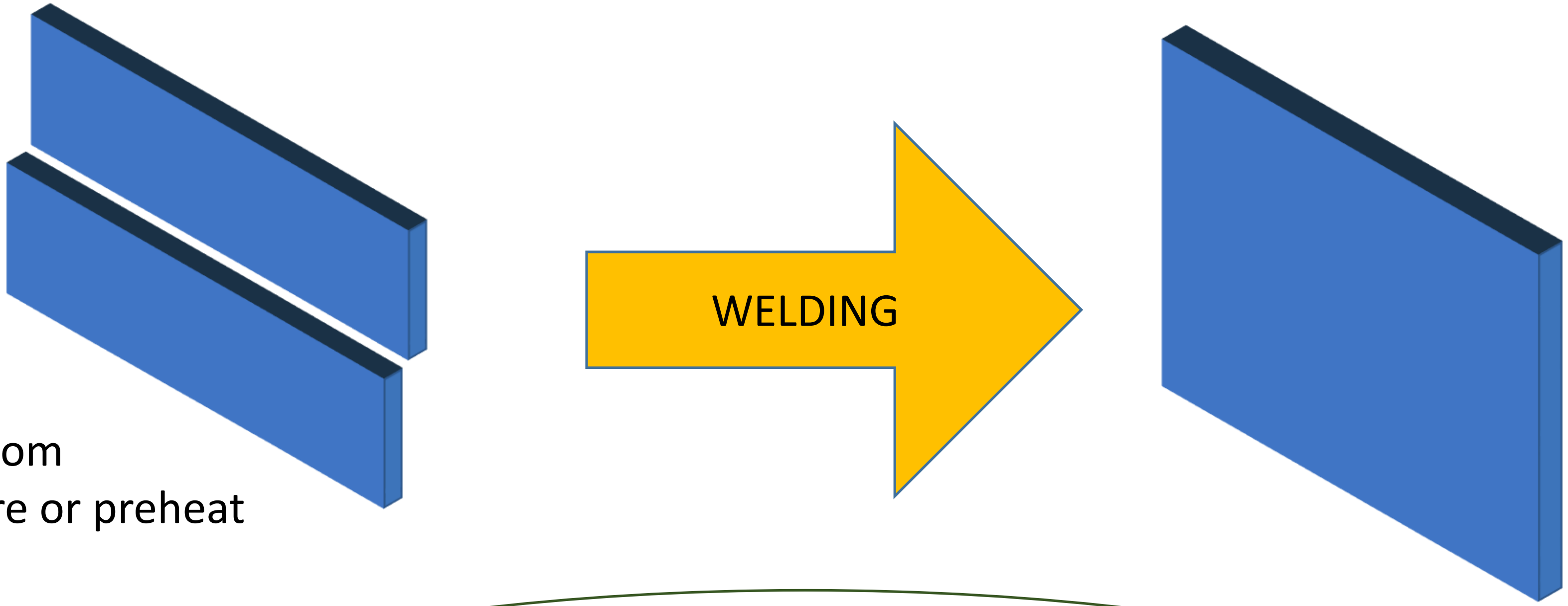
Heat removal

NPTEL Online Course on
Analysis and Modelling of Welding

G. Phanikumar

Department of MME, IIT Madras

Why is heat removal critical for welding?

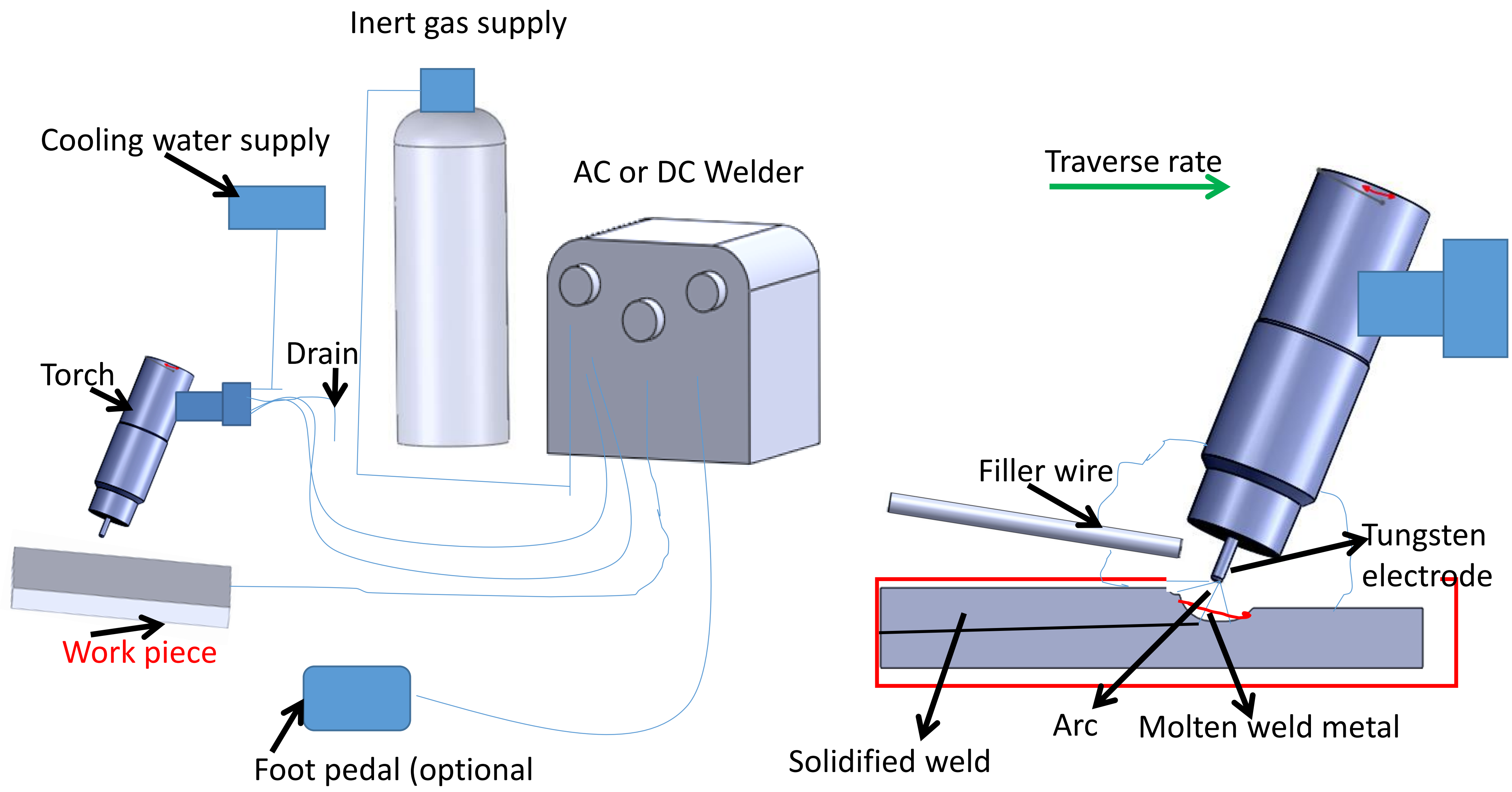


Plates at room temperature or preheat

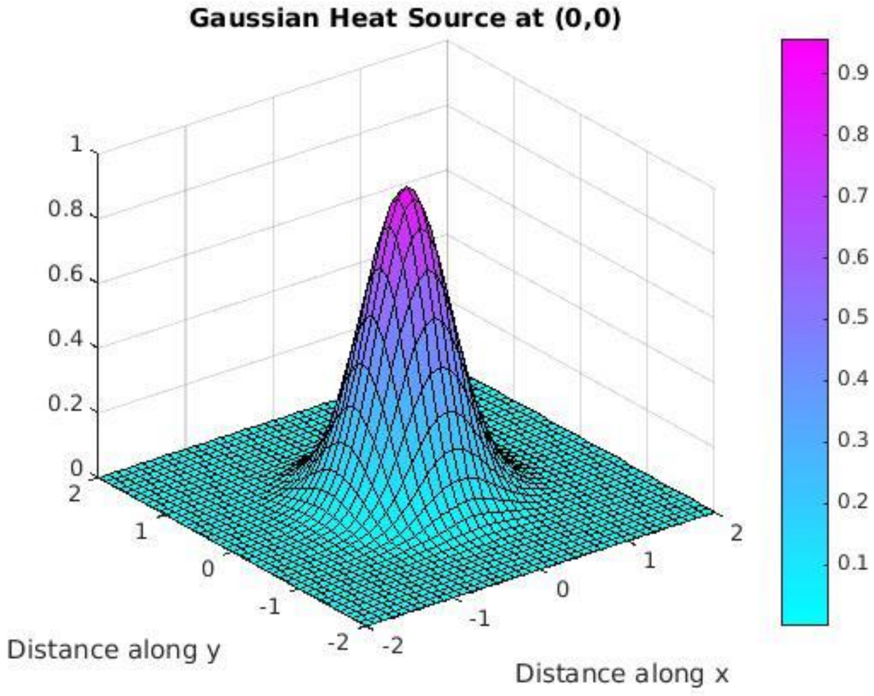
Joint at room temperature

All of or more than the heat given by heat source to base material for heating, melting and even some evaporation of the base material should eventually be taken away from the system to the surroundings.

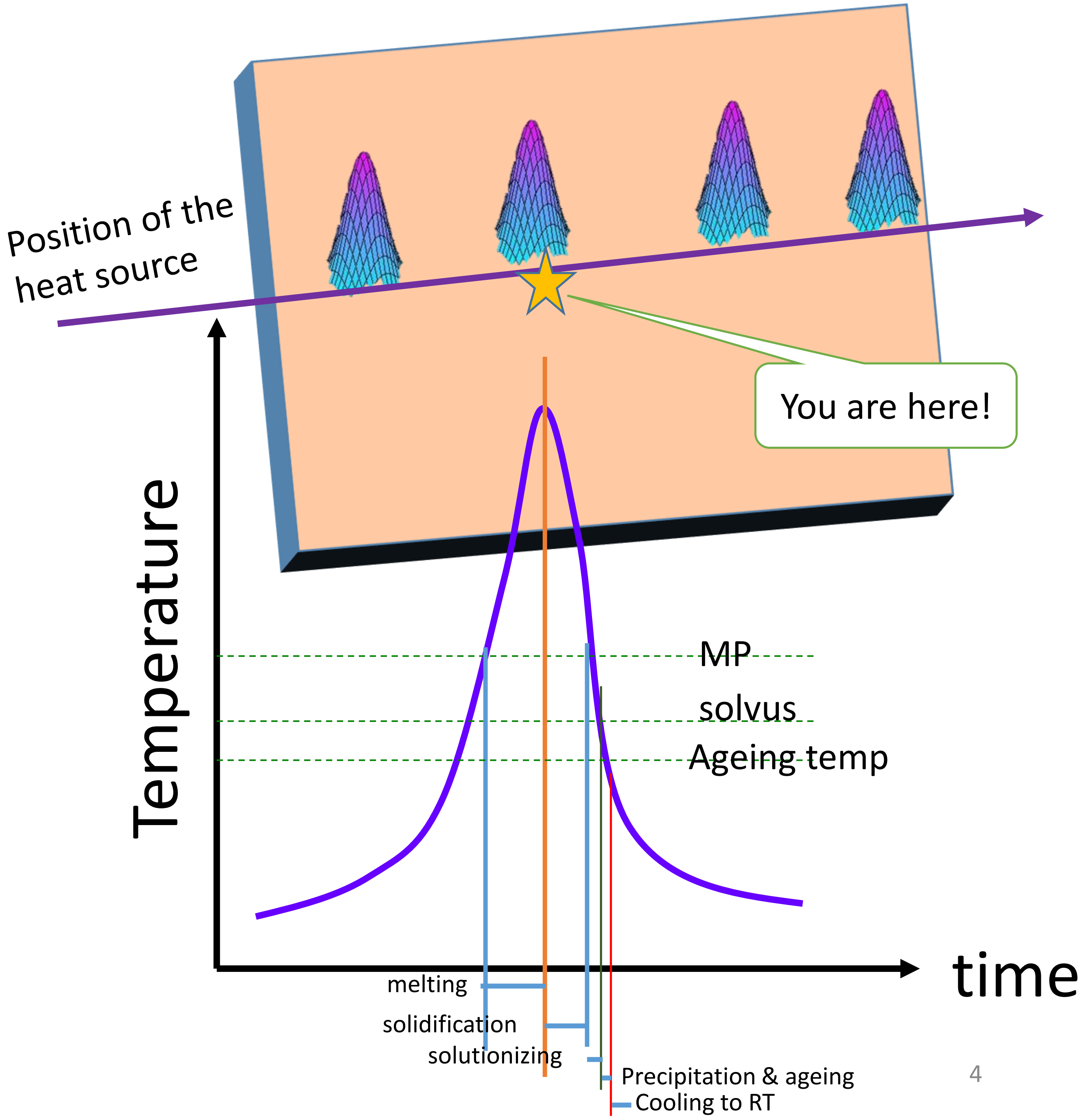
Domain (System) and Boundary (Surroundings)



Thermal history at a location below heat source



Moving heat source



Modes of heat removal

- Conduction : base material away from weld
- Heat sinks: Gas through nozzles, gas jets

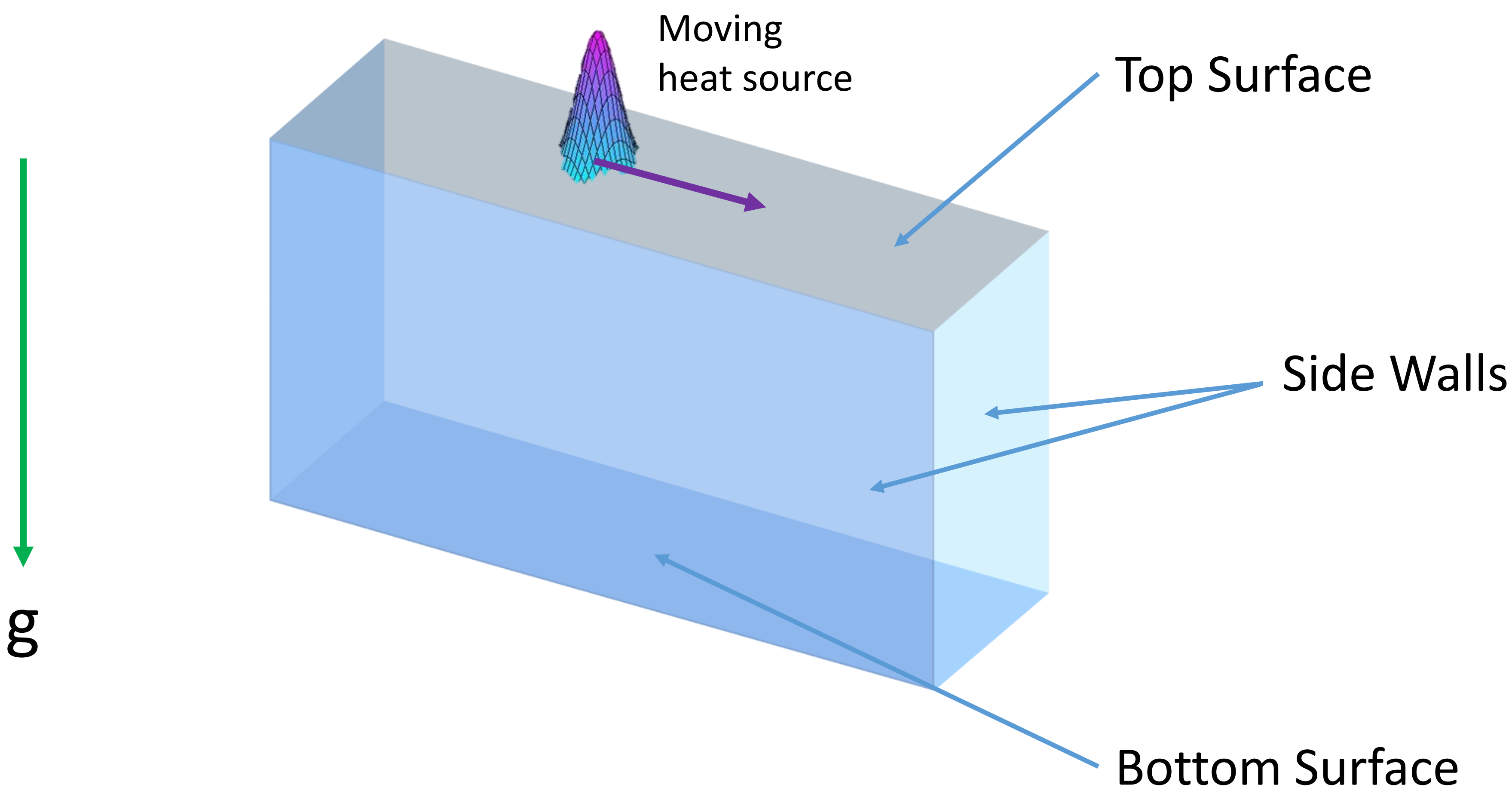
Thermal Modelling of Weldment

- Convection : gas and ambient air
- Contact with fixtures and holding table
- Water-cooled copper back-up plates

- Radiation

Boundary conditions

Domain Boundaries

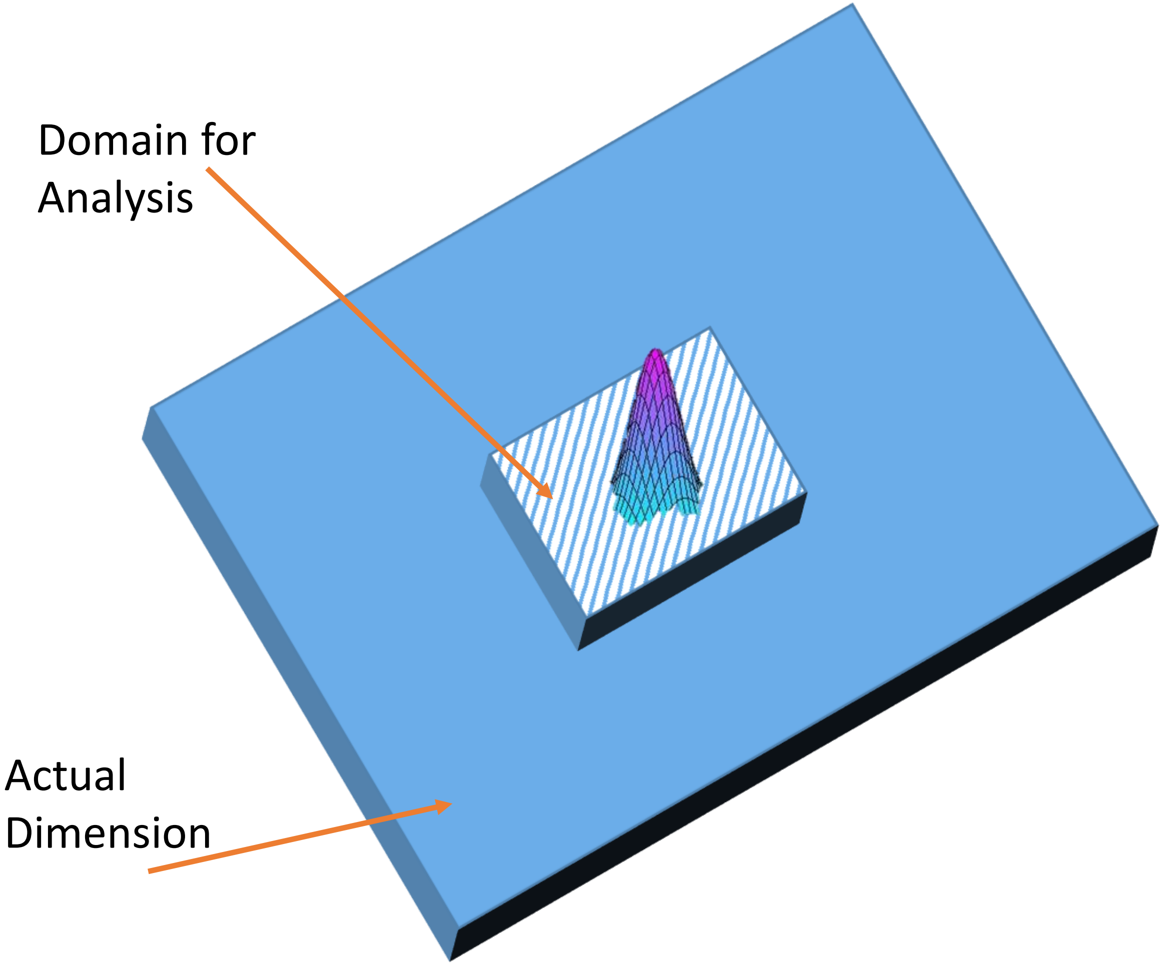


Faces that are :

- Exposed to heat source
- Exposed to heat loss
- Placed on Table

For complicated geometries there will be multiple such faces and walls

Domain size versus Actual size

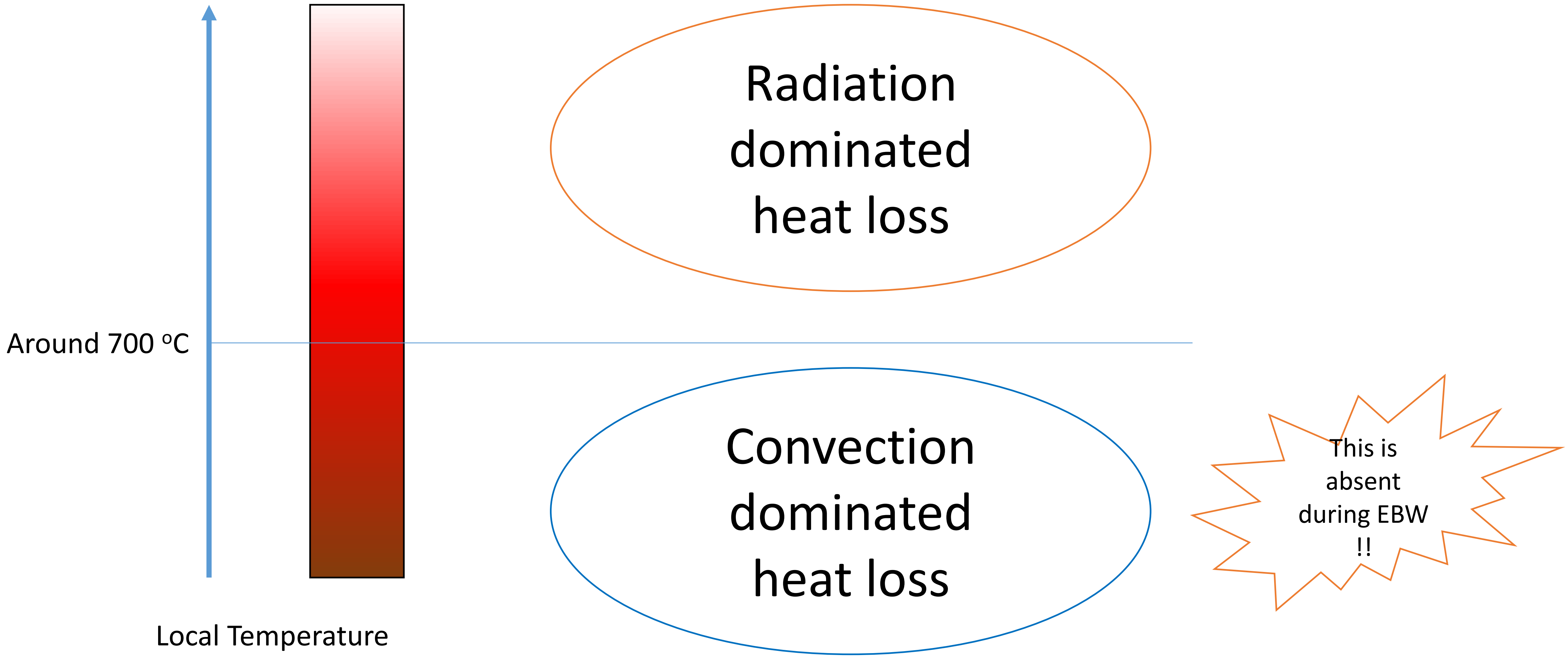


Domain size for analysis may be limited for feasibility with the welding software.

How far are the side walls from those of actual sample and the weld?

Constant temperature condition may be applicable sometimes.

Choice between Radiation and Convection



Fourier heat conduction

At the boundary, the following heat flux balance should hold:

$$j = -k \left.\frac{\partial T}{\partial x}\right|_i$$

Here, k is the thermal conductivity of the base material and j is the heat flux (loss) to the surroundings.
Note that this is at the boundary (i) and x is the distance into base material from surroundings.

Erratum: watch out this correction while viewing the video.

Our task is to express *j* according to the mode of heat loss to the surroundings

Heat loss through radiation

Heat Flux : Wm^{-2}

$$j = \sigma\varepsilon(T^4 - T_\infty^4)$$

View factors are often unity in welding.

Stefan-Boltzmann constant $\sigma = 5.67051 \times 10^{-8}$ $Wm^{-2}K^{-4}$

Emissivity ε depends on surface conditions.

Far field temperature T_∞ is often room temperature.

T is the temperature of the base material at the boundary.

Linearizing radiation heat loss

$$j = \sigma\varepsilon(T^4 - T_\infty^4) = \sigma\varepsilon(T^2 + T_\infty^2)(T + T_\infty)(T - T_\infty)$$

Linearize the equation to look like:

$$j = \sigma\varepsilon(T^4 - T_\infty^4) = h_r(\mathrm{T}) \cdot (T - T_\infty)$$

Here, *T* is the temperature of the base material at the boundary.

Heat loss through convection

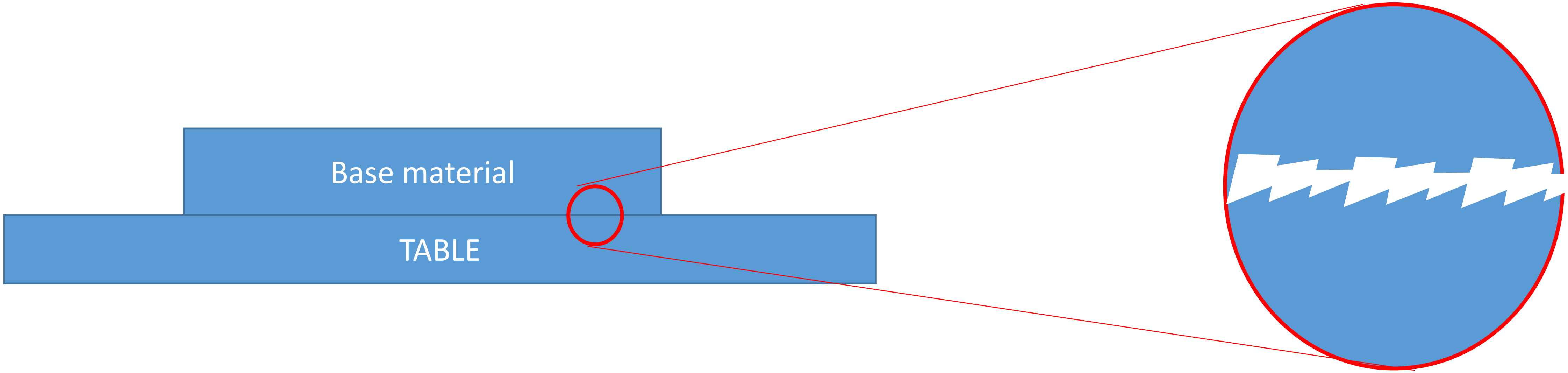
Heat Flux : Wm^{-2}

$$j = h(T - T_\infty)$$

Heat transfer coefficient h depends on material, surrounding and the geometry

Are there ways to estimate or determine *h* ?

Contact resistance



Conducting pastes can be used to avoid contact resistance

Discontinuous contact with a solid surface can also be handled using heat transfer coefficient.

Nusselt number

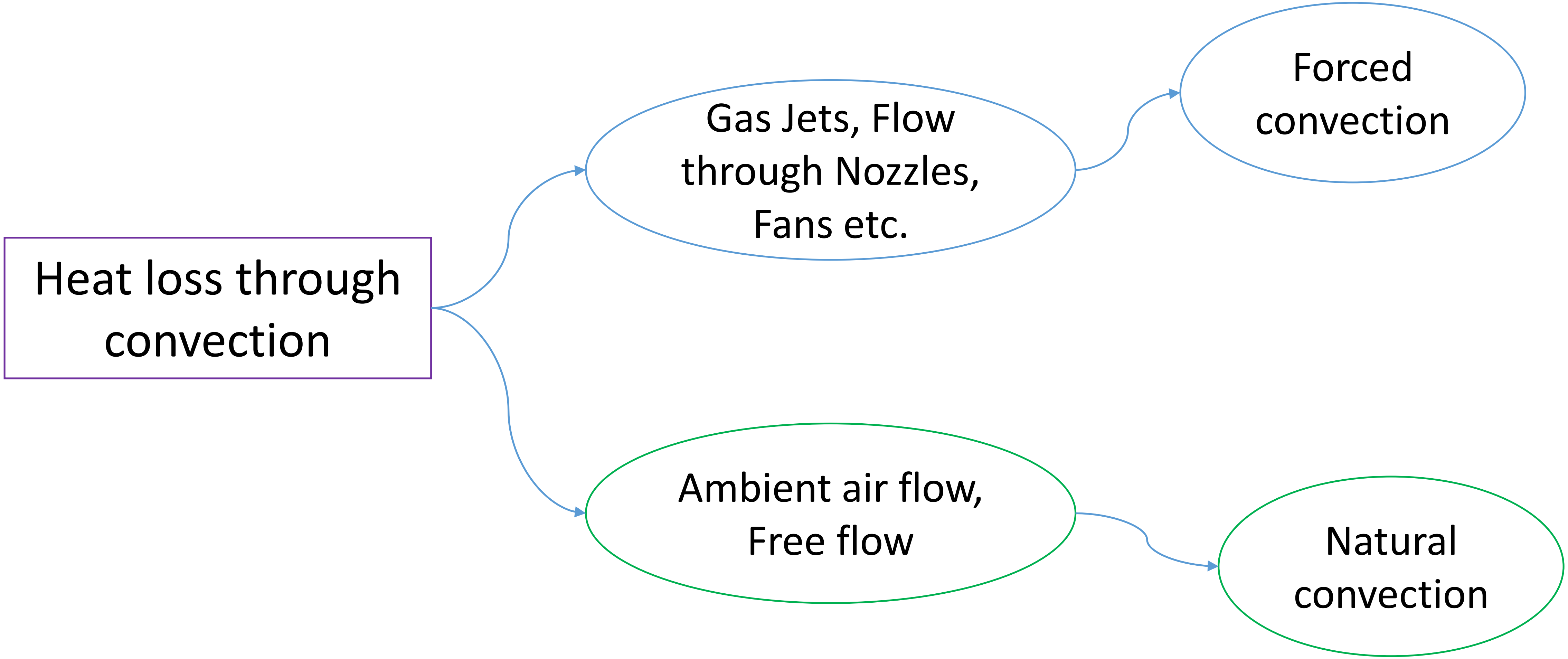
$$Nu_x = \frac{hx}{k}$$

Here, Nu is the non-dimensional number, h is the heat transfer coefficient
x is the characteristic distance and k is the thermal conductivity of the fluid medium !
Watch out that k is not the thermal conductivity of the base material in this expression.

Characteristic distance :

Distance from edge along the plate in the direction of flow
Diameter of the nozzle
Etc.

Estimating the heat transfer coefficient



Nusselt number correlations for forced convection

Often given as correlations using Reynold's number and Prandtl number

$$Re_x = \frac{\rho V x}{\mu}$$
$$Pr = \frac{\nu}{\alpha}$$

Here, ρ is the density of the fluid / gas medium in the surroundings, V is the velocity of the fluid, x is the characteristic distance and μ is the dynamic viscosity of the fluid, $\nu = \mu/\rho$ is the kinematic viscosity of the fluid and α is the thermal diffusivity of the fluid.

Example:

Nusselt number for turbulent external flow over a flat plate at uniform surface temperature valid for
$0.6 < Pr < 60$ and $Re < 10^8$:

$$Nu_x = 0.0296 Re_x^{0.8} Pr^{1/3}$$

Ref: Page 260 of Heat Transfer by Adrian Bejan, John Wiley & Sons (1993) ISBN: 0471502901

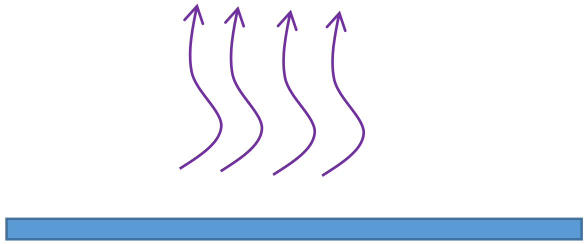
Nusselt number correlations for natural convection

Often given as correlations using Rayleigh number

$$Ra_x = \frac{g\beta(T - T_\infty)x^3}{\alpha v}$$

Here, g is the acceleration due to gravity, β is coefficient of thermal expansion, x is the characteristic distance, α is the thermal diffusivity of the fluid and ν is the kinematic viscosity of the fluid.

What is Grashof number? Nusselt number correlations for natural convection are also given in terms of Grashof numbers !



Example:

Hot plate facing upward, valid for $10^4 < Ra_L < 10^7$

$$\overline{Nu_L} = 0.54\, Ra_L^{1/4}$$

Ref: Page 358 of Heat Transfer by Adrian Bejan, John Wiley & Sons (1993) ISBN: 0471502901

Determining heat transfer coefficient

Embed Thermocouples at different depths from the boundary

Capture Thermal History in the base material

Perform **Inverse Heat Transfer** Analysis

Obtain empirical correlations for either h or j

Precautions

- Conditions for which the correlations are valid versus conditions prevailing during welding : is there sufficient match?
- Inspect the values used for h : are they reasonable and justified?
- Sensitivity of these values w.r.t. minor changes in experimental process conditions : are the values robust?
- If correlations are used, are the average values appropriate and sufficient?

End of lesson on heat removal