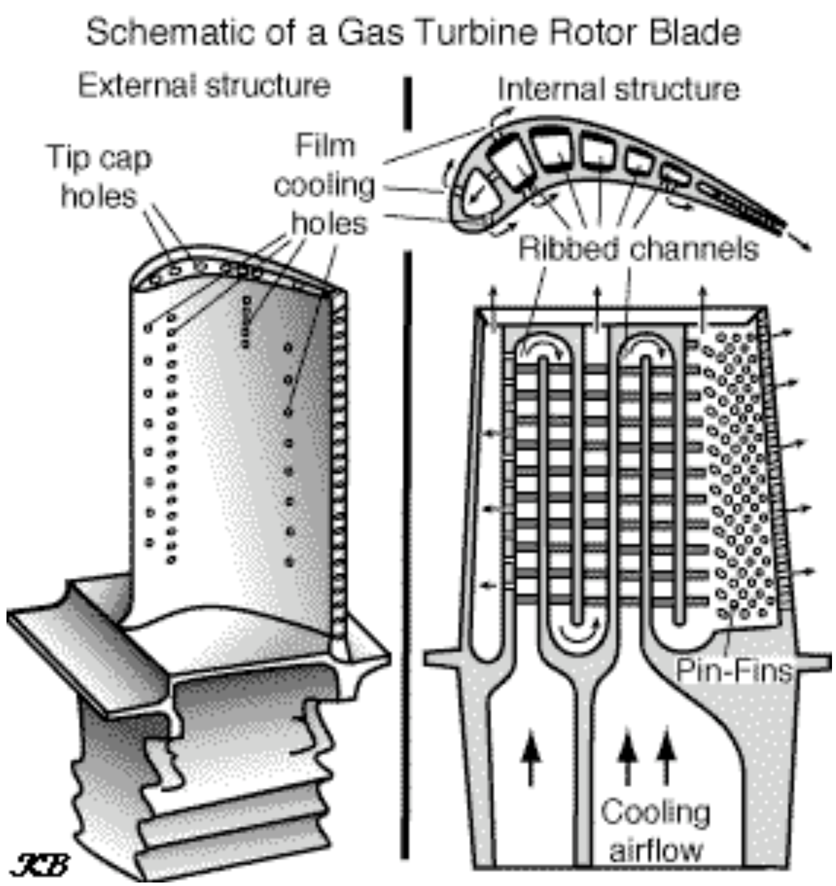
Advanced Physical Models

- Heat Transfer
- Buoyancy
- *Combustion and reaction modeling*
- *Multiphase flows*
- *Solidification and melting*

Heat Transfer

Thermal analysis are crucial in many industrial applications



Turbulence is enhanced is internal turbine cooling passages to improve heat transfer

Roughness elements (ribs) are placed in the channels

Heat Transfer

"passage of thermal energy from a hot to cold material"

This "passage" occurs typically in three modes

1) Conduction: diffusion process. Heat in transferred by direct contact
2) Convection: associated to a fluid motion. Heat is transferred by conduction enhanced by the motion of the fluid particles
    1) Natural convection: the fluid motion is generated by the heat transfer: the fluid close to a hot surface becomes lighter and rises. The driving force is buoyancy - gravity driven motion
    2) Forced convection: the fluid motion is driven by external means
3) Radiation: wave propagation process. The heat is transferred by means of electromagnetic waves

Heat Transfer Modeling

An energy equation must be solved together with the momentum and the continuity equations

For incompressible flows the energy equation is decoupled from the others (ρ is NOT a function of the temperature)

For laminar flows the energy equation can be solved directly; for turbulent flows after Reynolds-averaging the equation contains an unclosed correlation:

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\frac{\mu}{\rho}\frac{\partial U_i}{\partial x_j}\right) + \frac{\partial\left(-\overline{u_i' u_j'}\right)}{\partial x_j} \qquad \text{Momentum}$$

$$\frac{\partial T}{\partial t} + U_j \frac{\partial T}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu}{Pr}\frac{\partial T}{\partial x_j}\right) + \frac{\partial\left(-\overline{T' u_j'}\right)}{\partial x_j} \qquad \text{Energy}$$

Heat Transfer Modeling

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\frac{(\mu+\mu_t)}{\rho}\frac{\partial U_i}{\partial x_j}\right]$$

Momentum

$$\frac{\partial T}{\partial t} + U_j \frac{\partial T}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\frac{1}{\rho}\left(\frac{\mu}{Pr} + \frac{\mu_t}{Pr_t}\right)\frac{\partial T}{\partial x_j}\right]$$

Energy

The Prandtl number is the measure of the momentum diffusivity vs. the thermal diffusivity

$$Pr = c_p\, \mu/\kappa$$

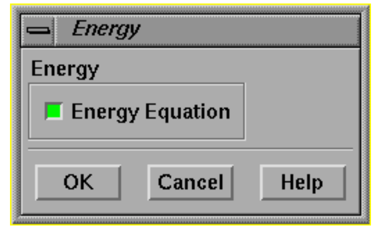
Pr is order 1 for gases (typically 0.7 for air)

Pr_t is an additional parameter in the turbulence model (typically 0.9)

Set-Up for Heat Transfer Calculations

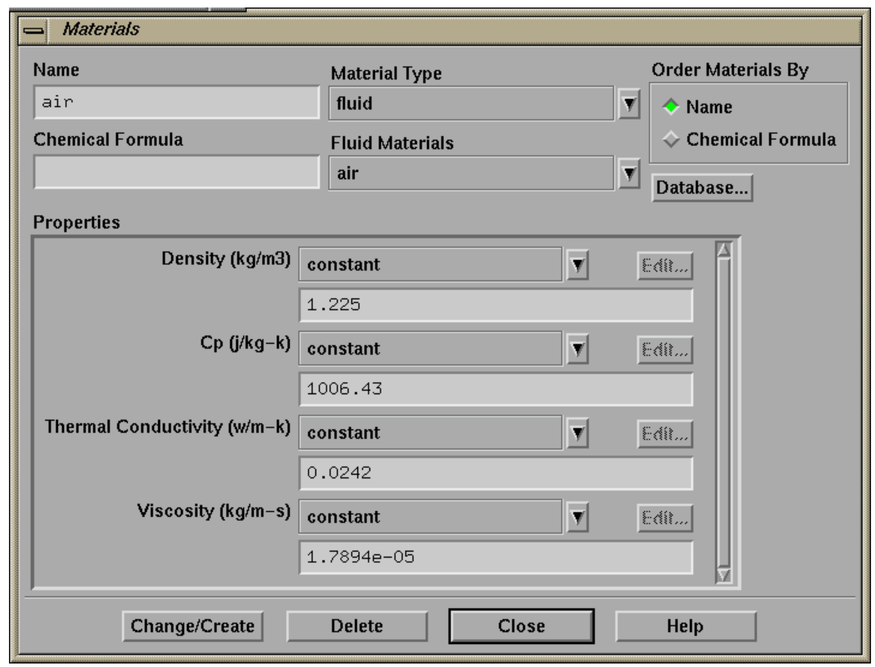
Define → Models → Energy

Activate the energy equation



Define → Materials

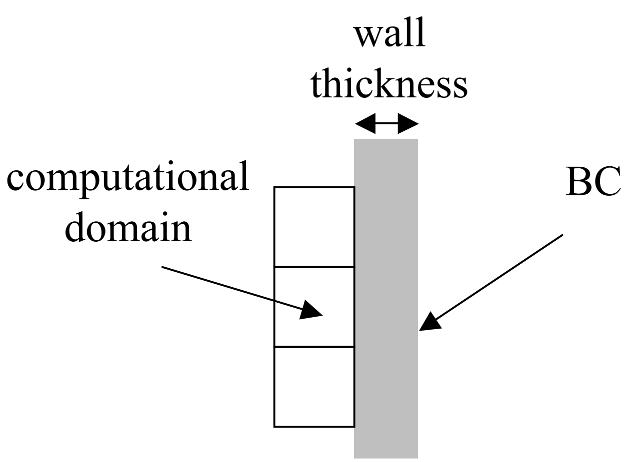
Specify material properties

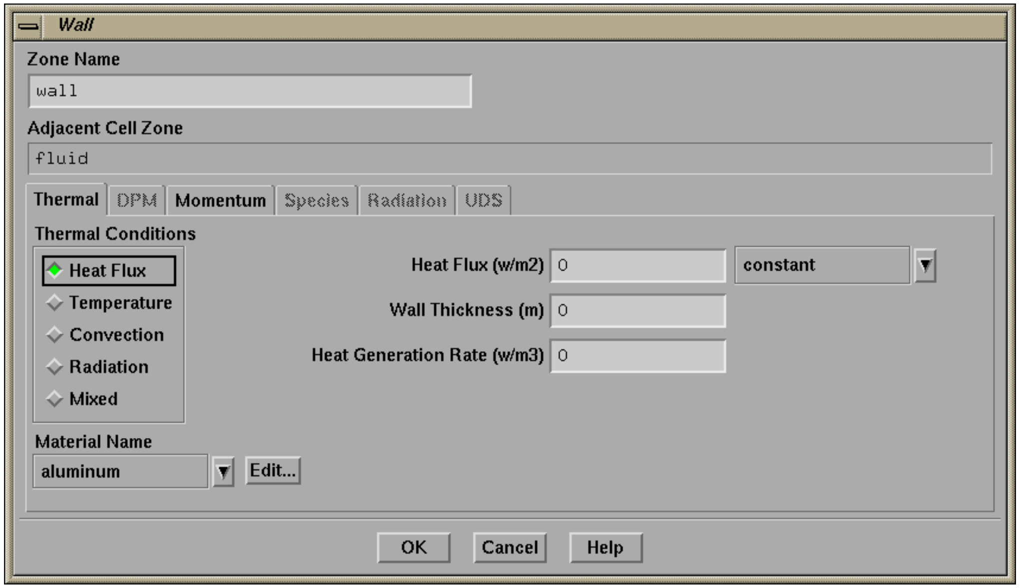


Wall thermal boundary conditions

The options are:

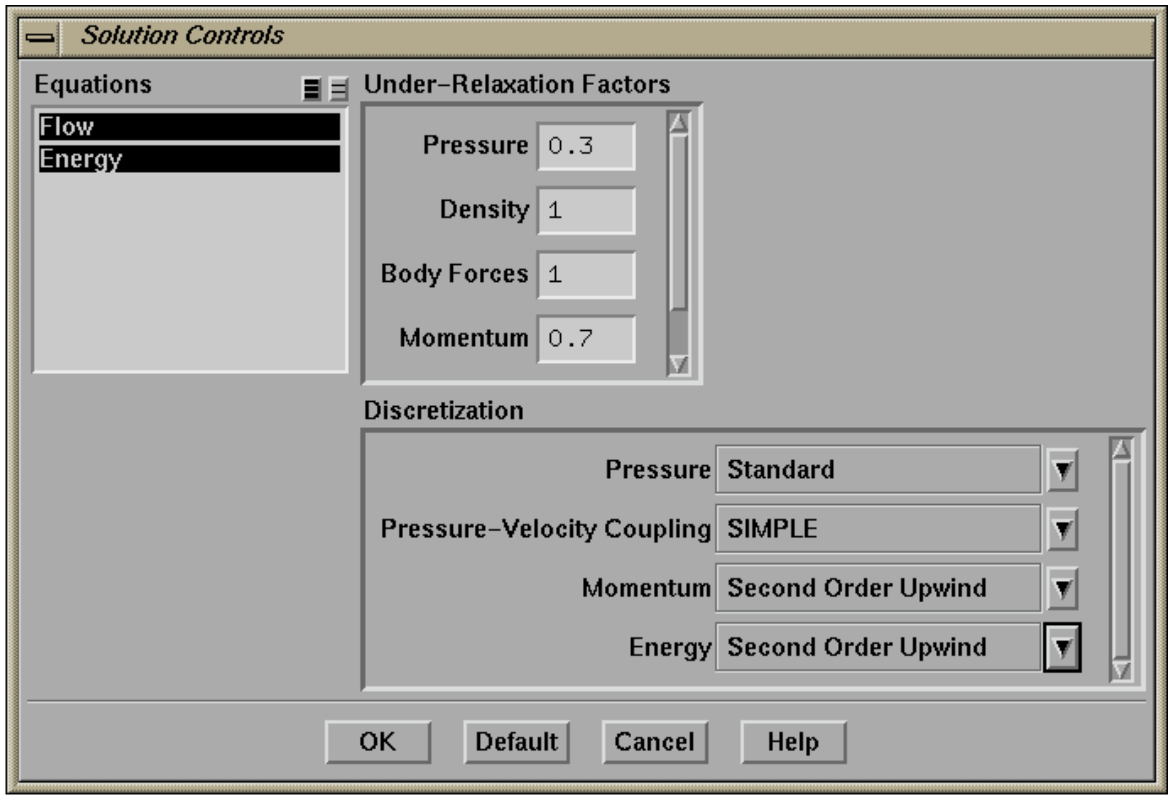
1) Fixed temperature
2) Fixed thermal flux (temperature gradient)





Flow-thermal simulations

For the energy equations all the numerical options (discretization, under-relaxation, etc.) are available



For incompressible fluids the temperature and momentum equations are decoupled

Periodic flows

Many heat-transfer devices are characterized by geometrically periodic configurations (ribbed passages)

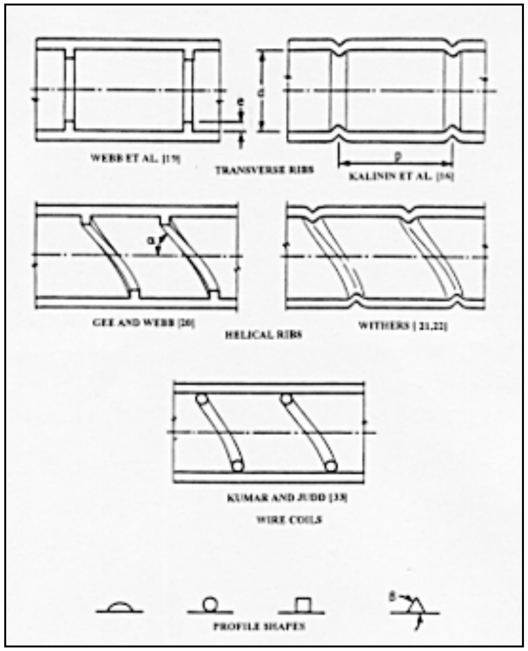
Temperature behaves like the pressure: it varies in the streamwise direction but its variation (gradient) is periodic

The energy equations can be rewritten in terms of a scaled temperature:

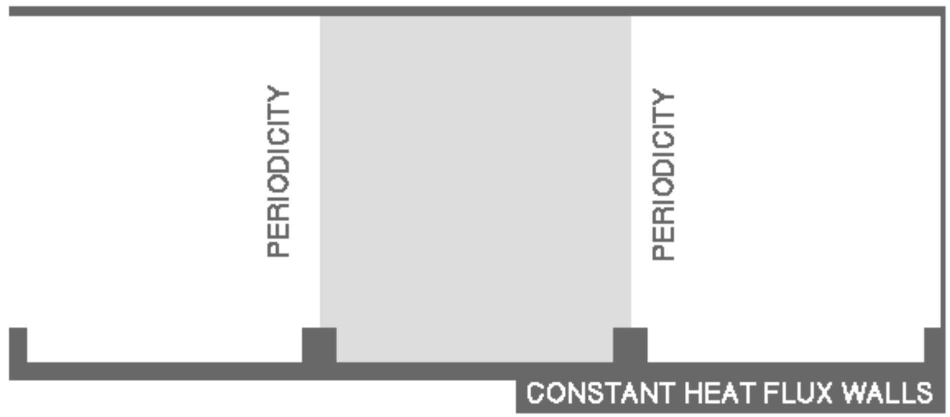
$$\theta = \frac{T - T_{wall}}{T_b - T_{wall}}$$

And the modified energy equation can be solved with periodic BC

Example of Heat Transfer Calculations

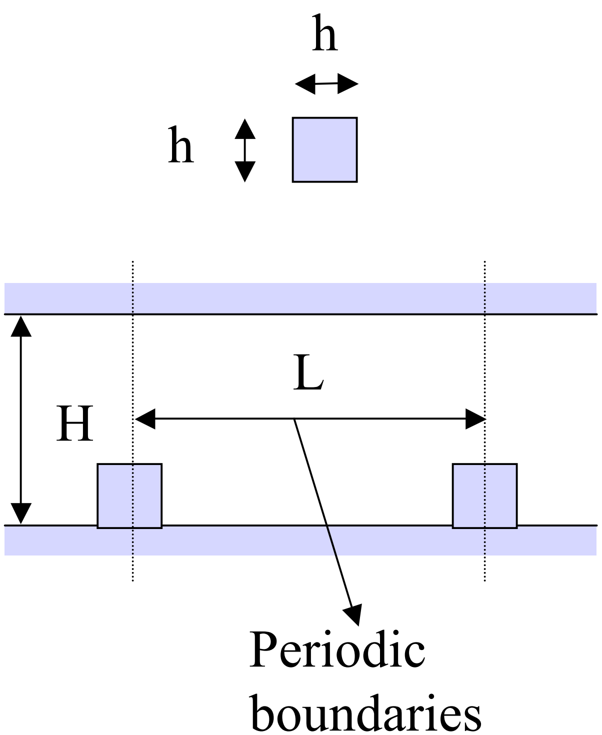


Ribbed Passages



Wall heat transfer (temperature gradients) are strongly connected to wall friction coefficients and therefore to turbulence modeling

Example: Ribbed Channel Flow



Problem set-up

Material Properties:
$\rho = 1 kg/m^3$
$\mu = 0.0001 kg/ms$
$Cp = 1000\ J/Kg/^oK$
$k = 0.142\ W/m\ ^oK$

Reynolds number:
h = 1m, L=10m, H=L
$Re_h = \rho U_b h/\mu = 10{,}000$

Boundary Conditions:
Periodicity $m=\rho U_b H=10 Kg/s$
No-slip walls

Initial Conditions:
$u = 1; v = p = 0$

Turbulence model:
k-ε

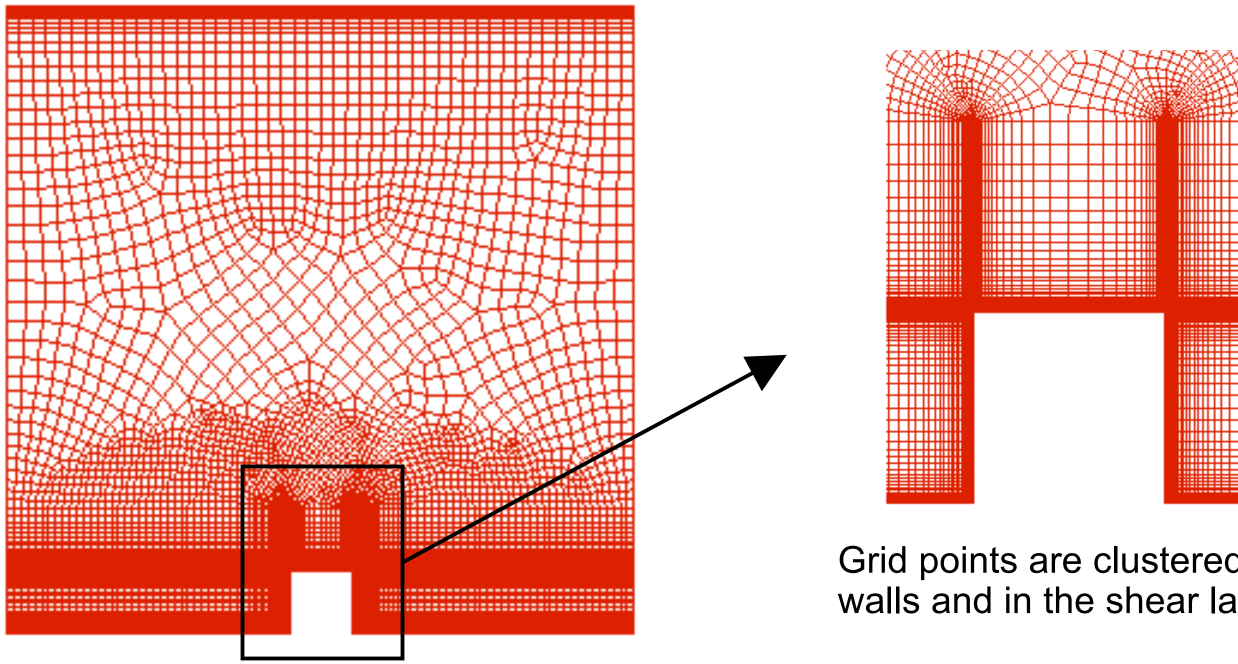
Solver Set-Up

Segregated Solver

Discretization:
2^{nd} order upwind
SIMPLE

Multigrid
V-Cycle

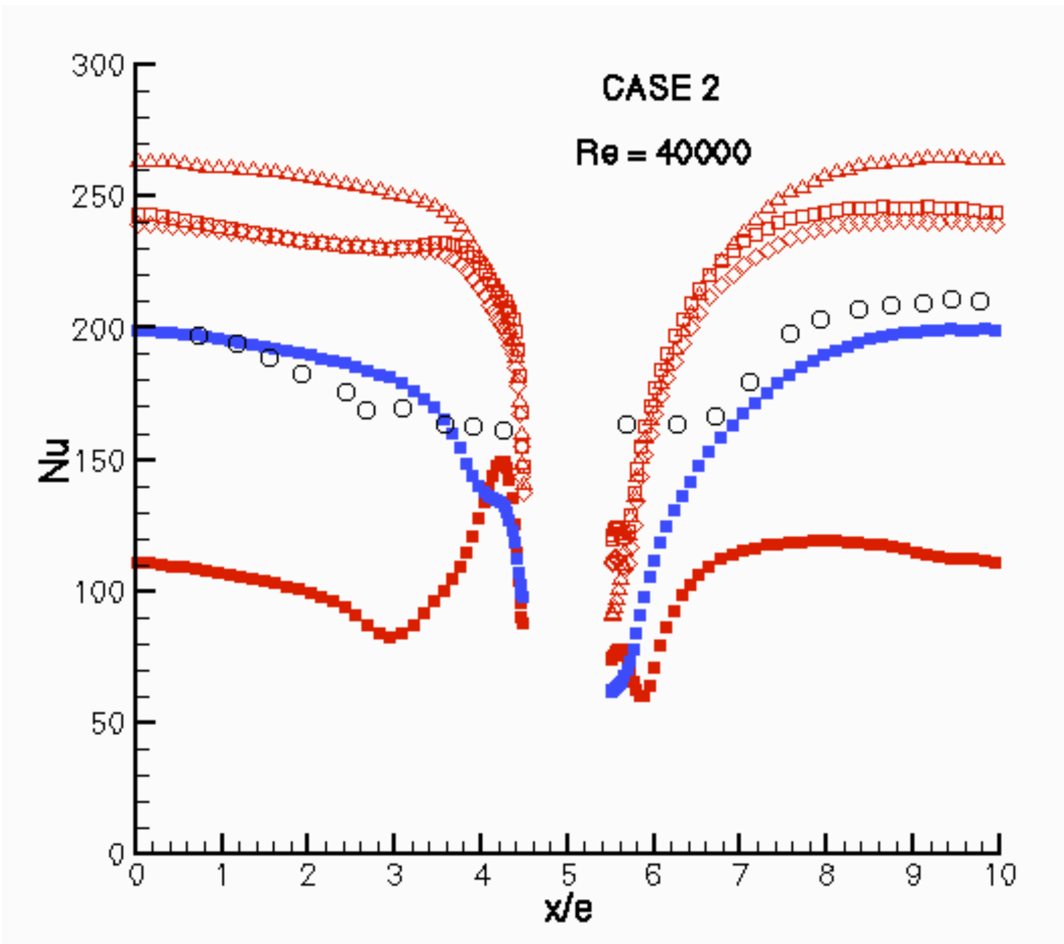
Grids in Ribbed Channel Flows

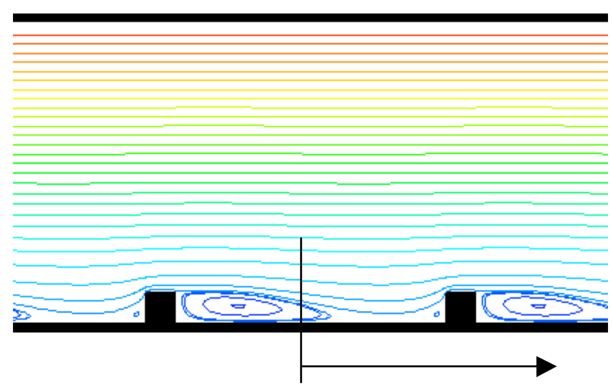


Grid points are clustered at the walls and in the shear layers

Unstructured gridding allows to separate the bottom and top BLs having different resolutions in the streamwise direction

Heat Transfer Predictions

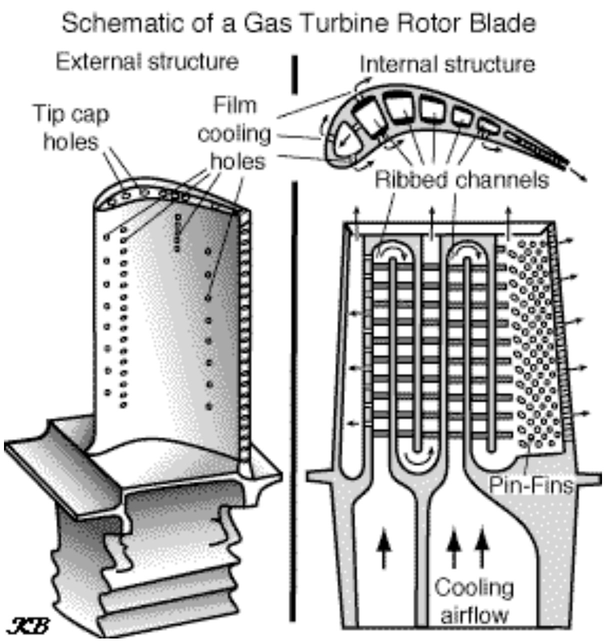


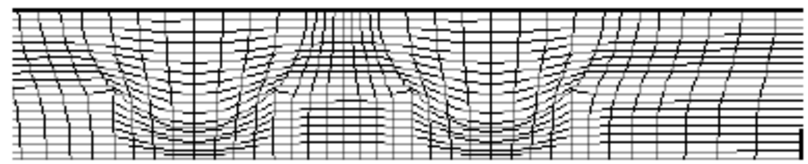


Conjugate Heat Transfer

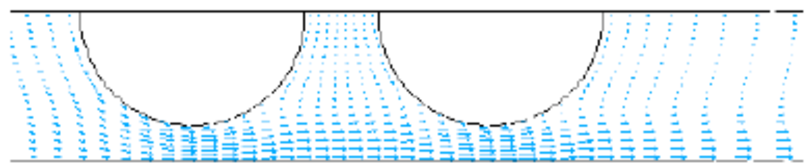
In many cases the correct prediction of the thermal field in a device requires the inclusion of conduction effects in solids

Conjugate simulations are referred to coupled fluid-solid temperature calculations

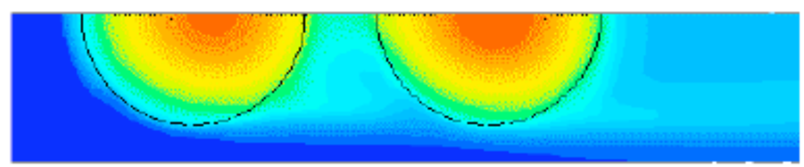




Grid



Velocity vectors

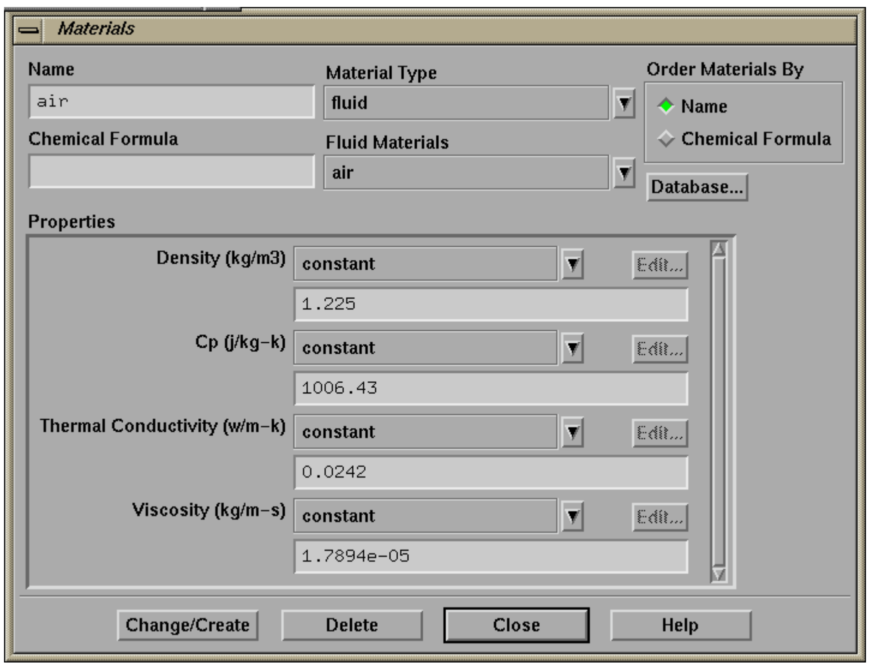


Temperature contours

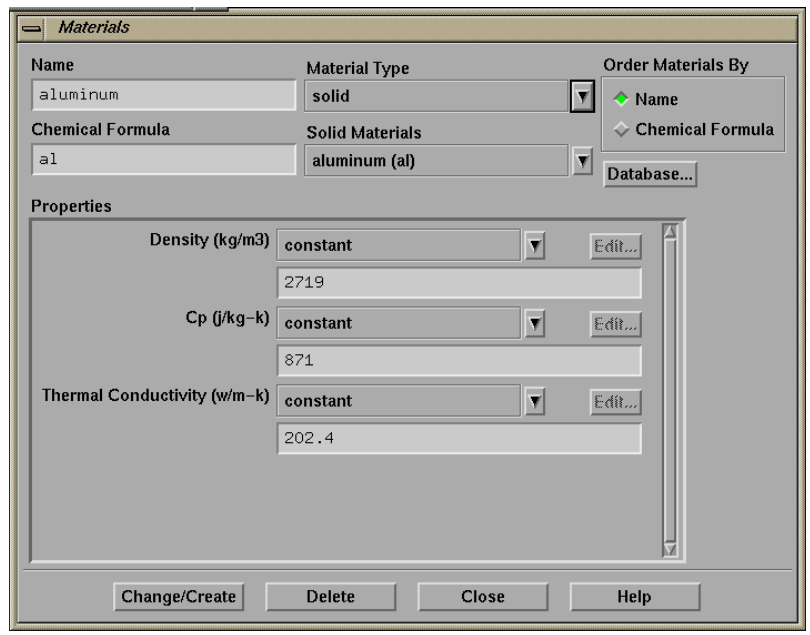
Set-Up Conjugate Heat Transfer

We need to specify two zones (fluid and solid) in the grid generation
And then specify the material properties

Define → Materials → Fluid

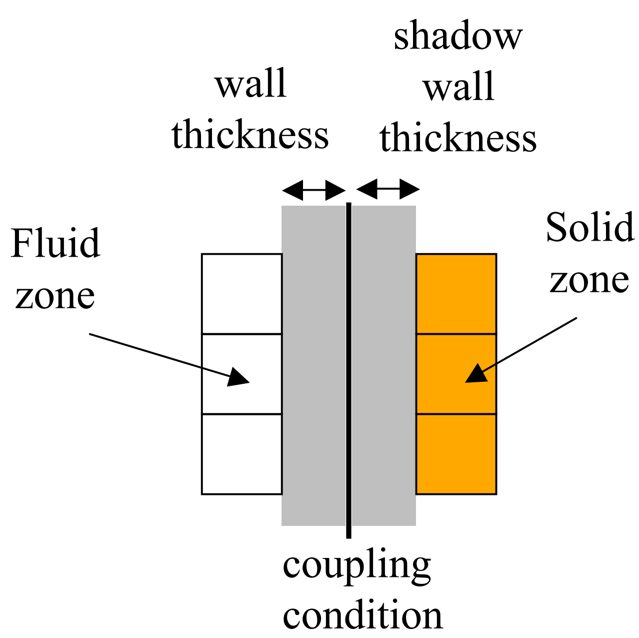


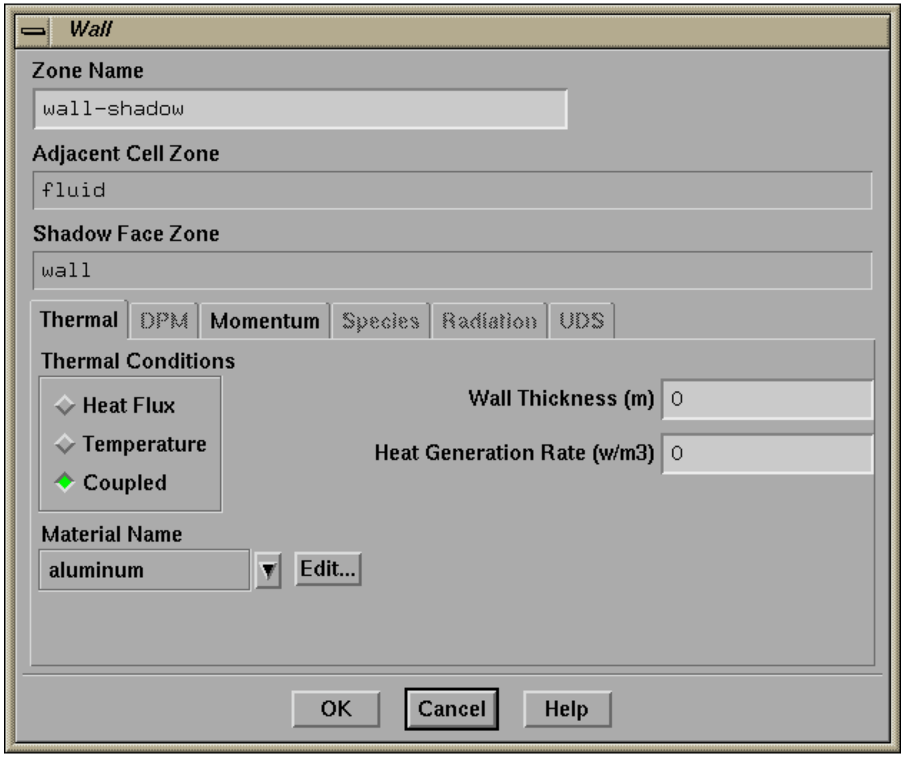
Define → Materials → Solid



Wall thermal boundary conditions

The boundary between the two zones is ALWAYS a wall and a shadow zone is created automatically by Fluent





Natural Convection

The fluid motion is induced by the heat transfer

Density and temperature are related; hotter gases rise…

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p$$

Thermal expansion coefficient is a characteristic property of fluids

The momentum equation must be written in compressible form (density is varying) and includes a source term

$$S_i = \rho\, g_i$$

Boussinesq approximation

Treat the fluid as incompressible provides faster convergence and simplifies the analysis

Rewrite the forcing term in the NS equations using linearization of the bouyancy force

$$(\rho - \rho_0)g \approx -\rho_0\beta(T - T_0)g$$

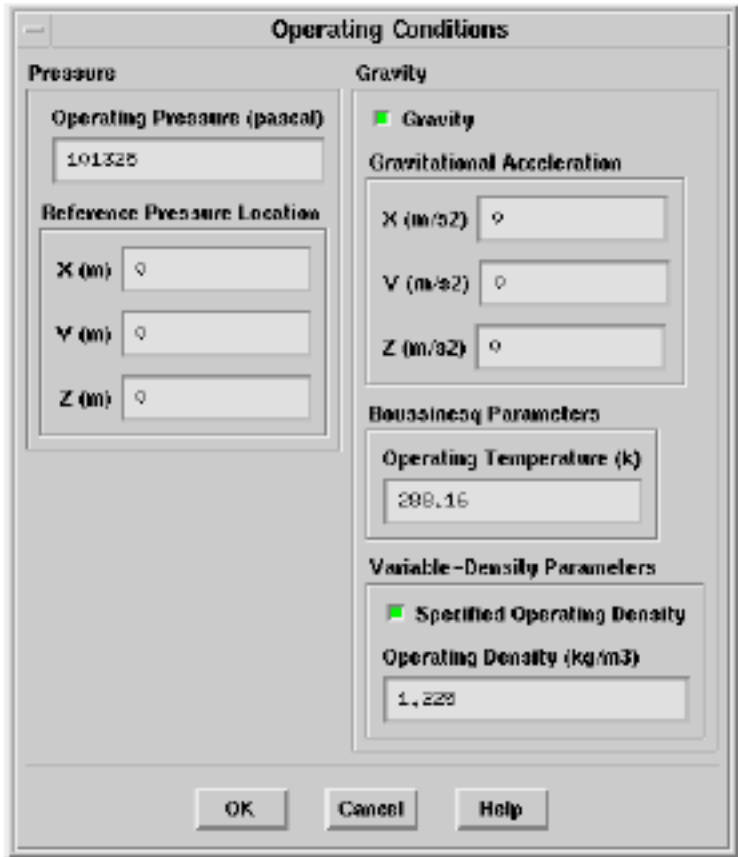
The momentum and energy equations are coupled by via the temperature!

Typically called Boussinesq fluids…

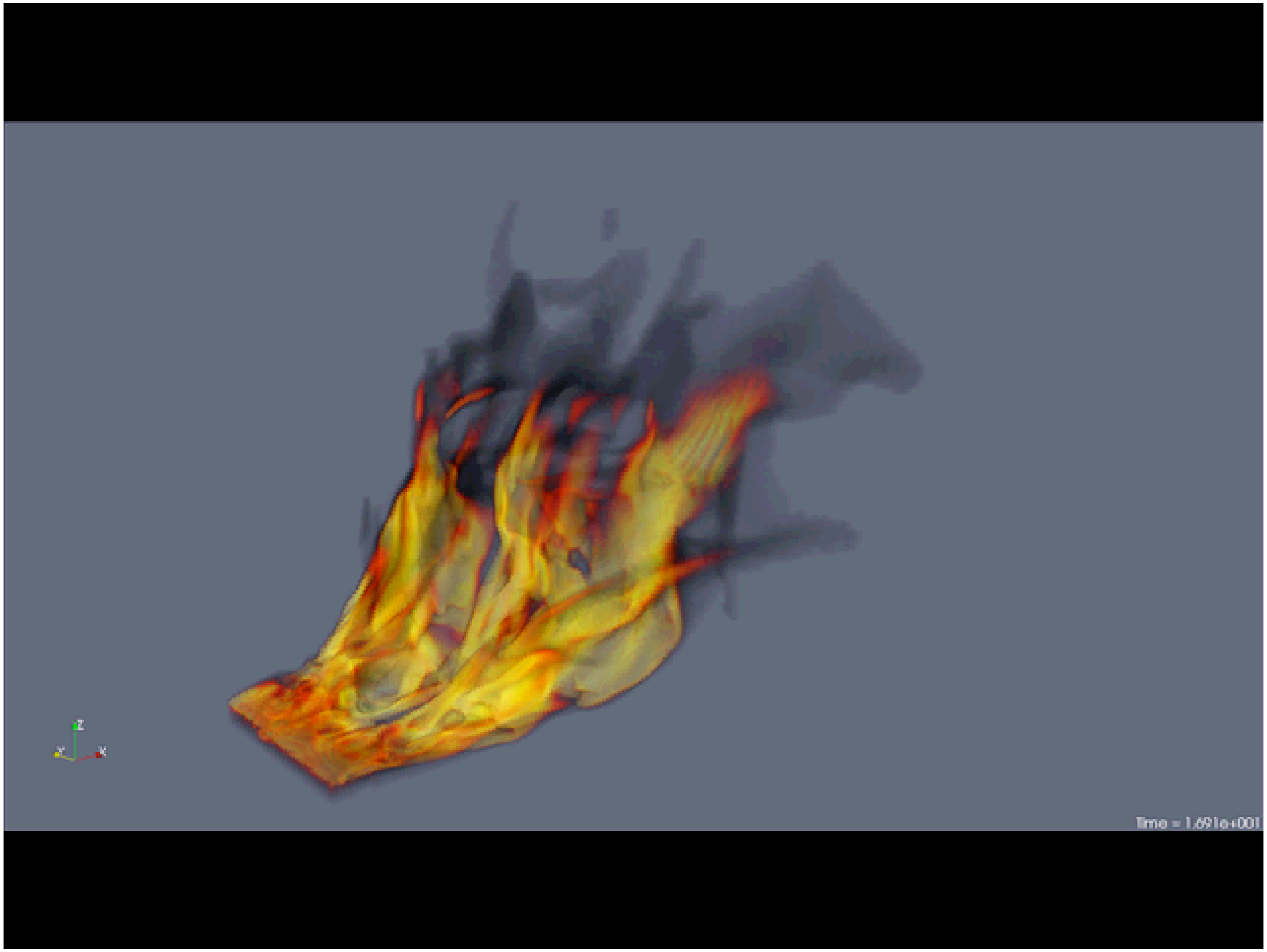
Setting up Natural Convection Simulations

Operating conditions allow to specify gravity and Boussinesq parameter (reference temperature)

β is specified as a material property

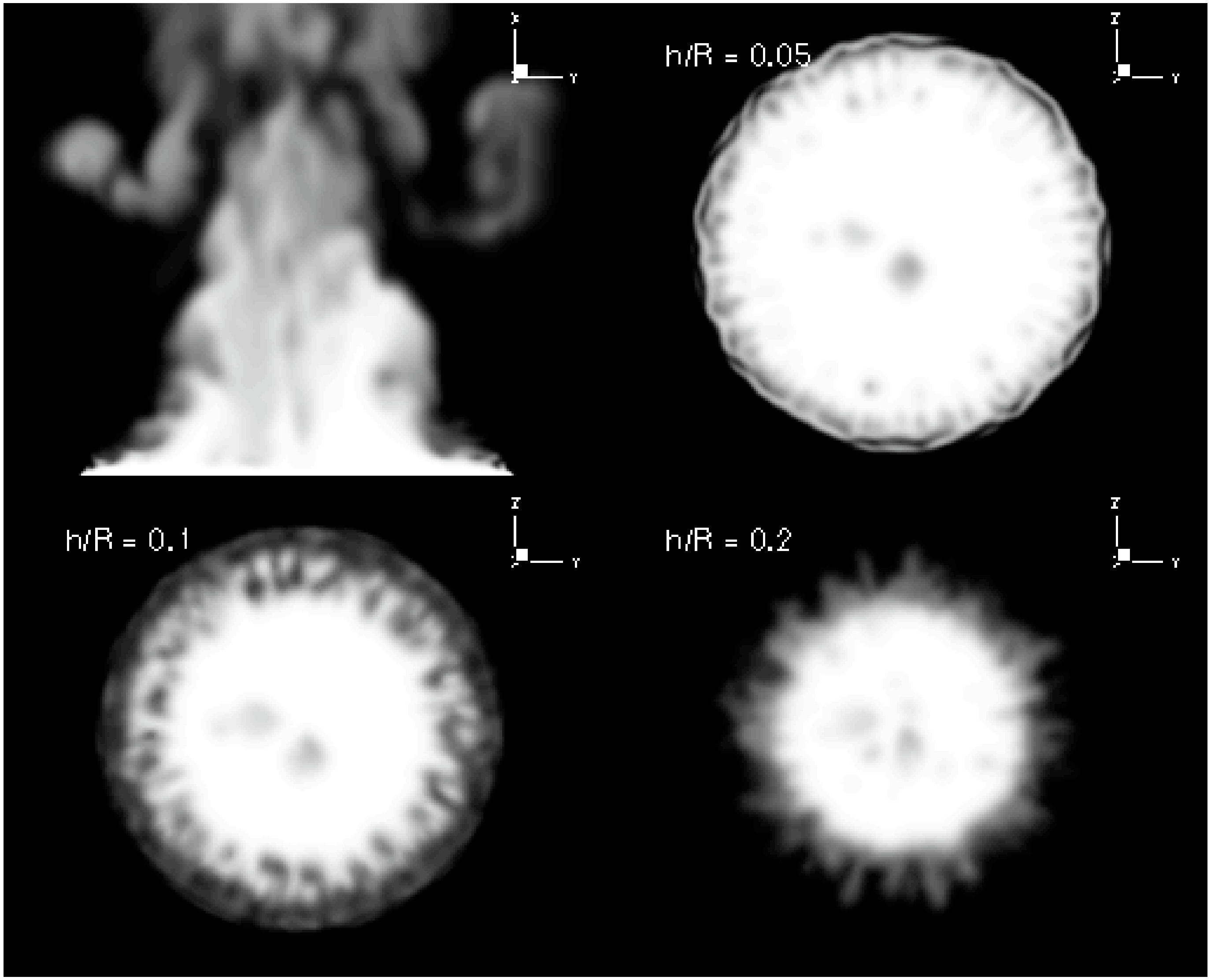


Fire Simulations



S. Domino, Sandia National Lab.

Helium Plume - not heat transfer, just buoyancy



Multi-Fluid mixing problem

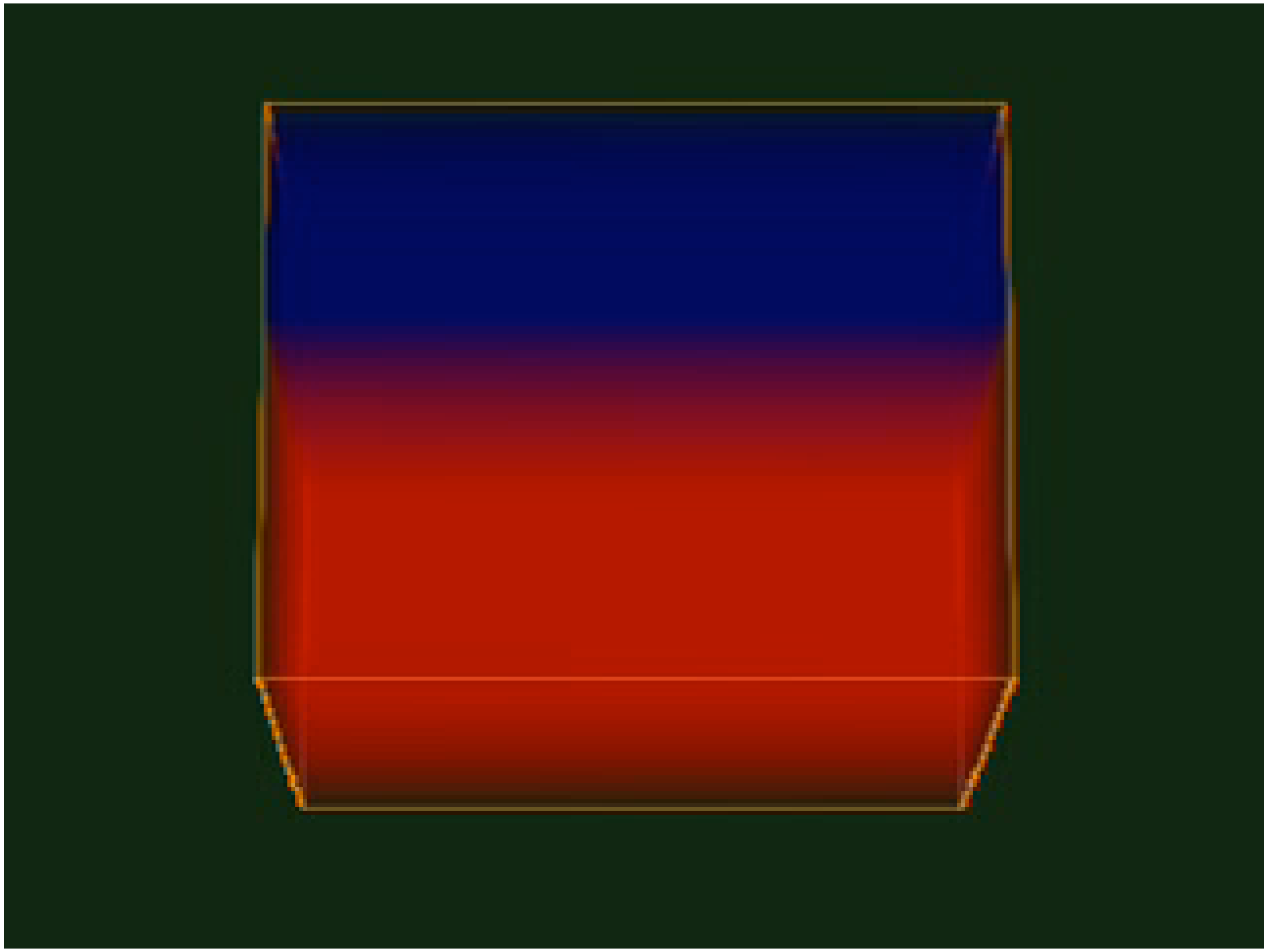
Describe the system as a mixture of two fluids, introduce the concept of mixture fraction (ϕ=0 fluid A, ϕ =1 fluid B)

Mixture properties are described as a function of ϕ

The fluid might have density variation (ρ_A, ρ_B) this is mapped into a variation in the mixture fraction $\rho=\rho(\phi)$

We can still use Boussinesq-like relationship and drive the flow by variations in mixture fraction

Raileght-Taylor instability



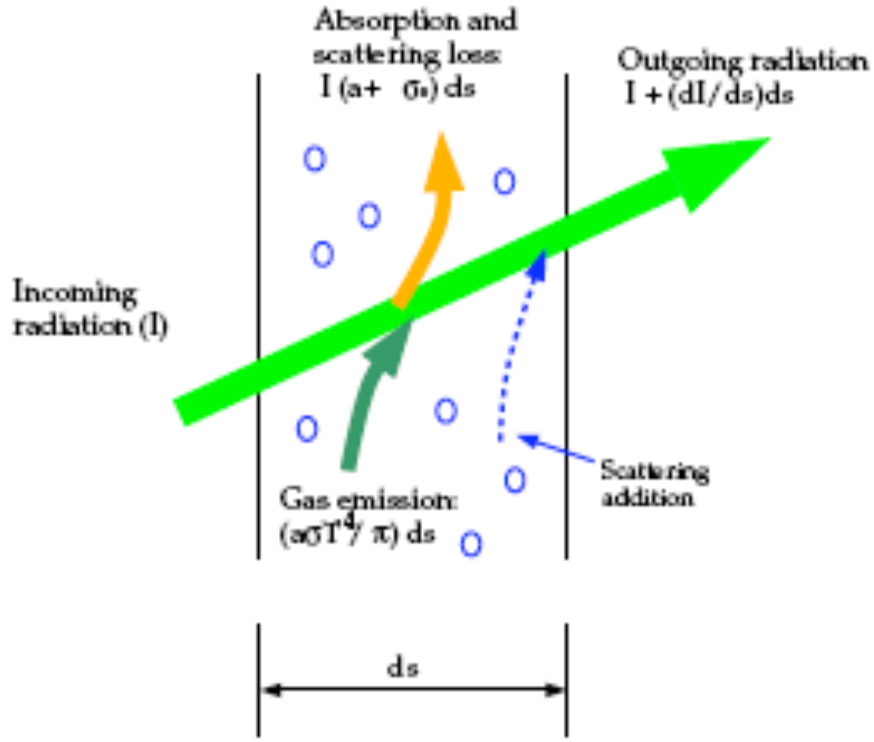
http://www.llnl.gov/casc/asciturb/movies.html

Radiative Heat Transfer

Transfer of heat due to electromagnetic waves

Complex physical phenomena due to its wave nature and the interactions with the environment

Several models depending on the conditions

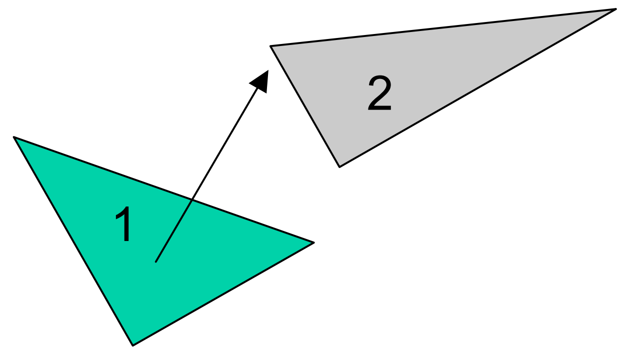


Radiative Heat Transfer - Surface to Surface

Simplest approach - no interaction with the environment

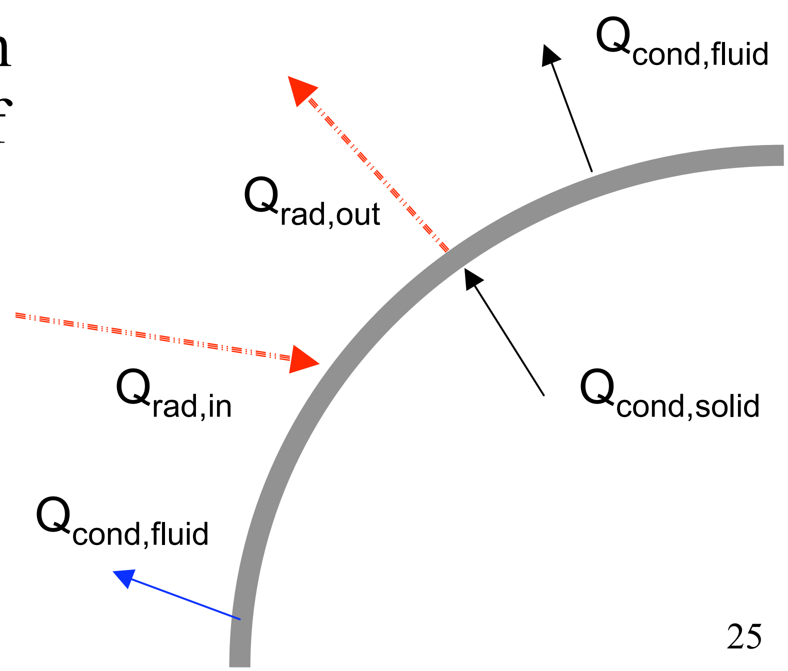
View factors

F_{12} = fraction of thermal power leaving object 1 and reaching object 2



The end result is a quantification of the net flux out and in each of the surfaces in the model

The boundary condition is based on a energy balance



Radiative Heat Transfer

More sophisticated models attempt to reproduce the interaction between the environment and the electromagnetic waves

Comments on Thermo-fluid simulations

In incompressible flows the energy equation is decoupled from the momentum equations and can be solved a posteriori with the velocity field frozen

Additional modeling is involved for the solution of thermal equation in the RANS context (therefore additional approximations and errors)

Wall quantities (temperature and heat flux) are very sensitive to the modeling of near-wall turbulence

Conjugate heat transfer (coupled fluid/solid) are often necessary to describe accurately a physical device

Natural convection introduces a coupling between velocity and temperature field