0 = h \cdot (T_{ext} - T)$

◉ Heat rate

$q_0 = \frac{P_0}{A}$

P_0 P_Res*step1(t[1/h]) W



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  - PCB - Heat Flux
  - Equation View
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  - Initial Values 1
  - Thermal Insulation 1
  - Resistors - Heat Flux
  - Radiation - Heat Flux
  - Thermal Insulation 2
  - Convective Heat Flux - Ref Power 35 m/s
  - Convective Heat Flux - Ref Power 55 m/s
  - PCB Heat Flux
  - Equation View
- Multiphysics
  - Nonisothermal Flow 1 *(nitf1)*

Radiation Heat Flux Settings

Heat Flux

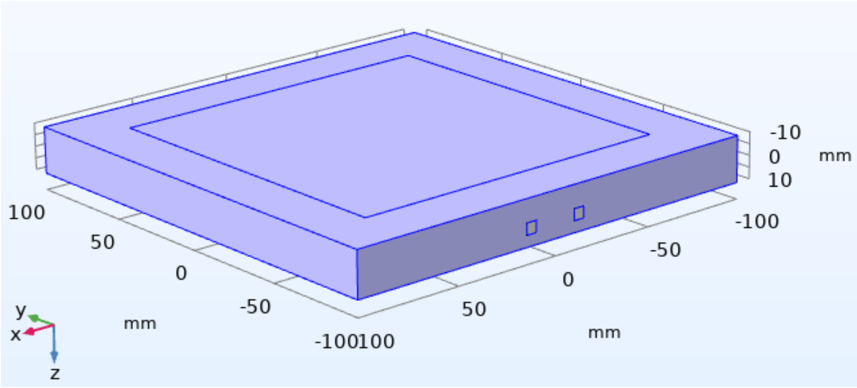
- ○ General inward heat flux
- ○ Convective heat flux

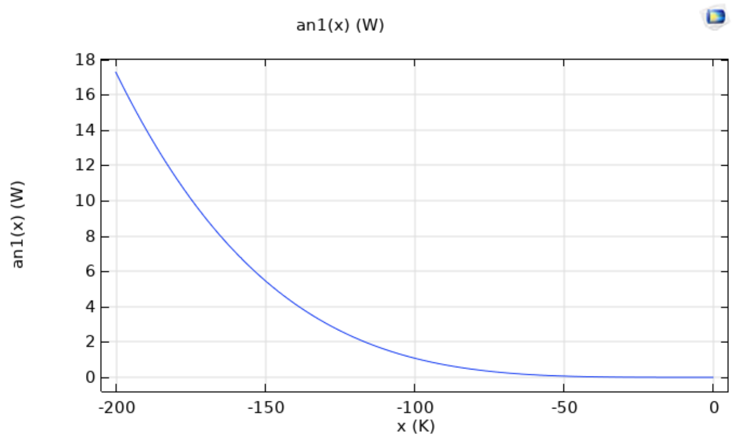
$q_0 = h \cdot (T_{ext} - T)$

- ● Heat rate

$q_0 = \frac{P_0}{A}$

P_0: an1(T-T_amb) W





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- Heat Transfer in Solids and Fluids *(ht)*
  - Solid 1
  - Fluid 1
  - Initial Values 1
  - Thermal Insulation 1
  - Inflow - Initial Conditions
  - Inflow - T input
  - Outflow 1
  - Resistors - Heat Flux
  - Radiation - Heat Flux
  - Thermal Insulation 2
  - PCB - Heat Flux
  - Equation View
- Heat Transfer in Solids 2 *(ht2)*
  - Solid 1
  - Initial Values 1
  - Thermal Insulation 1
  - Resistors - Heat Flux
  - Radiation - Heat Flux
  - Thermal Insulation 2
  - Convective Heat Flux - Ref Power 35 m/s
  - Convective Heat Flux - Ref Power 55 m/s
  - PCB Heat Flux
  - Equation View
- Multiphysics
  - Nonisothermal Flow 1 *(nitf1)*

PCB Heat Flux Settings

Heat Flux

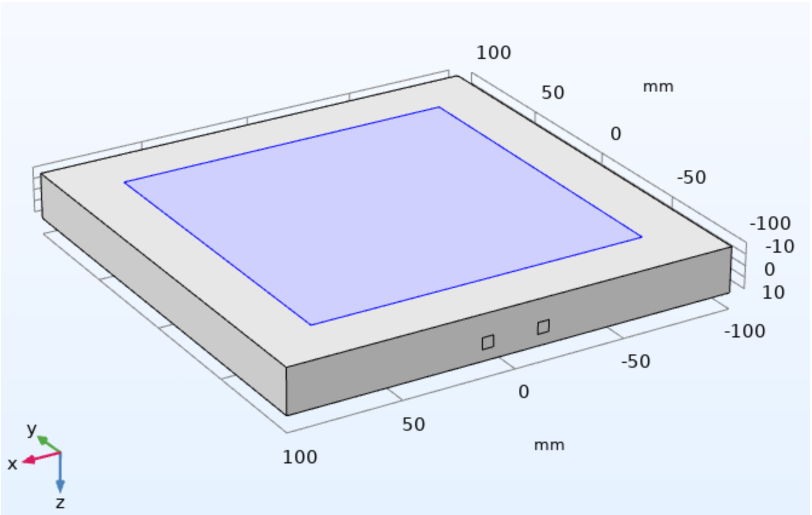
- ○ General inward heat flux
- ○ Convective heat flux

$q_0 = h \cdot (T_{ext} - T)$

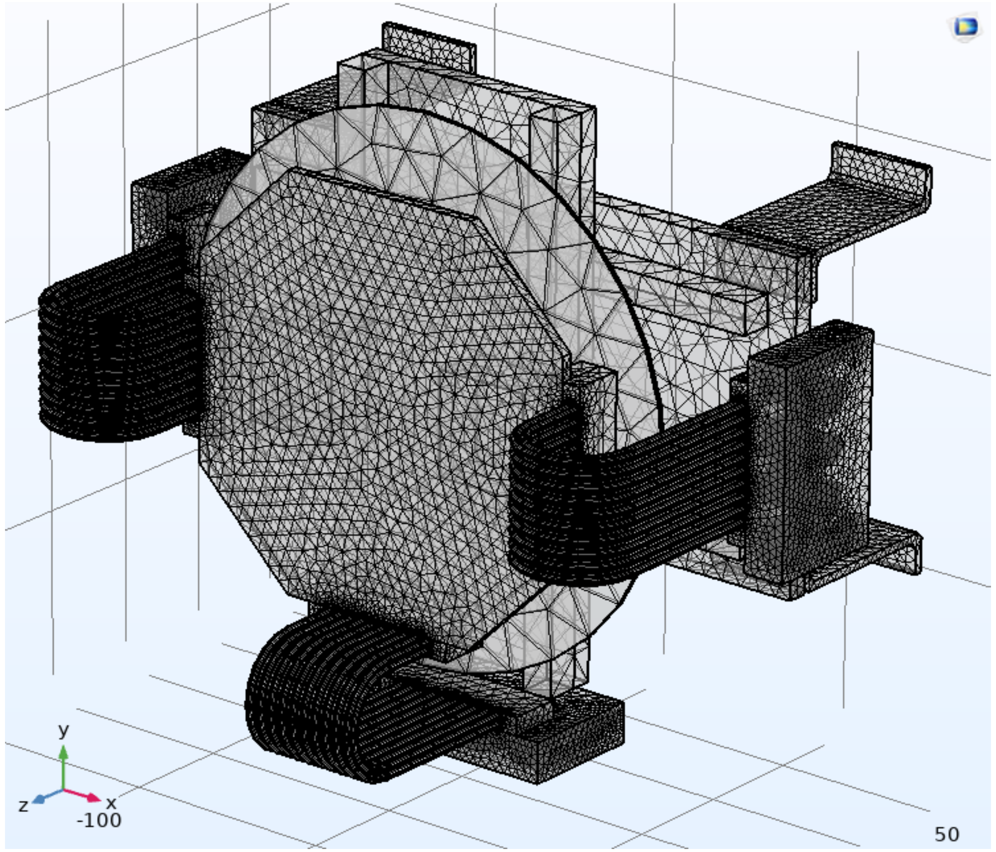
- ◉ Heat rate

$q_0 = \frac{P_0}{A}$

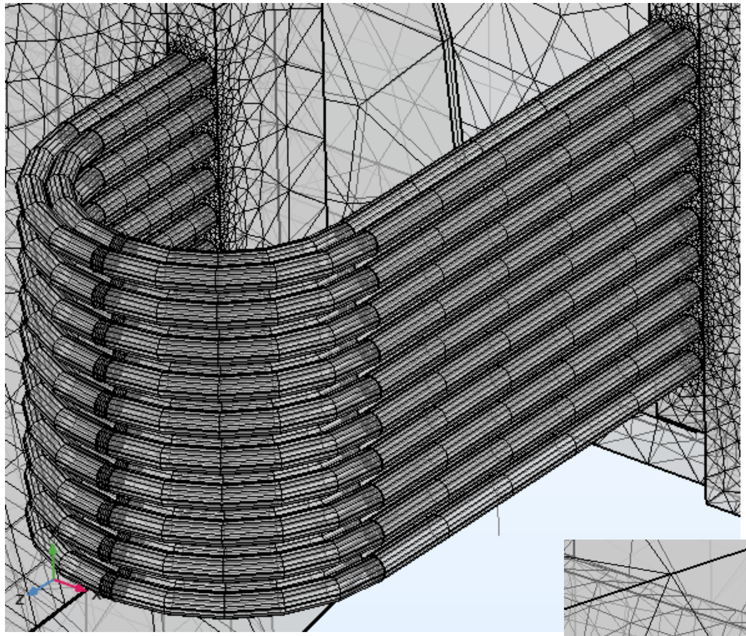
P_0 P_sample*step1(t[1/h]) W



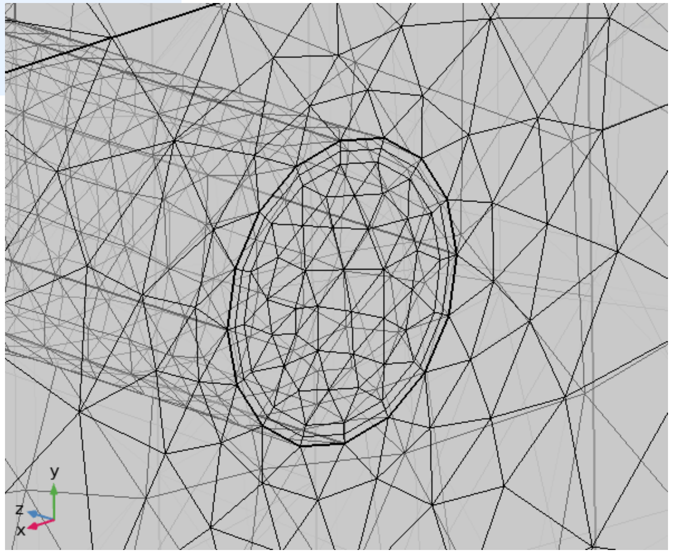
Malla – Thermal Links



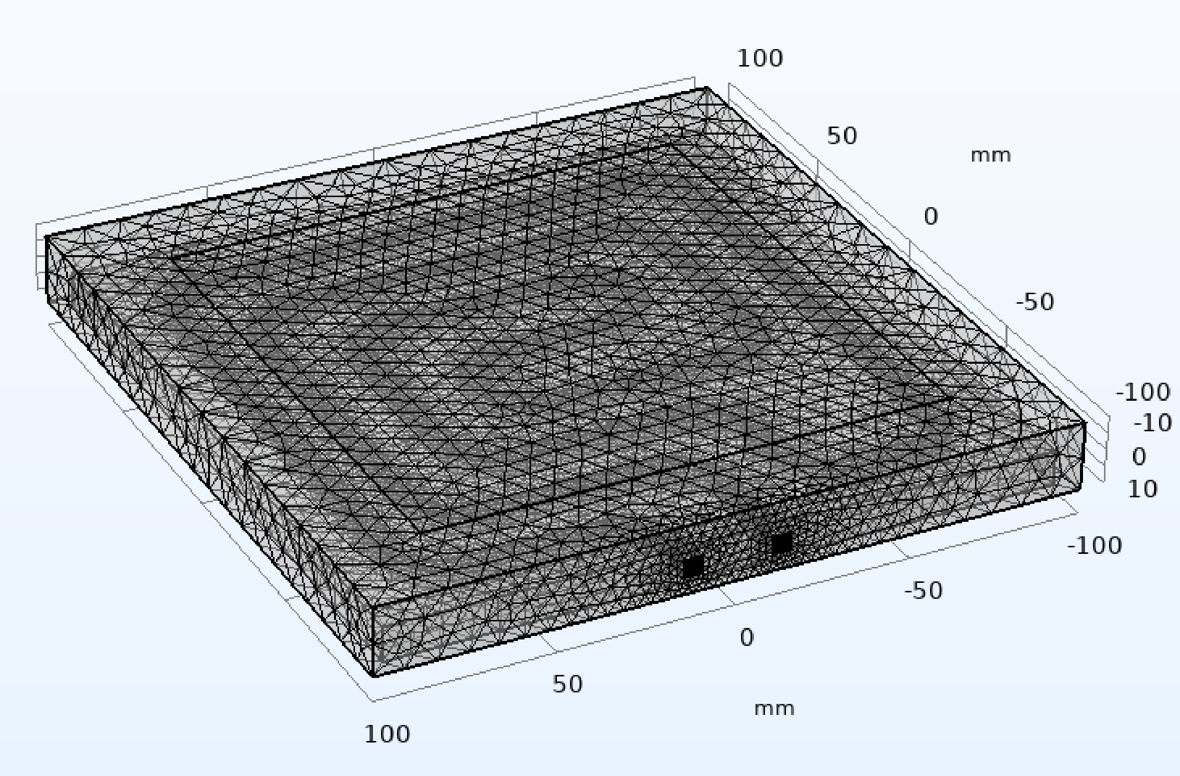
Swept



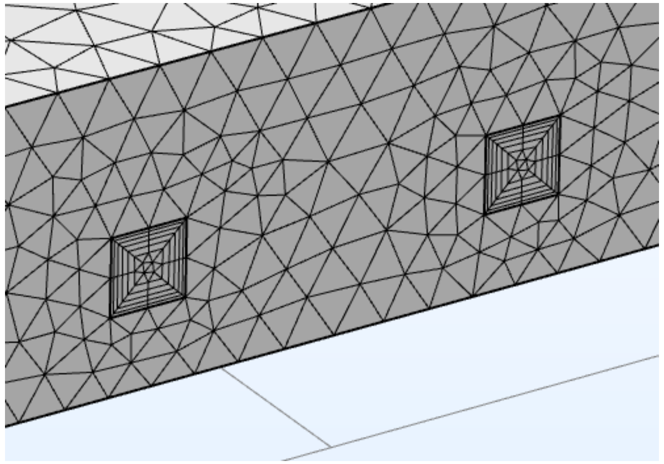
Boundary Layer



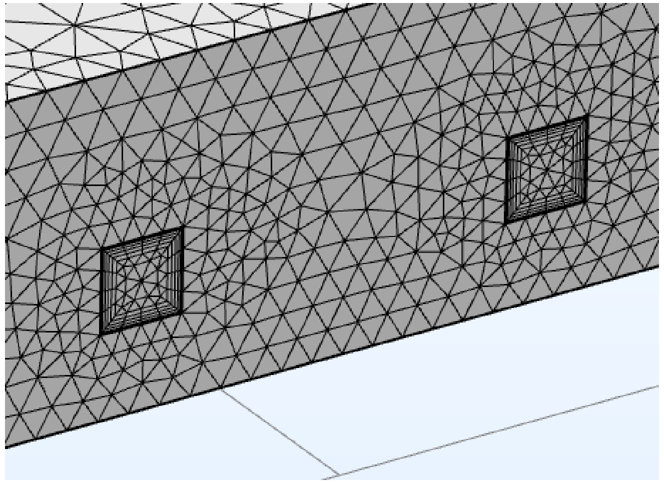
Malla – Refrigeración directa



Malla Normal



Malla Fina



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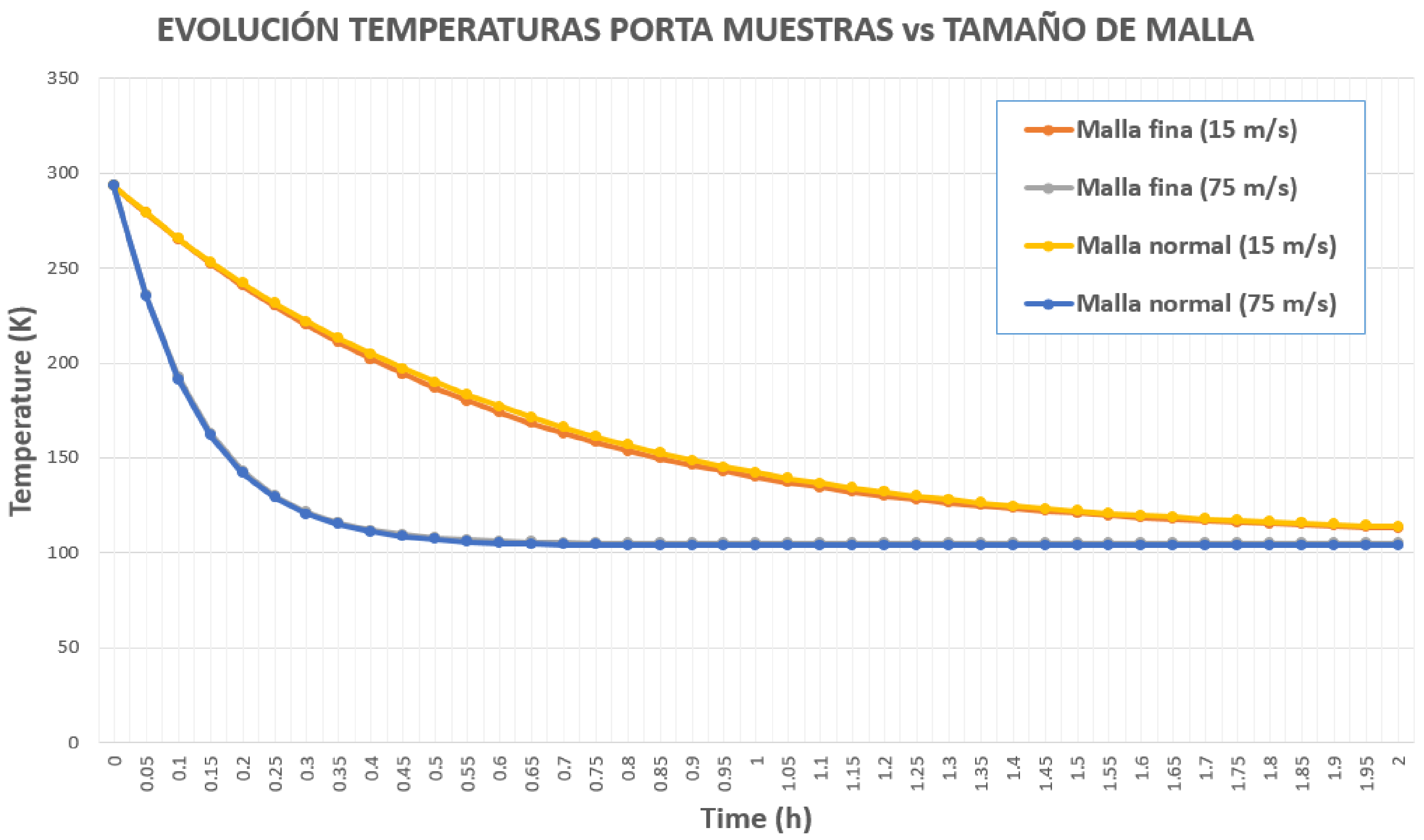
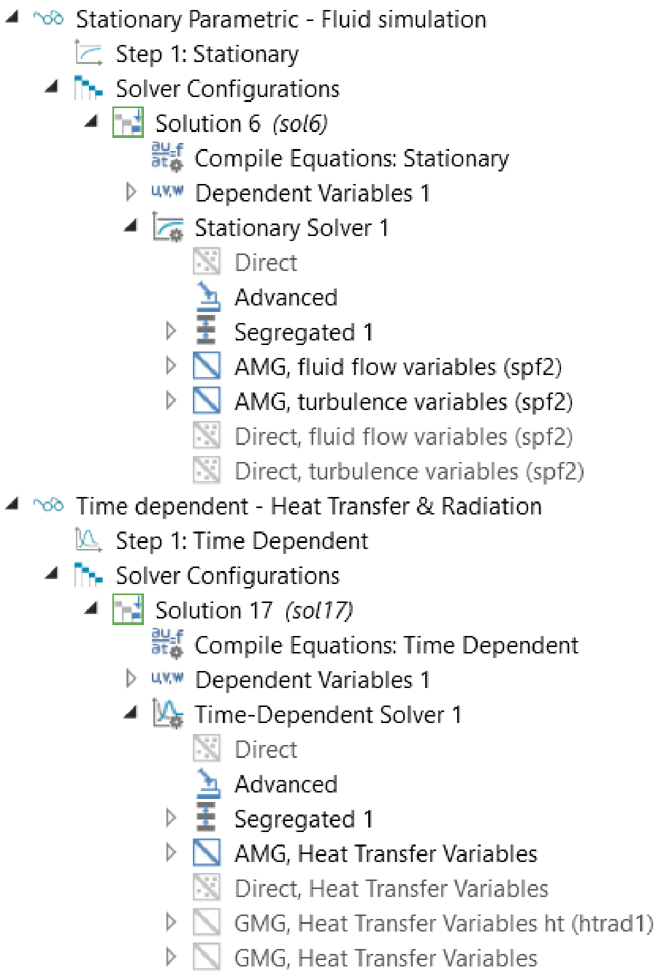
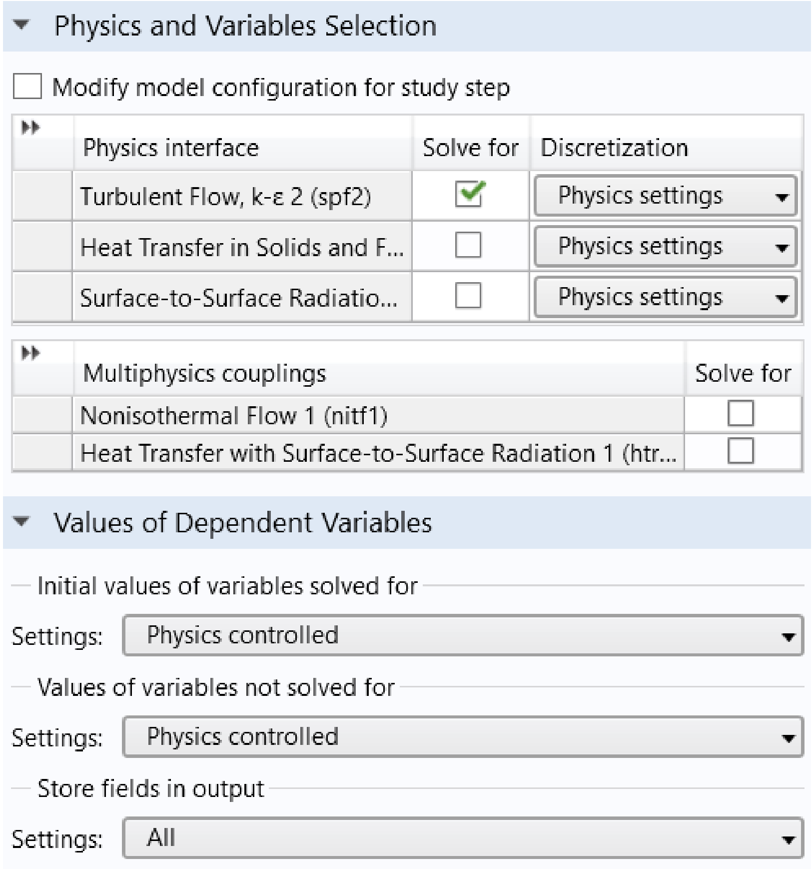
Malla – Refrigeración directa



Estudio – Thermal Links



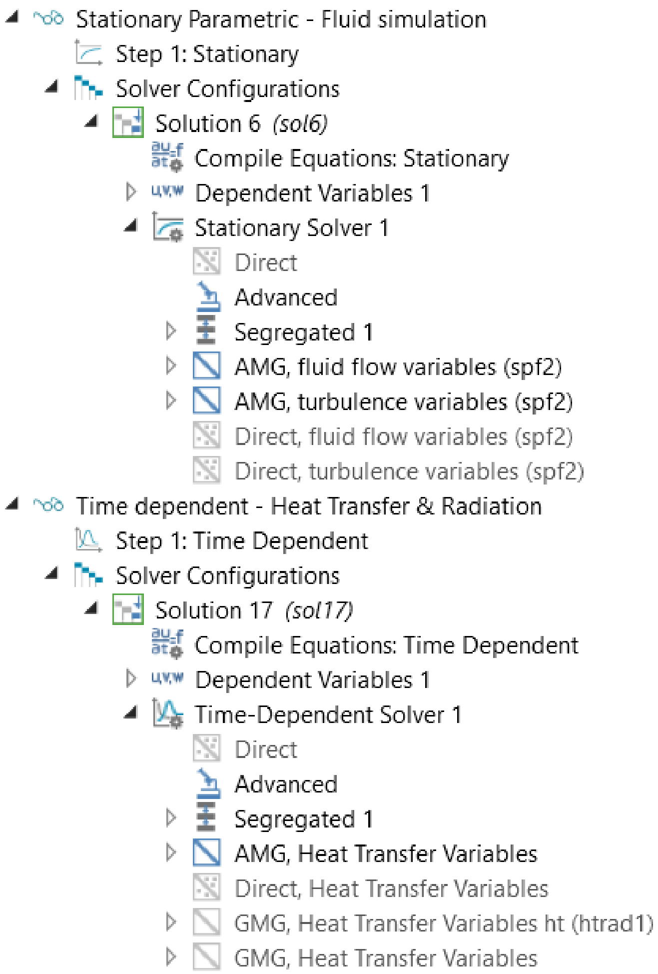
Stationary Settings



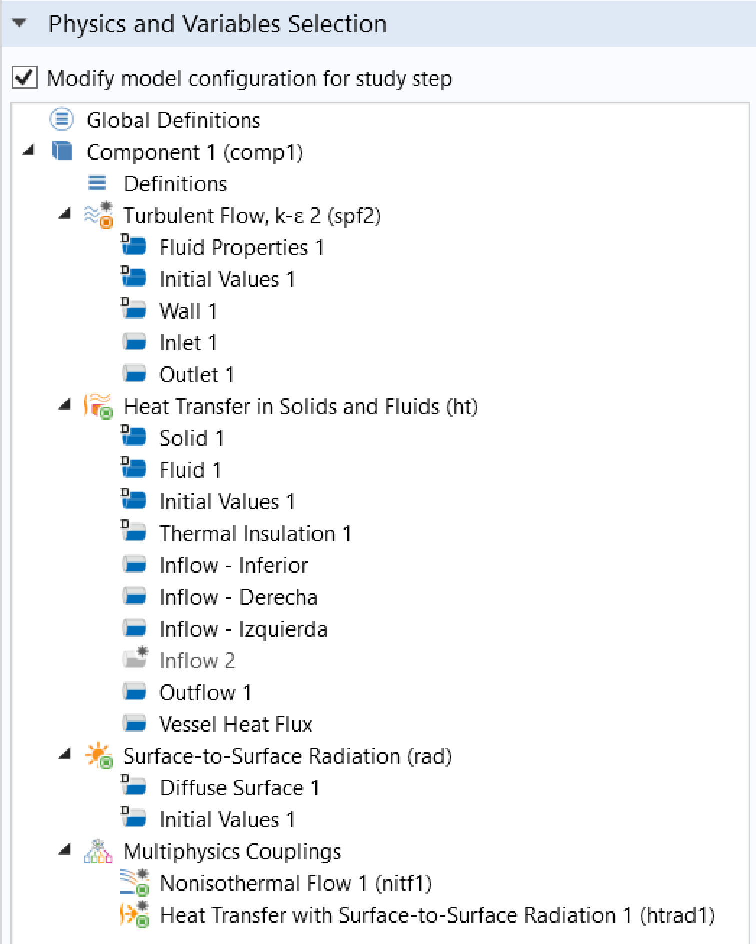
Las propiedades físicas del Nitrógeno se consideran NO DEPENDIENTES de la temperatura.

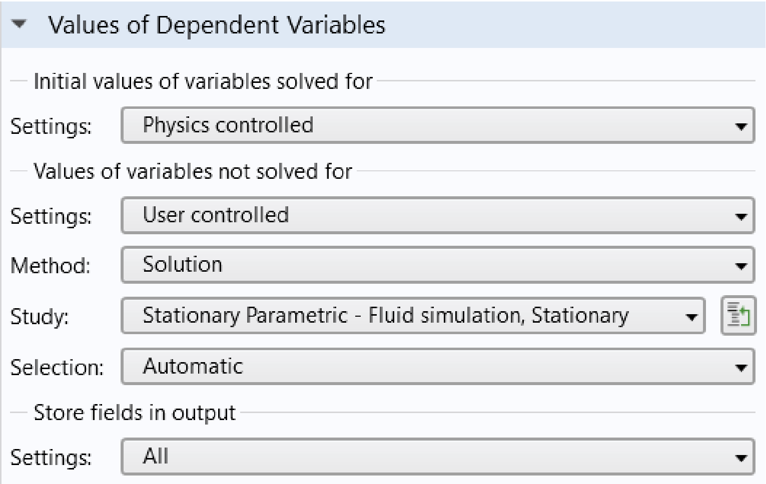
Property	Variable	Value	Unit
Density	rho	3.4	kg/m³
Dynamic viscosity	mu	6.96e-6	Pa·s
Thermal conductivity	k_iso ; kii...	0.0098	W/(m·K)
Heat capacity at constant pressure	Cp	1040	J/(kg·K)
Ratio of specific heats	gamma	1.47	1

Estudio – Thermal Links



Time dependent Settings





Estudio – Refrigeración Directa

- Parametric (V_in ; P_Res = 0 W ; T_in = 100 K; P_sample = 15W)
  - Parametric Sweep
  - Step 1: Turbulent Flow Initial Conditions
  - Step 2: Time Dependent
  - Solver Configurations
    - Solution 1 *(sol1)*
      - Compile Equations: Turbulent Flow Initial Conditions
      - Dependent Variables 1
      - Stationary Solver 1
        - Direct
        - Advanced
        - Segregated 1
        - AMG, fluid flow variables
        - Direct, Heat Transfer Variables
        - Direct, turbulence variables (spf)
        - Direct, fluid flow variables
        - AMG, Heat Transfer Variables ht (nitf1)
        - GMG, Heat Transfer Variables ht (nitf1)
        - AMG, turbulence variables (spf)
      - Solution Store 1 *(sol2)*
      - Compile Equations: Time Dependent
      - Dependent Variables 2
      - Time-Dependent Solver 1
        - Direct
        - Advanced
        - Segregated 1
        - AMG, fluid flow variables
        - Direct, Heat Transfer Variables
        - Direct, turbulence variables (spf)
        - Direct, fluid flow variables
        - AMG, Heat Transfer Variables ht (nitf1)
        - GMG, Heat Transfer Variables ht (nitf1)
        - AMG, turbulence variables (spf)
    - Parametric Solutions 1 *(sol3)*
      - V_in=35, T_in=100, P_Res=0, P_sample=15 *(sol4)*
      - V_in=55, T_in=100, P_Res=0, P_sample=15 *(sol5)*
  - Job Configurations

Stationary Settings

Physics and Variables Selection

☑ Modify model configuration for study step

- Global Definitions
- Component 1 (comp1)
  - Definitions
  - Turbulent Flow, k-ω (spf)
    - Fluid Properties 1
    - Initial Values 1
    - Wall 1
    - Inlet 1
    - Outlet 1
  - Heat Transfer in Solids and Fluids (ht)
    - Solid 1
    - Fluid 1
    - Initial Values 1
    - Thermal Insulation 1
    - Inflow - Initial Conditions
    - Inflow - T input
    - Outflow 1
    - Resistors - Heat Flux
    - Radiation - Heat Flux
    - Thermal Insulation 2
    - PCB - Heat Flux
  - Heat Transfer in Solids 2 (ht2)
    - Solid 1
    - Initial Values 1
    - Thermal Insulation 1
    - Resistors - Heat Flux
    - Radiation - Heat Flux
    - Thermal Insulation 2
    - Convective Heat Flux - Ref Power 35 m/s
    - Convective Heat Flux - Ref Power 55 m/s
    - PCB Heat Flux
  - Multiphysics Couplings
    - Nonisothermal Flow 1 (nitf1)

Las propiedades físicas del Nitrógeno se consideran **DEPENDIENTES** de la temperatura.

Dynamic viscosity	mu	eta(T)	Pa·s
Ratio of specific heats	gamma	1.4	1
Heat capacity at constant pressure	Cp	Cp(T)	J/(kg·K)
Density	rho	rho(pA,T)	kg/m^3
Thermal conductivity	k_iso ;...	k(T)	W/(m·K)

Estudio – Refrigeración Directa

- Parametric (V_in ; P_Res = 0 W ; T_in = 100 K; P_sample = 15W)
  - Parametric Sweep
  - Step 1: Turbulent Flow Initial Conditions
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        - Segregated 1
        - AMG, fluid flow variables
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        - AMG, Heat Transfer Variables ht (nitf1)
        - GMG, Heat Transfer Variables ht (nitf1)
        - AMG, turbulence variables (spf)
      - Solution Store 1 *(sol2)*
      - Compile Equations: Time Dependent
      - Dependent Variables 2
      - Time-Dependent Solver 1
        - Direct
        - Advanced
        - Segregated 1
        - AMG, fluid flow variables
        - Direct, Heat Transfer Variables
        - Direct, turbulence variables (spf)
        - Direct, fluid flow variables
        - AMG, Heat Transfer Variables ht (nitf1)
        - GMG, Heat Transfer Variables ht (nitf1)
        - AMG, turbulence variables (spf)
    - Parametric Solutions 1 *(sol3)*
      - V_in=35, T_in=100, P_Res=0, P_sample=15 *(sol4)*
      - V_in=55, T_in=100, P_Res=0, P_sample=15 *(sol5)*
  - Job Configurations

Time Dependent Settings

Physics and Variables Selection

☑ Modify model configuration for study step

- Global Definitions
- Component 1 (comp1)
  - Definitions
  - Turbulent Flow, k-ω (spf)
    - Fluid Properties 1
    - Initial Values 1
    - Wall 1
    - Inlet 1
    - Outlet 1
  - Heat Transfer in Solids and Fluids (ht)
    - Solid 1
    - Fluid 1
    - Initial Values 1
    - Thermal Insulation 1
    - Inflow - Initial Conditions
    - Inflow - T input
    - Outflow 1
    - Resistors - Heat Flux
    - Radiation - Heat Flux
    - Thermal Insulation 2
    - PCB - Heat Flux
  - Heat Transfer in Solids 2 (ht2)
    - Solid 1
    - Initial Values 1
    - Thermal Insulation 1
    - Resistors - Heat Flux
    - Radiation - Heat Flux
    - Thermal Insulation 2
    - Convective Heat Flux - Ref Power 35 m/s
    - Convective Heat Flux - Ref Power 55 m/s
    - PCB Heat Flux
  - Multiphysics Couplings
    - Nonisothermal Flow 1 (nitf1)

Values of Dependent Variables

Initial values of variables solved for

Settings:	User controlled
Method:	Solution
Study:	Parametric (V_in ; P_Res = 0 W ; T_in = 100 K; P_s
Solution:	Current
Use:	Current
Time (h):	Automatic

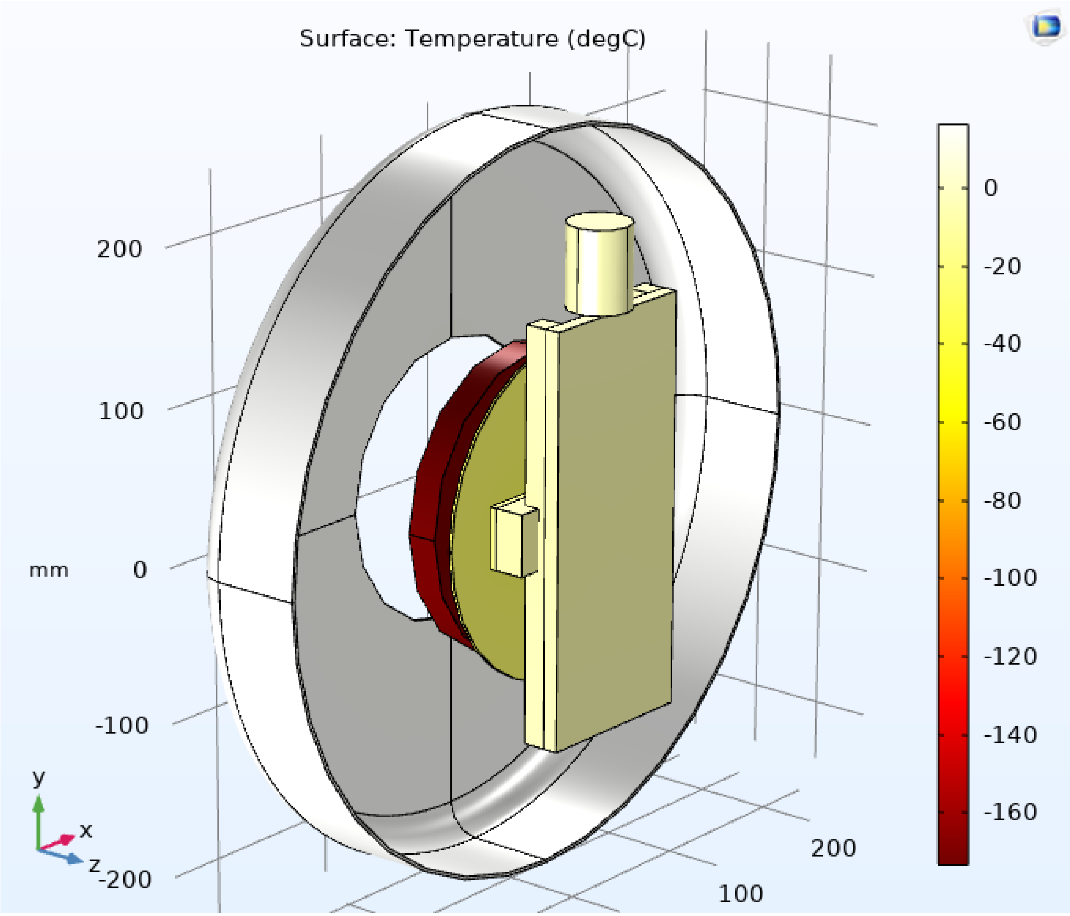
Values of variables not solved for

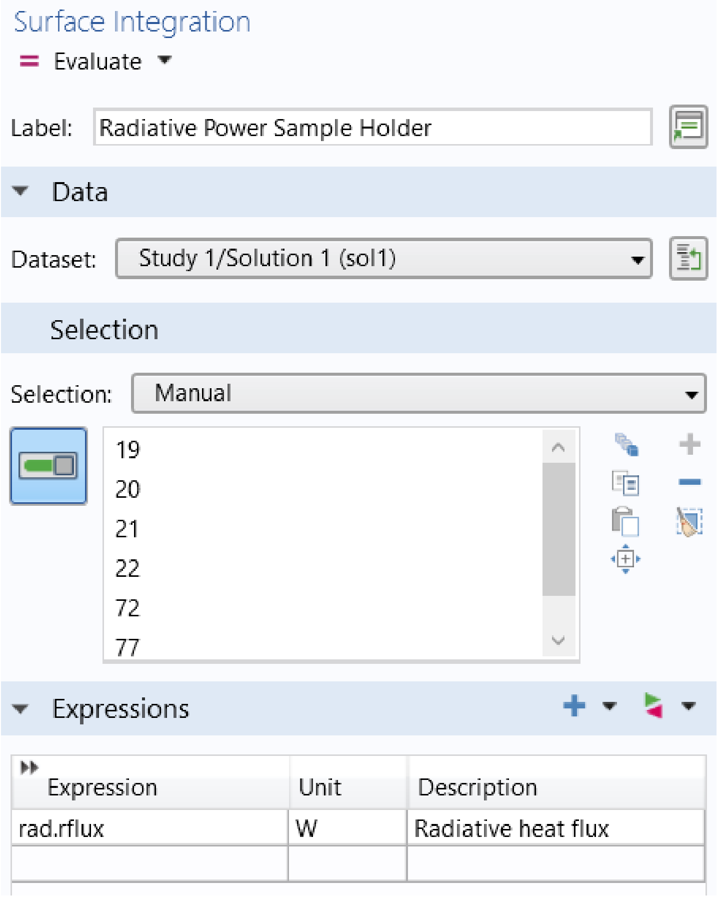
Settings:	Physics controlled

Store fields in output

Settings:	All

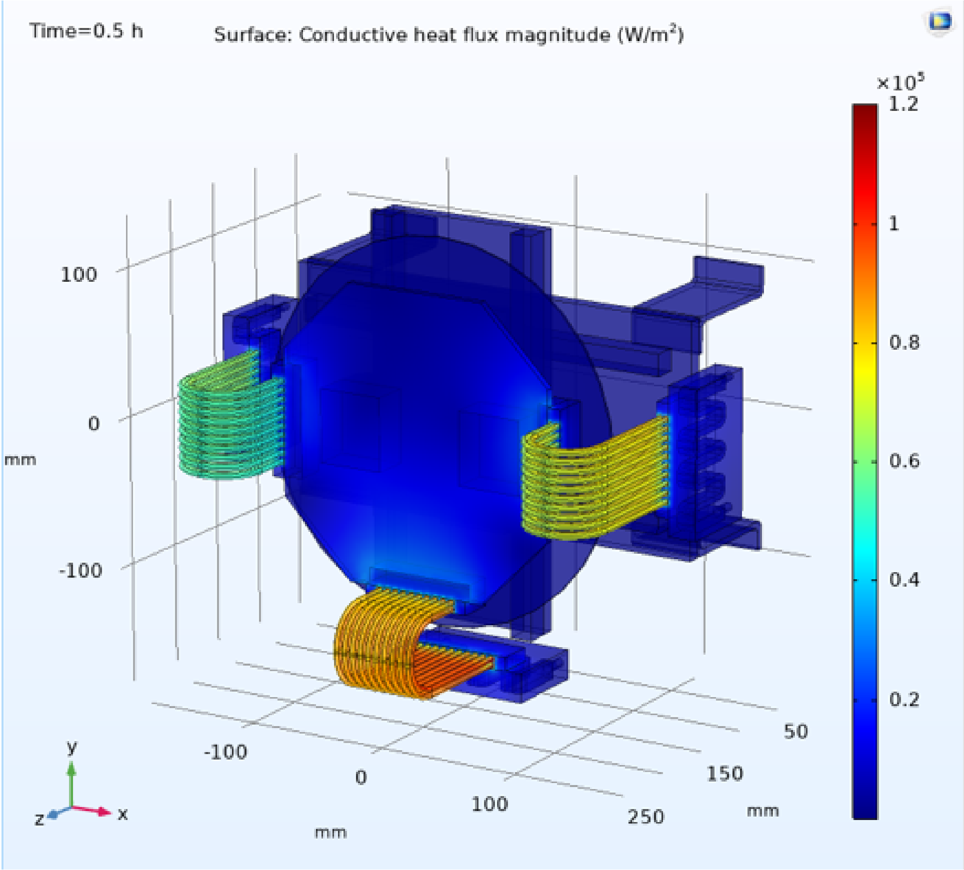
Resultados – Estimación radiación térmica

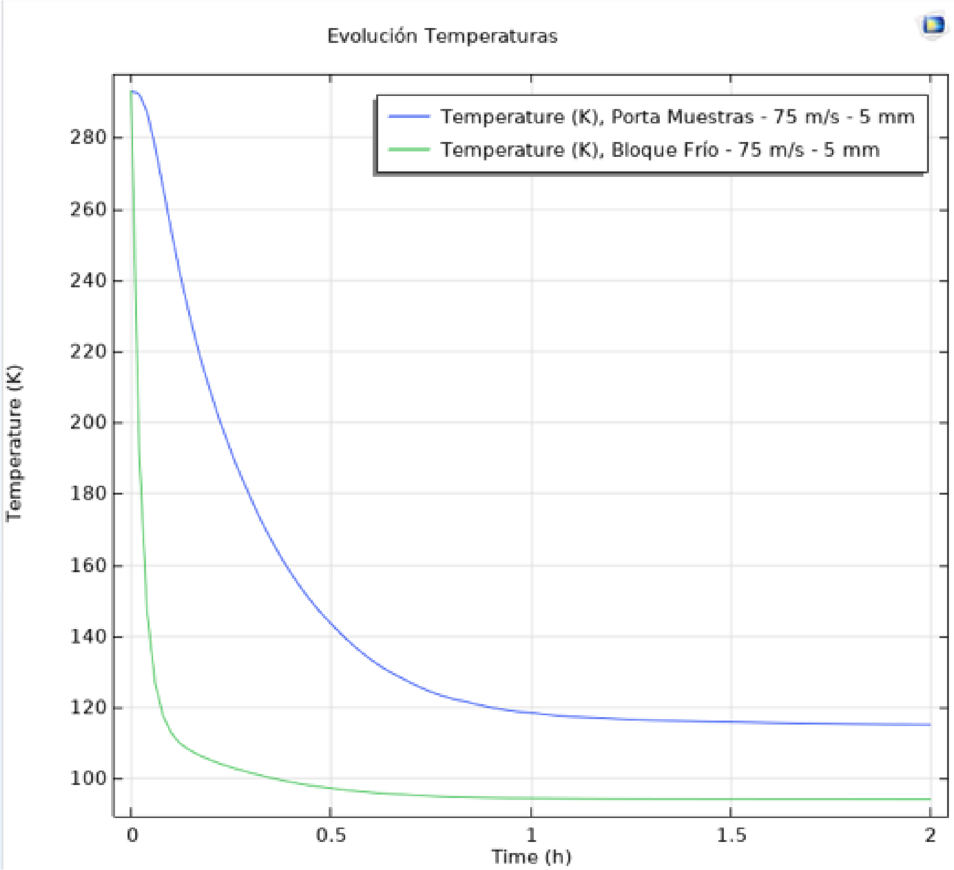




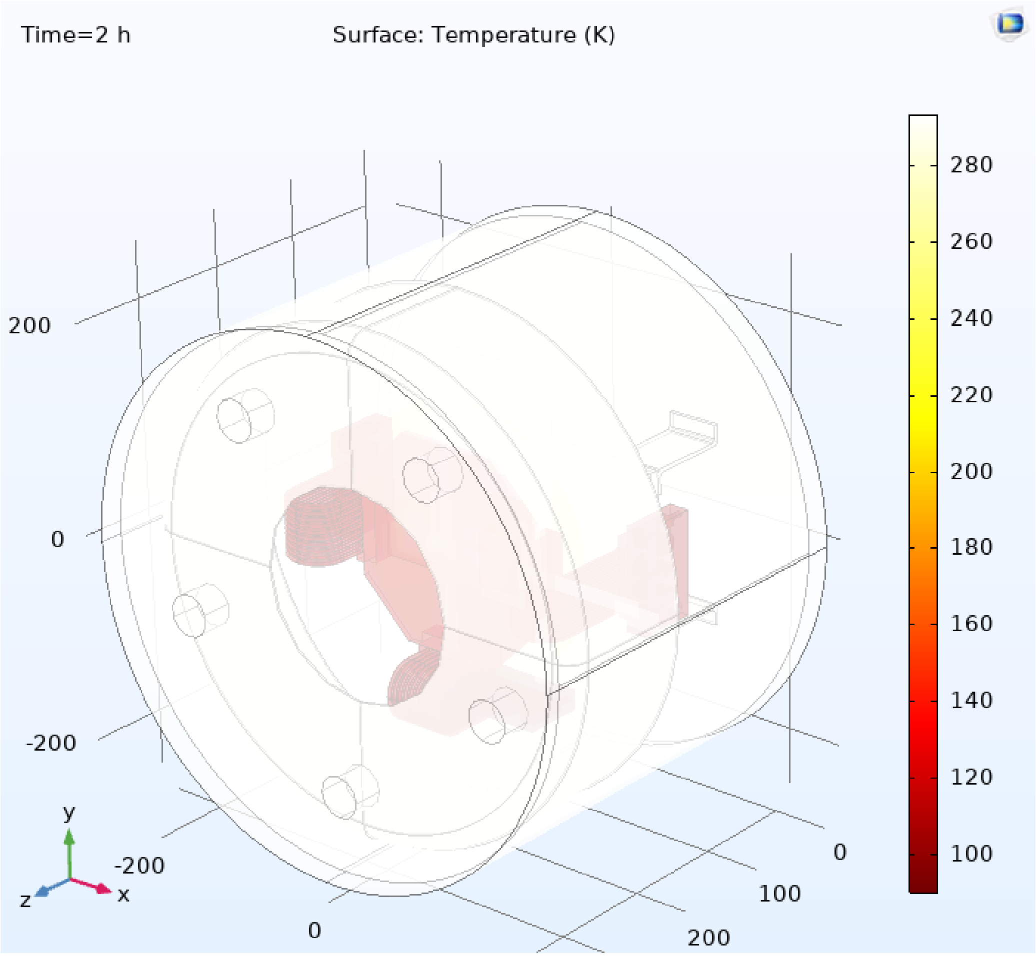
Radiative heat flux (W)
13.950

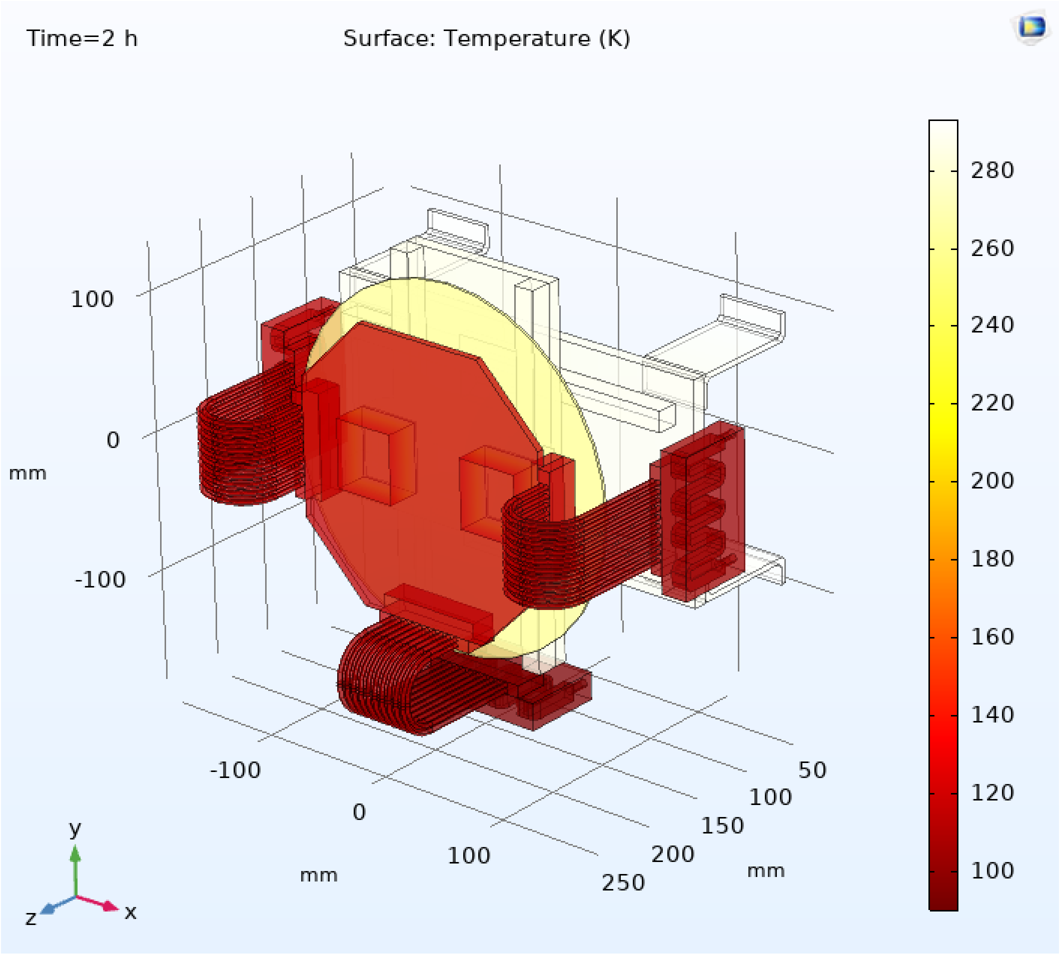
Resultados – Thermal Links



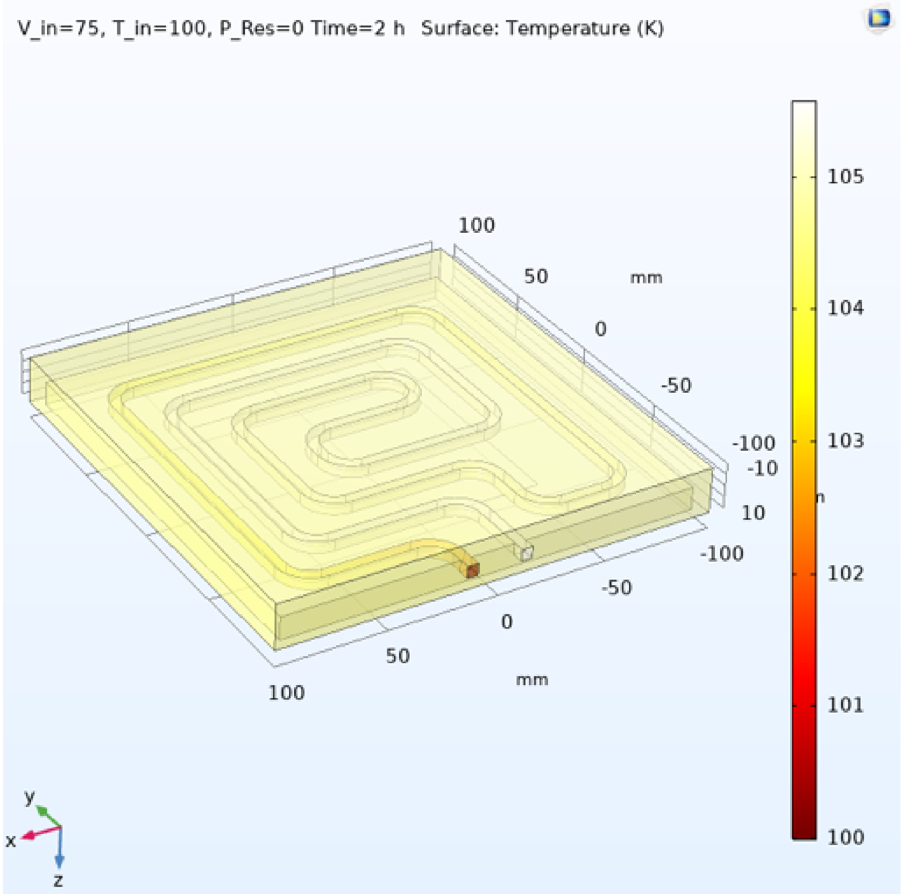


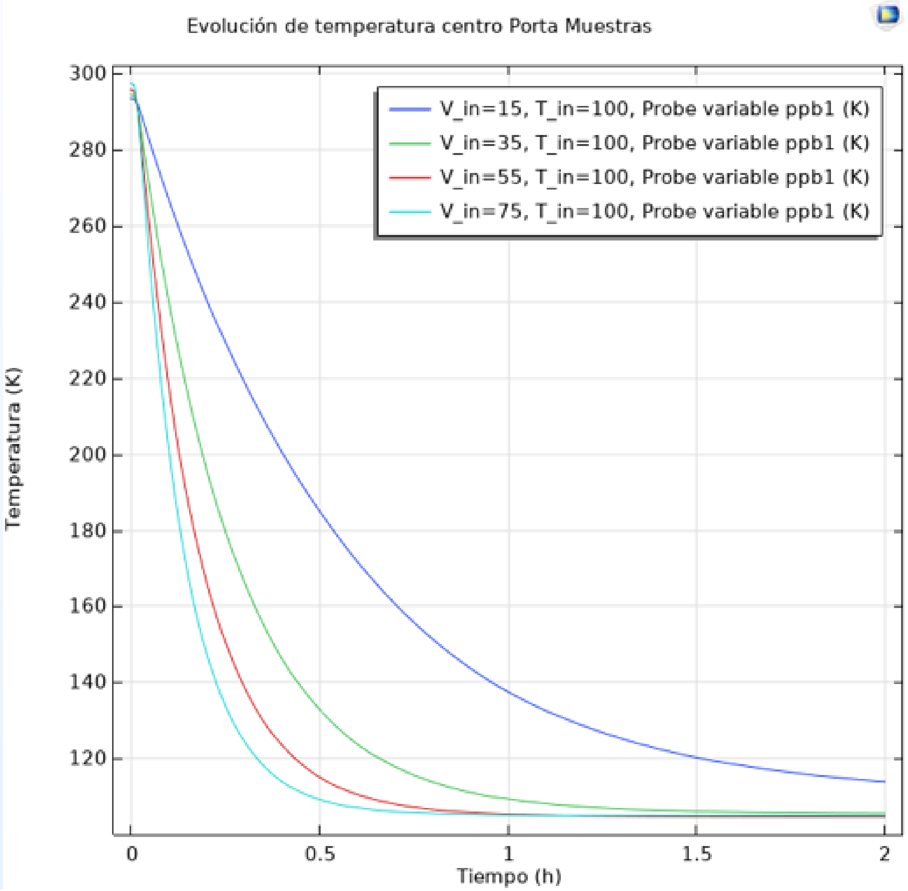
Resultados – Thermal Links



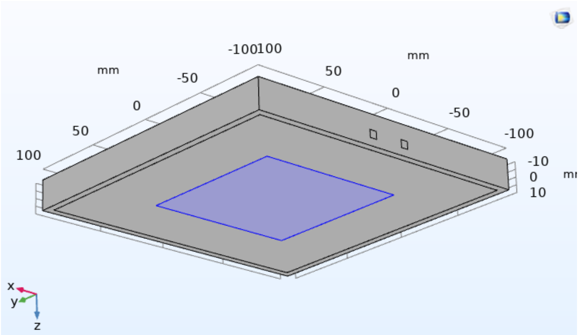


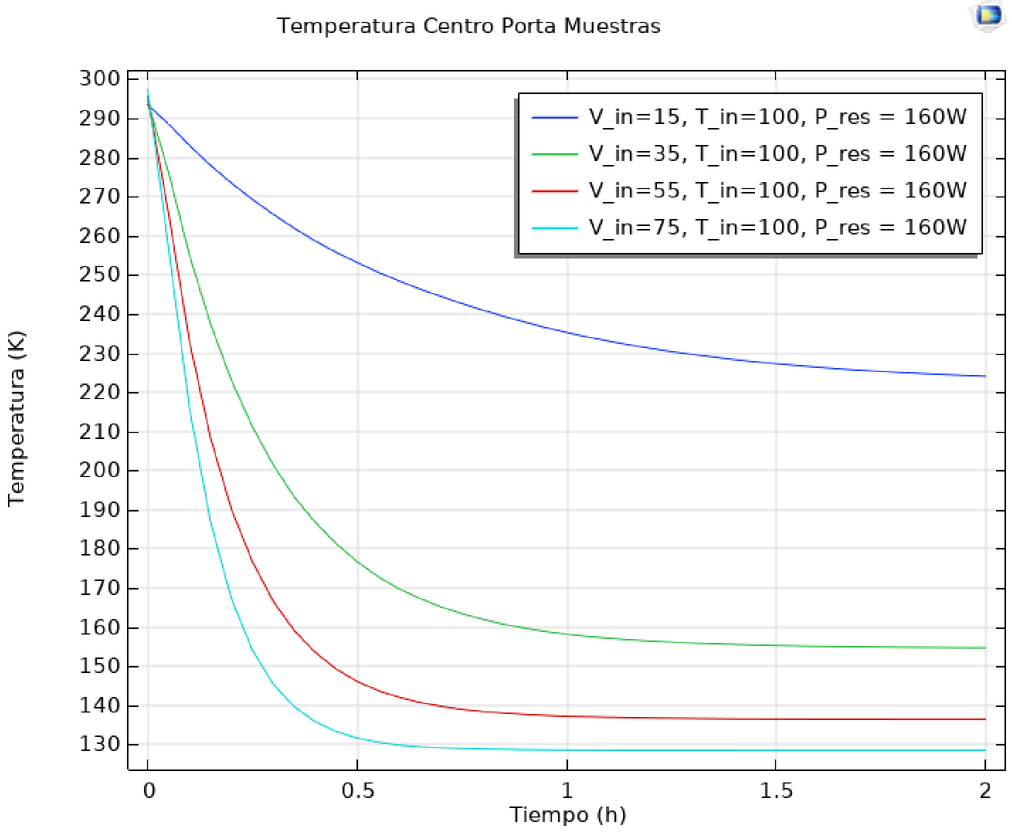
Resultados – Refrigeración directa

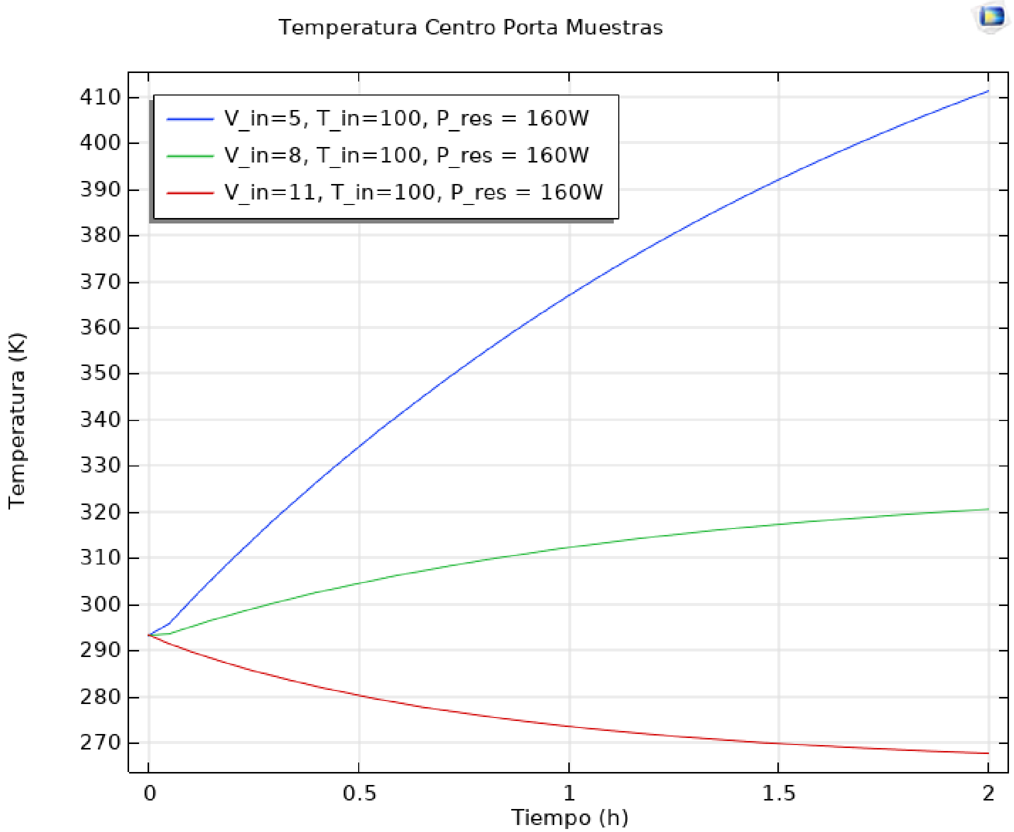




Resultados – Refrigeración directa







Elección en base a los resultados

- A la vista de los resultados obtenidos queda descartada la opción de utilizar Thermal Links debido a los altos tiempos de enfriamiento obtenidos, lo que supondrían gastos másicos de Nitrógeno más elevados.
- Se decide, por lo tanto, integrar el circuito de refrigeración en el porta muestras. Con los siguientes puntos a resolver:
  - Encontrar tuberías metálicas lo suficientemente flexibles para integrarlas junto al sistema de traslación.
  - Minimizar el número de conexiones en el circuito de refrigeración.

Modelo simplificado

Una vez seleccionado el método de enfriamiento del Porta Muestras se pretende encontrar una simplificación del modelo que, obteniéndose los resultados más aproximados posibles al modelo completo, permita realizar simulaciones en un **tiempo considerablemente inferior.**

Para ello, se pretende sustituir la simulación del fluido turbulento por una condición de contorno en la que simplemente se indique la **potencia de refrigeración** en función de la diferencia de temperatura entre la entrada y la salida del circuito.

Modelo simplificado

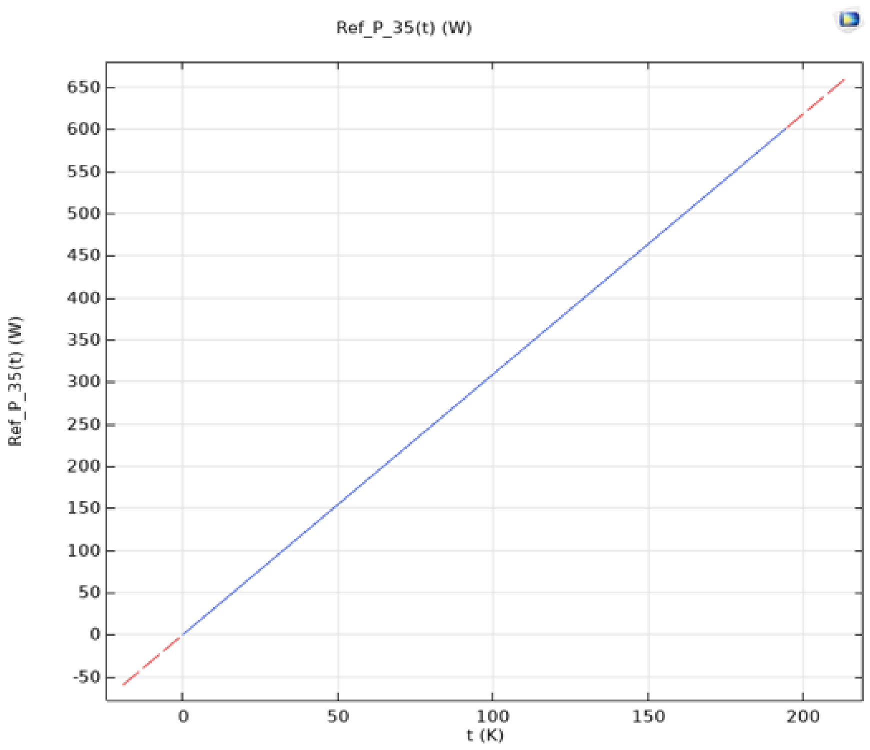
La gráfica de potencia de refrigeración con respecto a la temperatura se obtiene a partir de los resultados de temperatura del fluido a la salida del circuito de refrigeración obtenidos en el modelo completo.

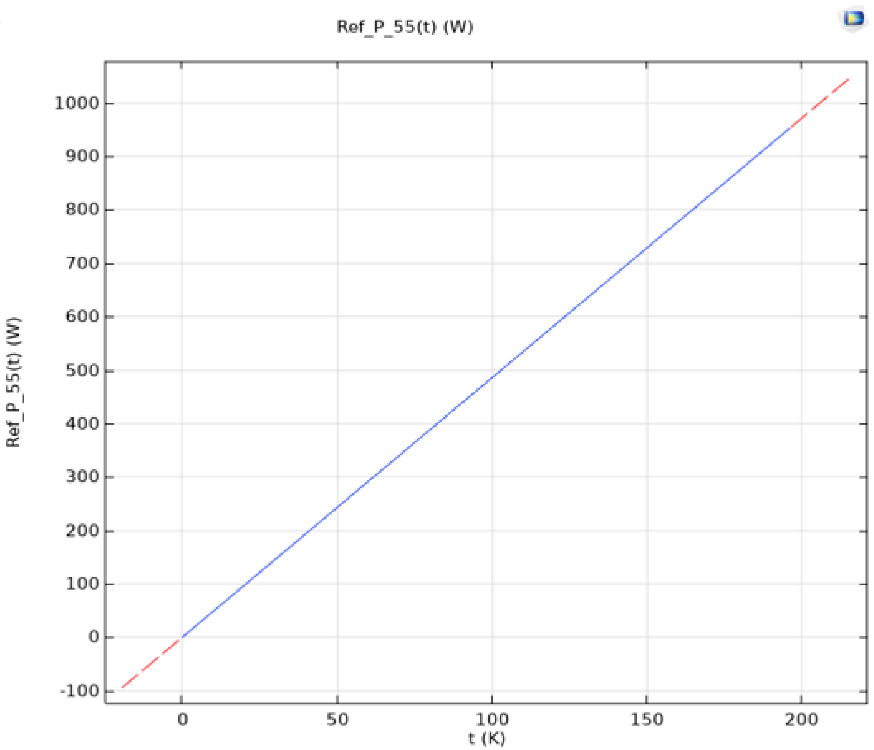
$$P[W] = \dot{m}\left[\frac{kg}{s}\right] \cdot (T_{OUT} - T_{IN})[K] \cdot C_p\left[\frac{J}{kg \cdot K}\right]$$

$$\dot{m}\left[\frac{kg}{s}\right] = S[m^2] \cdot V_s\left[\frac{m}{s}\right] \cdot \rho\left[\frac{kg}{m^3}\right]$$

Modelo simplificado

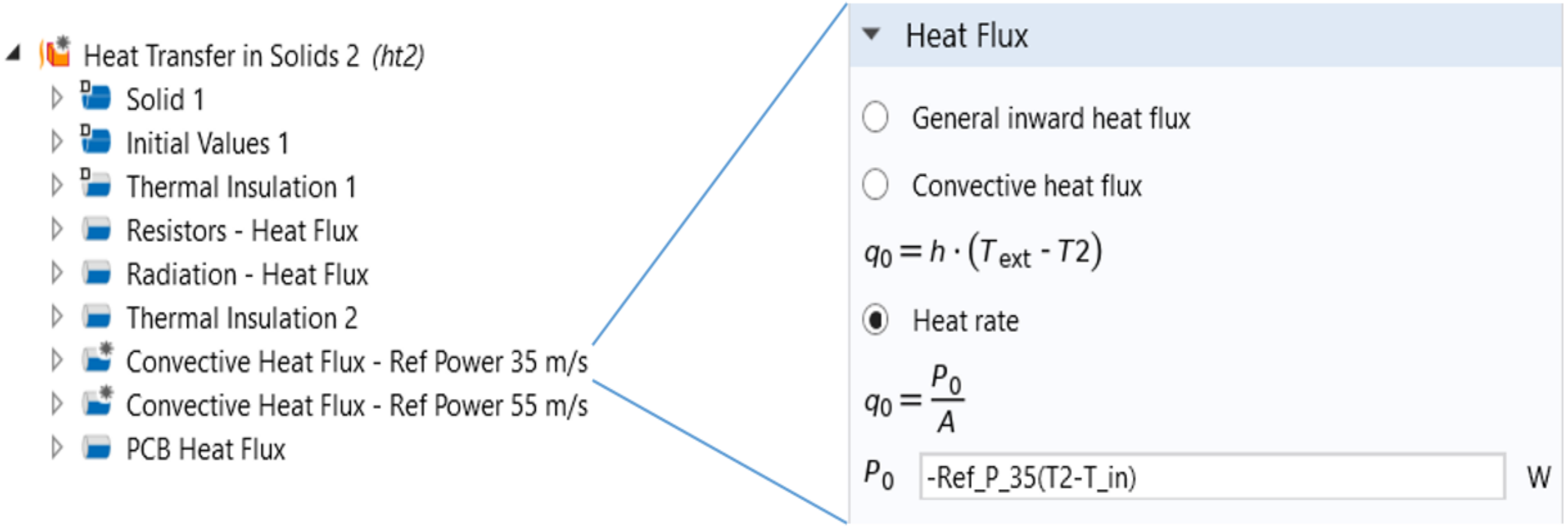
Una vez obtenida la función P(Tout-Tin), se introduce en COMSOL como una función de interpolación.





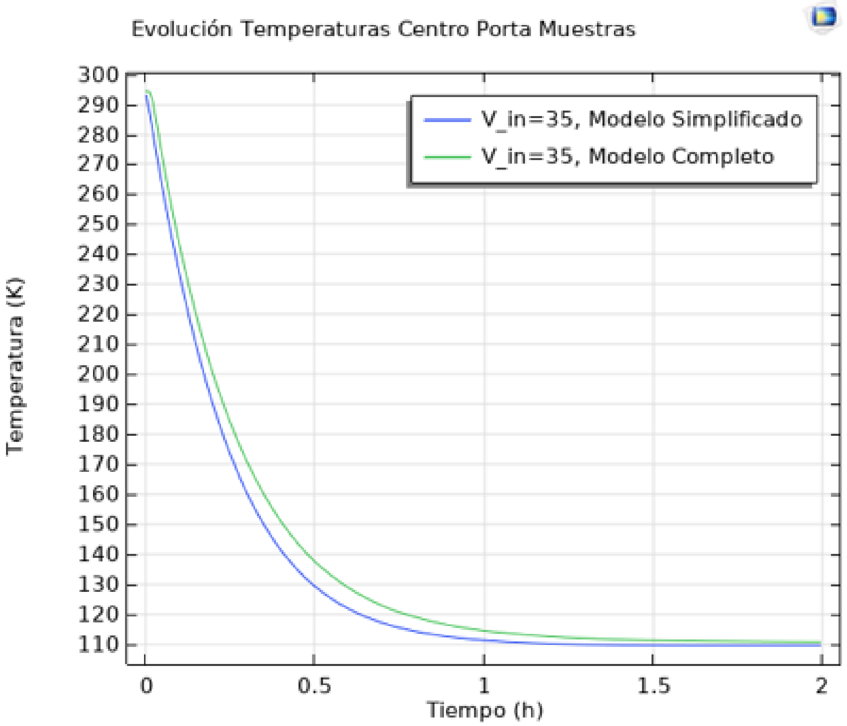
Modelo simplificado

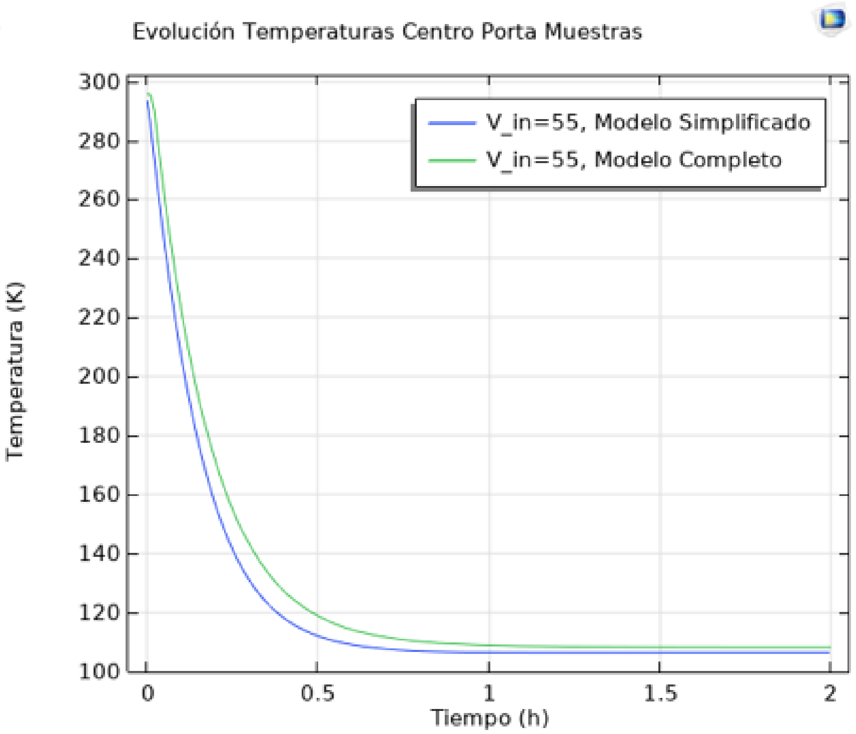
Utilizando la interfaz física “Heat Transfer in Solids”, se introducen estas funciones como condiciones de contorno “Heat Flux”.



Modelo simplificado

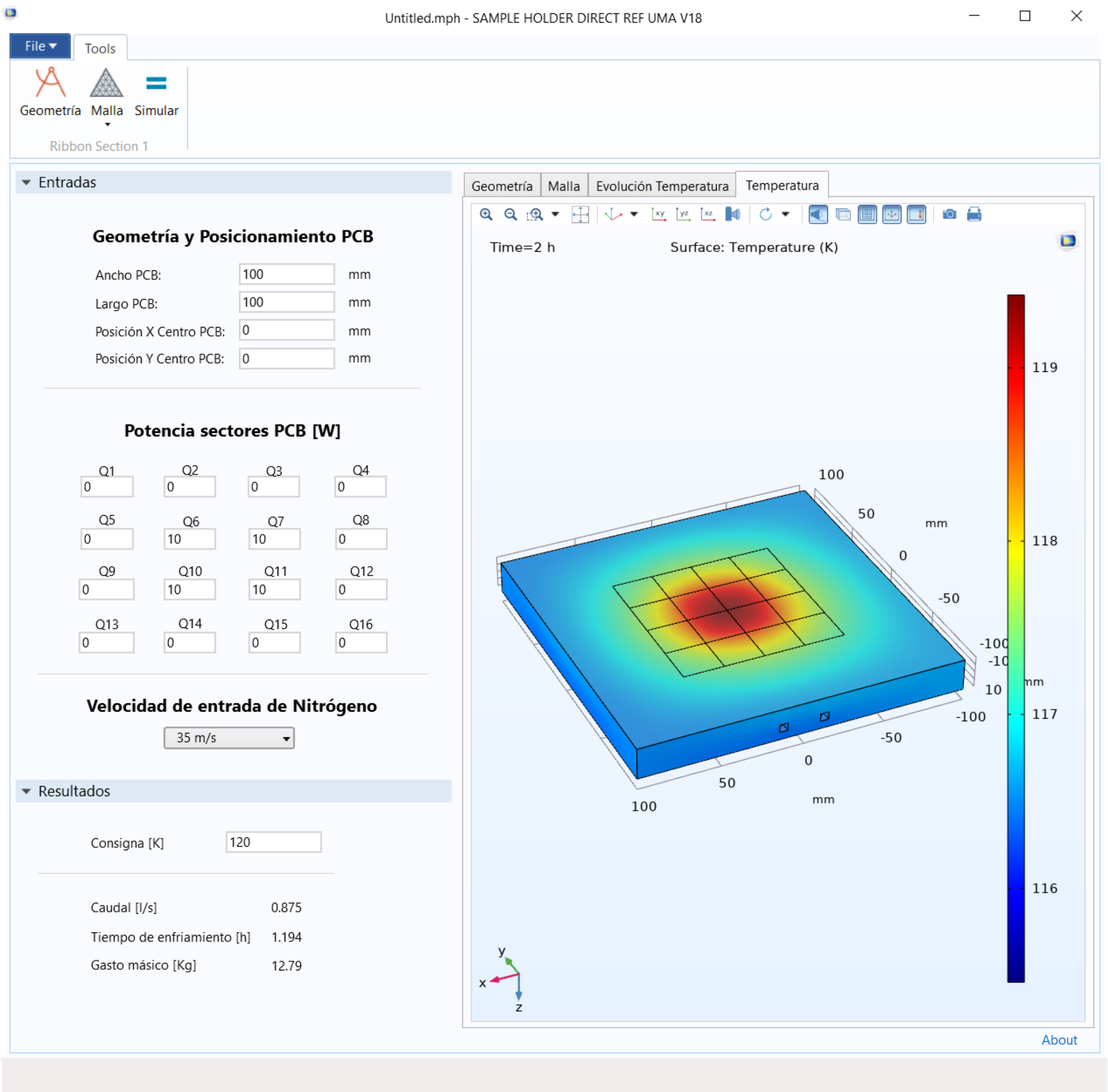
Los resultados obtenidos se ajustan con bastante exactitud a la solución obtenida con el modelo completo.





Aplicación

- Permite realizar simulaciones rápidas de curvas de enfriamiento y cálculos de gasto másico de Nitrógeno en función de las características de la PCB a testear.
- Cómo parámetros de entrada están las dimensiones de la PCB, la potencia calorífica generada por sus componentes y la velocidad de entrada de fluido.
- Como datos de salida se tienen las gráficas de distribución de temperatura y curvas de enfriamiento, y los datos calculados de Caudal, Tiempo de enfriamiento y Gasto másico de nitrógeno.



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