Lecture

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Radiative Heat Transfer

Modelling

in PHOENICS

Why Model Radiation?

- Some typical reasons…
- Warm surfaces in buildings will radiate heat to cooler surfaces.
- If you stand near the sun-warmed wall of a building you will feel hot.
- Many comfort indices involve a radiant temperature – we need to know what this is.
- In a fire or in a combustor, the hot smoky gases emit and absorb radiation – this affects the temperature distributions.
- Many other examples.

Difficulty of Modelling Radiation

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- Radiation travels in straight lines.
- It is not convected or diffused.
- Therefore obeys entirely different equations from those solved in CFD.
- Accurate tracking of radiation in a model is seriously expensive!
- Spalding recognised the need for engineers to get an adequate solution within reasonable computing time.
- This led to the development of the IMMERSOL radiation model.

“Optically Thin” and “Optically Thick”

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- Compare the “mean free path” of the radiation with typical distance between the radiating walls.

- Large mean free path - “optically thin”.
Radiation travels long distances without being absorbed.
- Typical example - ventilation in internal spaces.

- Small mean free path path - “optically thick”.
Radiation quickly absorbed - re-emitted - re-absorbed - etc.
- Typical example – hot smoky gases in fires, combustors.

Radiosity and Radiant Temperature

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- We need to consider the meanings of these quantities.
- Consider a small volume. The radiosity R (W/m^2) is defined as the sum all radiation fluxes traversing the volume.
- Imagine a small "black-body" probe inserted into the space, in thermal equilibrium with the local radiation.
- Define the temperature of such a probe as the local radiant temperature T3 (^oK).
- R and T3 are related by the equation:

  $R = \sigma (T3)^4$

- σ is the Stefan-Boltzmann constant = 5.67E8 W m^{-2} K^{-4}
- The IMMERSOL model solves for T3.

Equation for Radiant Temperature

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- In the thick optical limit (e.g. thick smoke) radiant temperature obeys a conduction-type equation.
- Wall temperatures form the boundary condition.
- Can be shown that the resistivity (i.e. temperature gradient / radiation flux) is $(3/16)\,(e+s)\,/\,\sigma T^3$.
- Note e, s are the emissivity, scattering coeffs per unit length
- In the thin optical limit (clear air) we ASSUME that radiant temperature obeys a similar equation.
- This is the big assumption of IMMERSOL.
- Given this, it is easy to show that the resistivity is

  $(0.25 / w_{gap}) / \sigma T^3$
- (Note w_{gap} is the distance between the hot and cold walls.)
- (Note this also assumes the temperature difference is small.)

Equation for Radiant Temperature

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- IMMERSOL has to cover both optically thin and thick, and intermediate states.
- We ASSUME (1) that T3 obeys a conduction-type equation (as discussed above) for the general case,
- ASSUME (2) a general approach can be obtained by adding the resistivities for thin and thick scenarios:
- Resistivity is $((3/16)\,(e+s) + 0.25 / w_{gap}) / (\sigma\, T^3)$

- Note for optically thin case (e+s) is zero, so first term drops out, leaving the correct (approximate) resistivity.
- For optically thick case (e.g. smoke), emissivity per unit length is large, so first term dominates – also correct.

Equation for Radiant Temperature

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- So, to summarise:

- IMMERSOL solves a conduction equation for T3 with the above resistivity, for given boundary wall temperatures.
- T3 can be used to establish:
  - wall surface temperatures via a surface heat balance,
  - comfort indices for wind or ventilation cases,
  - amount of radiative heating for smoke or combustion cases.

- Details of the derivation are in the POLIS article on Immersol.

Boundary Conditions

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- We have seen that the T3 equation is a conduction-type equation. There is no convection of T3.
- The boundary conditions for T3 are the wall temperatures.
- At some boundaries, the wall temperature may be specified.
- At others, the wall temperature is determined by solving a surface heat balance equation at the wall.
- Thermal radiation to/from the wall, heat convection at the surface, and heat conduction away from the surface, must all balance.
- The wall temperature derived from this balance is stored in the variable TWAL which can be plotted.

Flow Boundaries

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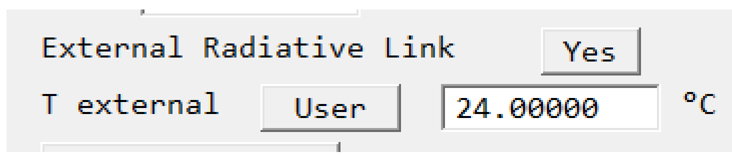
- At inflow or outflow boundaries need to specify whether radiation can pass through…
- And if so, what is the external temperature that the radiation "sees" through the boundary.
- This is set in the Attributes panel:



- In a Wind model with temperature and radiation (e.g. Urban Heat Island) this appears in the Wind attributes.
- Need to say "Yes" and give suitable "Sky temperature".
- E.g. "Survey of Sky EffectiveTemperature Models Applicable to Building Envelope Radiant Heat Transfer" by Algarni and Nutter.
- July 2015 / DOI:10.13140/RG.2.1.4212.5526 / Report number: AT-15-029

Example – Ventilation and Natural Convection in a Room

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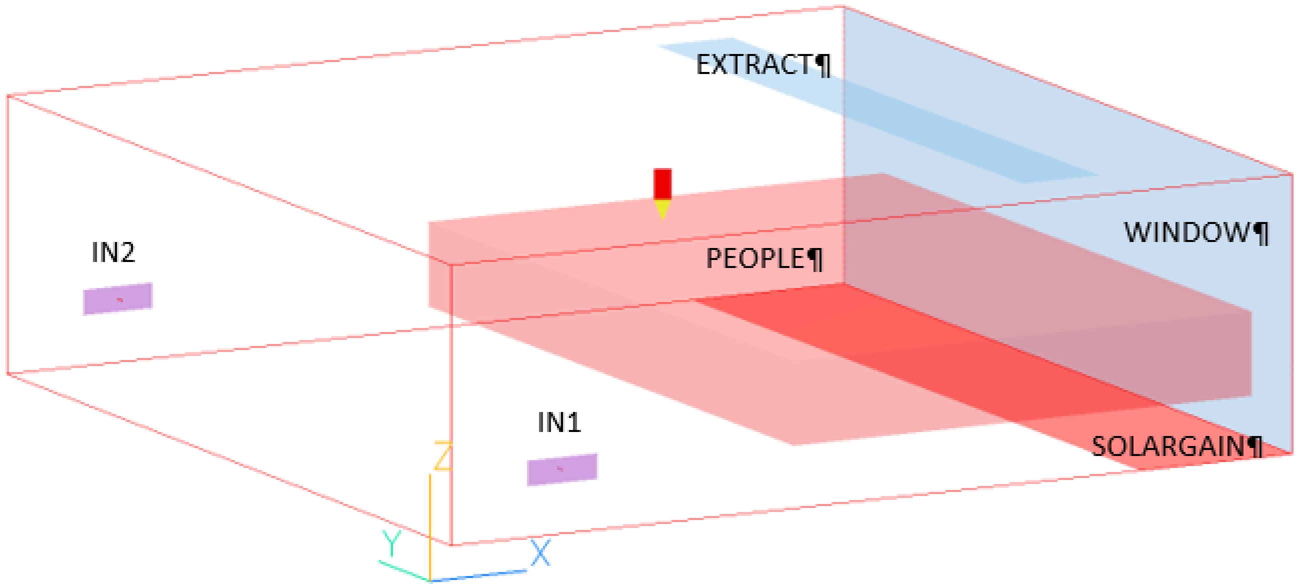
3 heat sources:

- people (the pink box),
- solar gain (on the floor near the window),
- window (with high external temperature).

surface emissivities = 1



Example – Ventilation and Natural Convection in a Room

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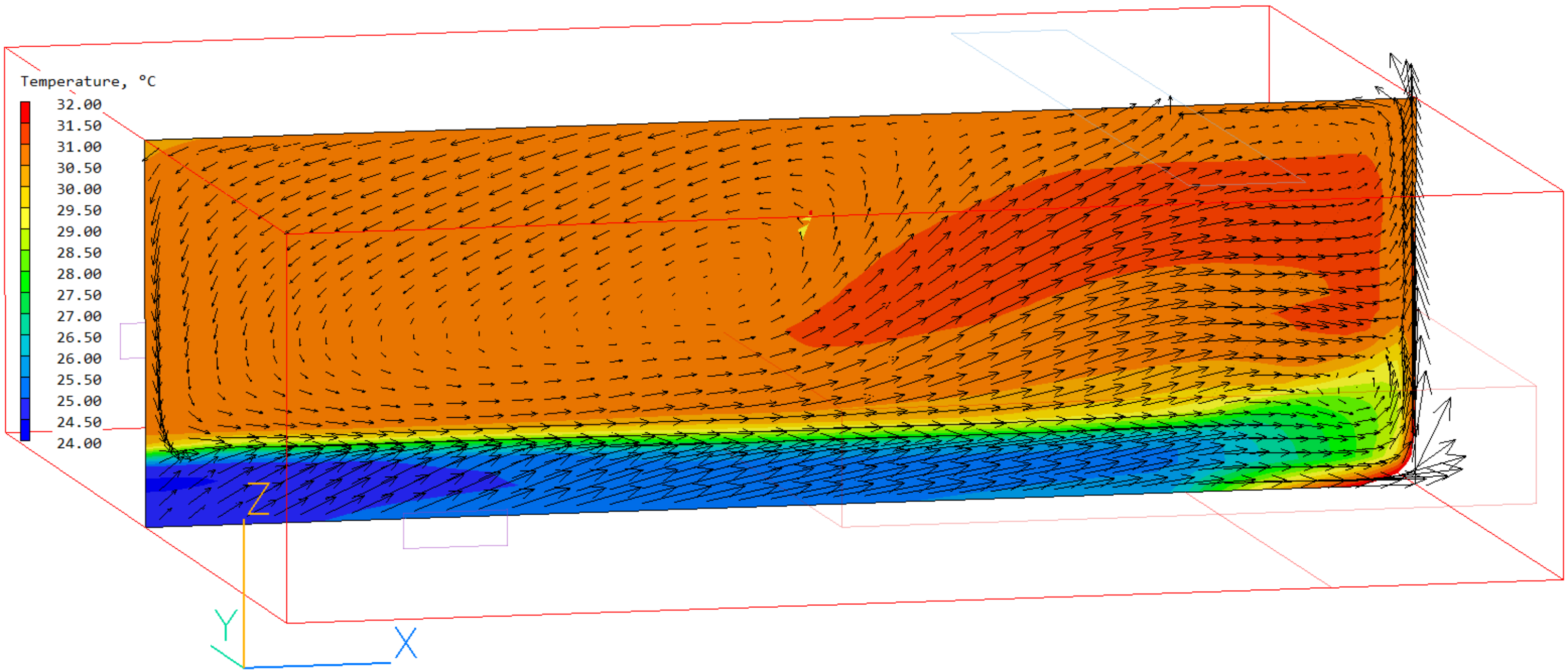
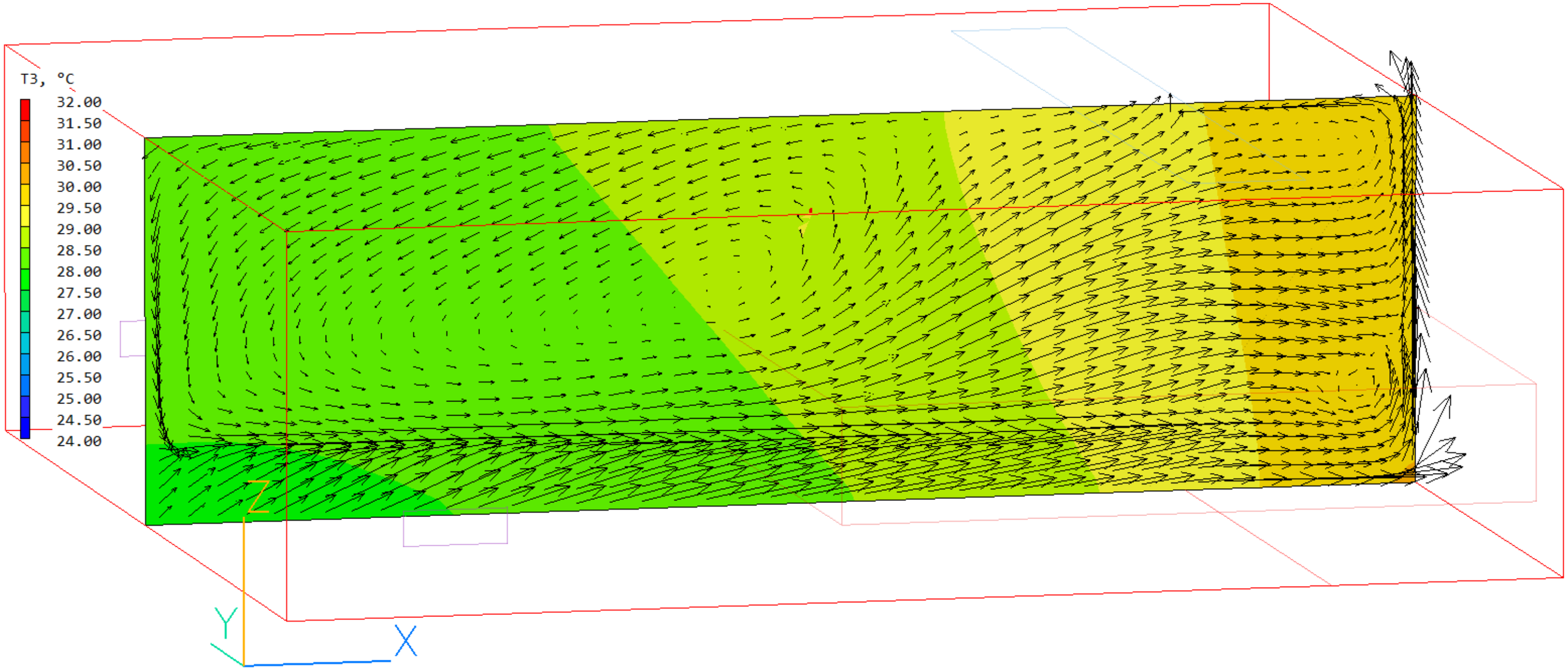
- Contours of temperature TEM1



Example – Ventilation and Natural Convection in a Room

- Contours of temperature T3



Example – Ventilation and Natural Convection in a Room

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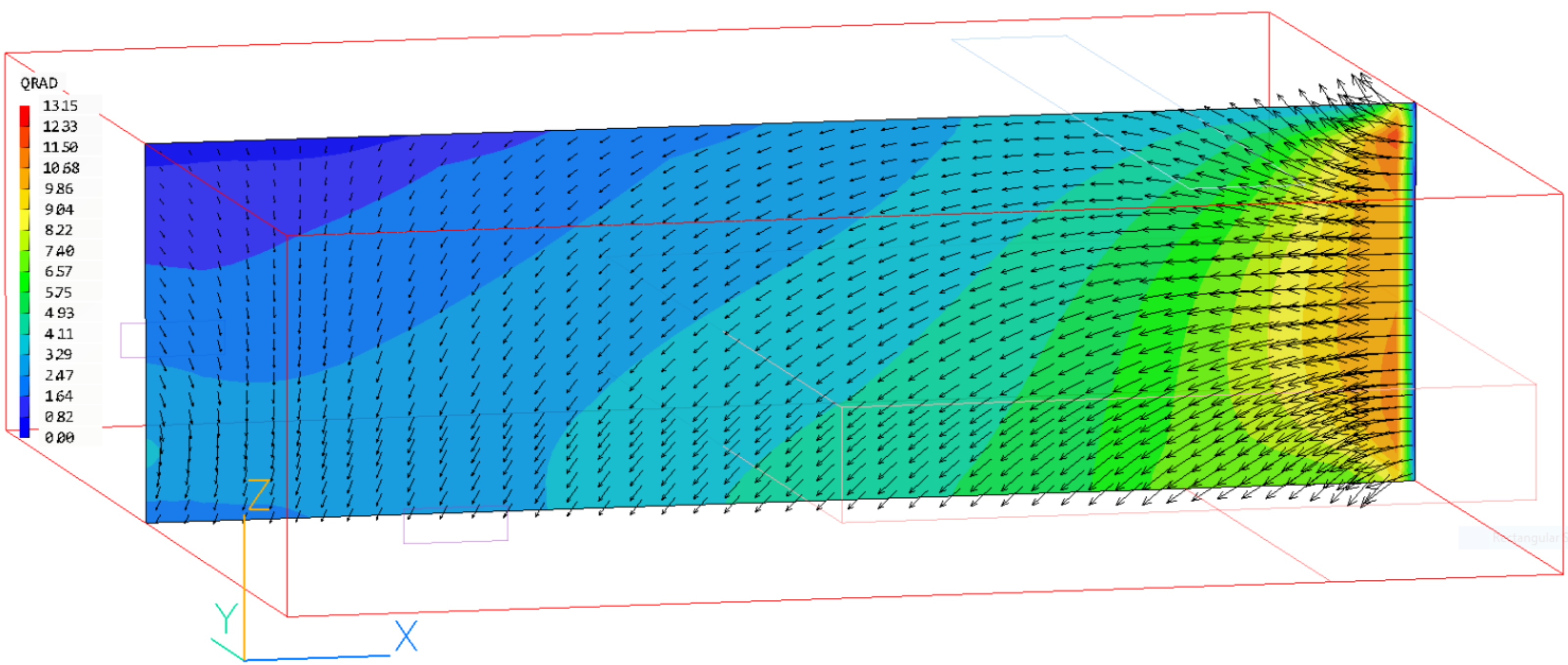
- Contours of Radiation Flux Intensity
- Vectors of Radiation Flux



Energy Source Term

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- The energy equation (TEM1) contains a source term corresponding to radiation absorbed/emitted by the gas (for optically thick cases).
- This term is proportional to σ * ($T3^4$ – $TEM1^4$)
- An equal and opposite source term appears in the T3 equation.
- For an optically thin medium the term is zero.
- In the RESULT file, the Nett Sources for TEM1 and T3 will not balance individually, due to this transfer of energy between T3 and TEM1.
- An overall heat balance (for TEM1 plus T3) is also printed, and this should be close to zero.

Example –
Duct Flow with Hot Wall

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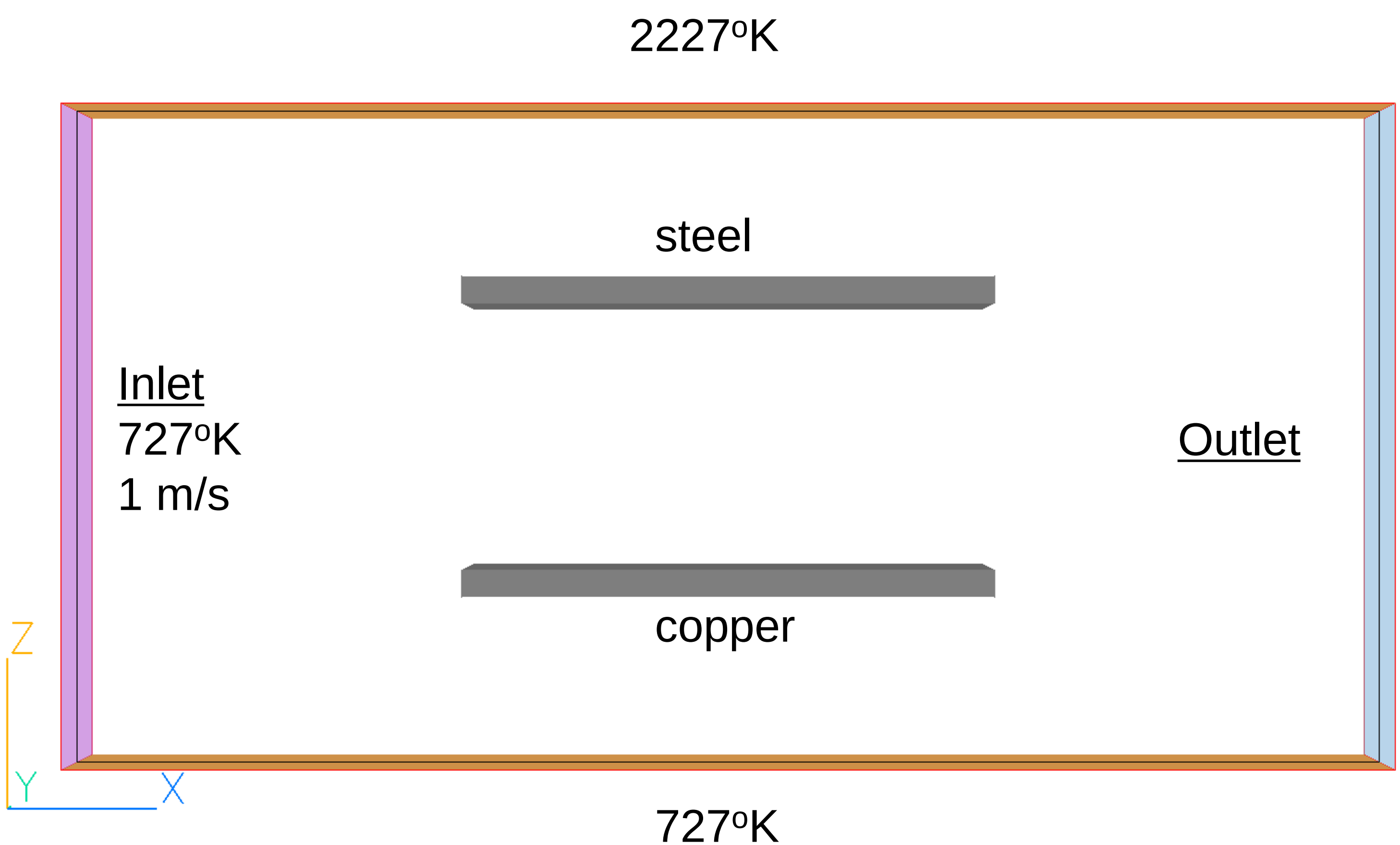

Example –
Duct Flow with Hot Wall

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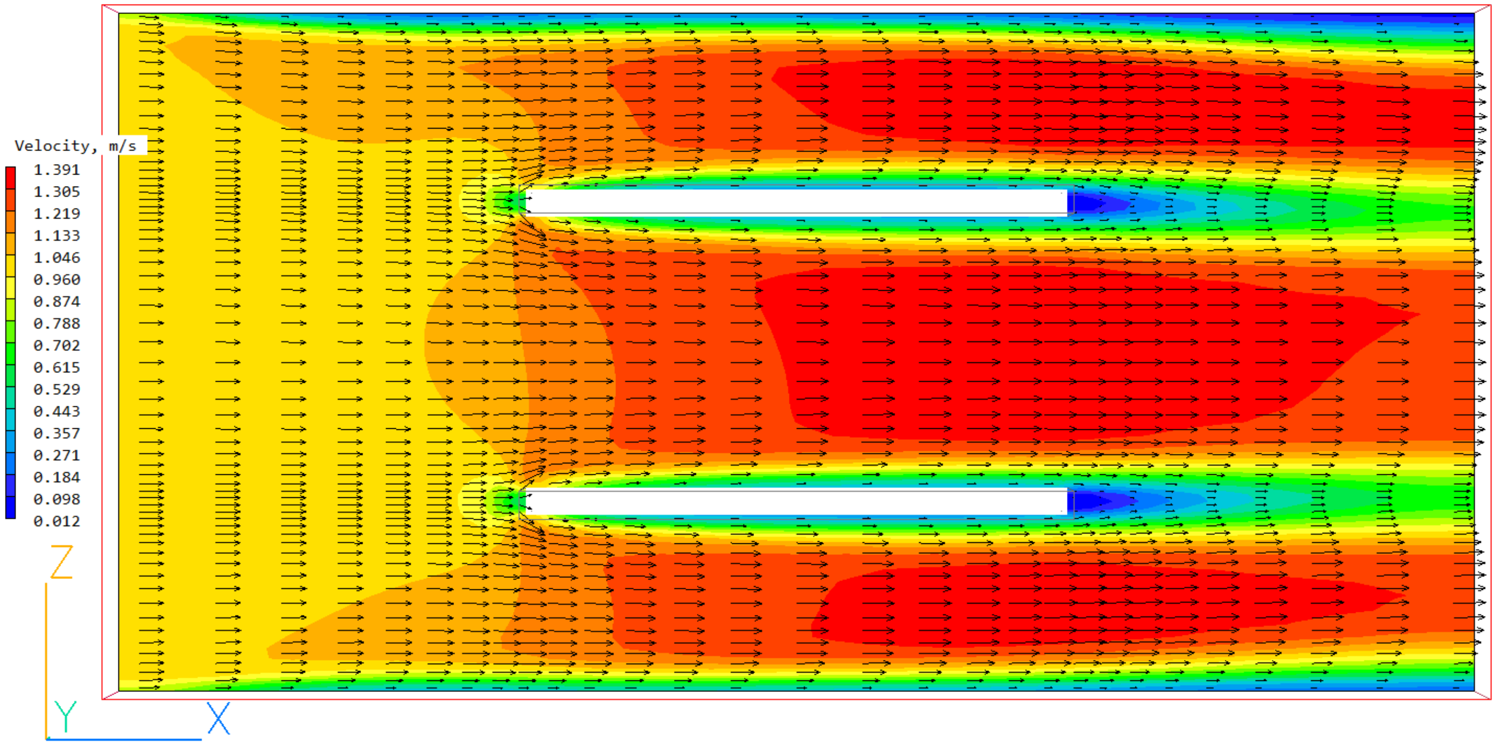
- Optically thin (gas absorption coeff / unit length = 0)
- Velocity contours



Example – Duct Flow with Hot Wall

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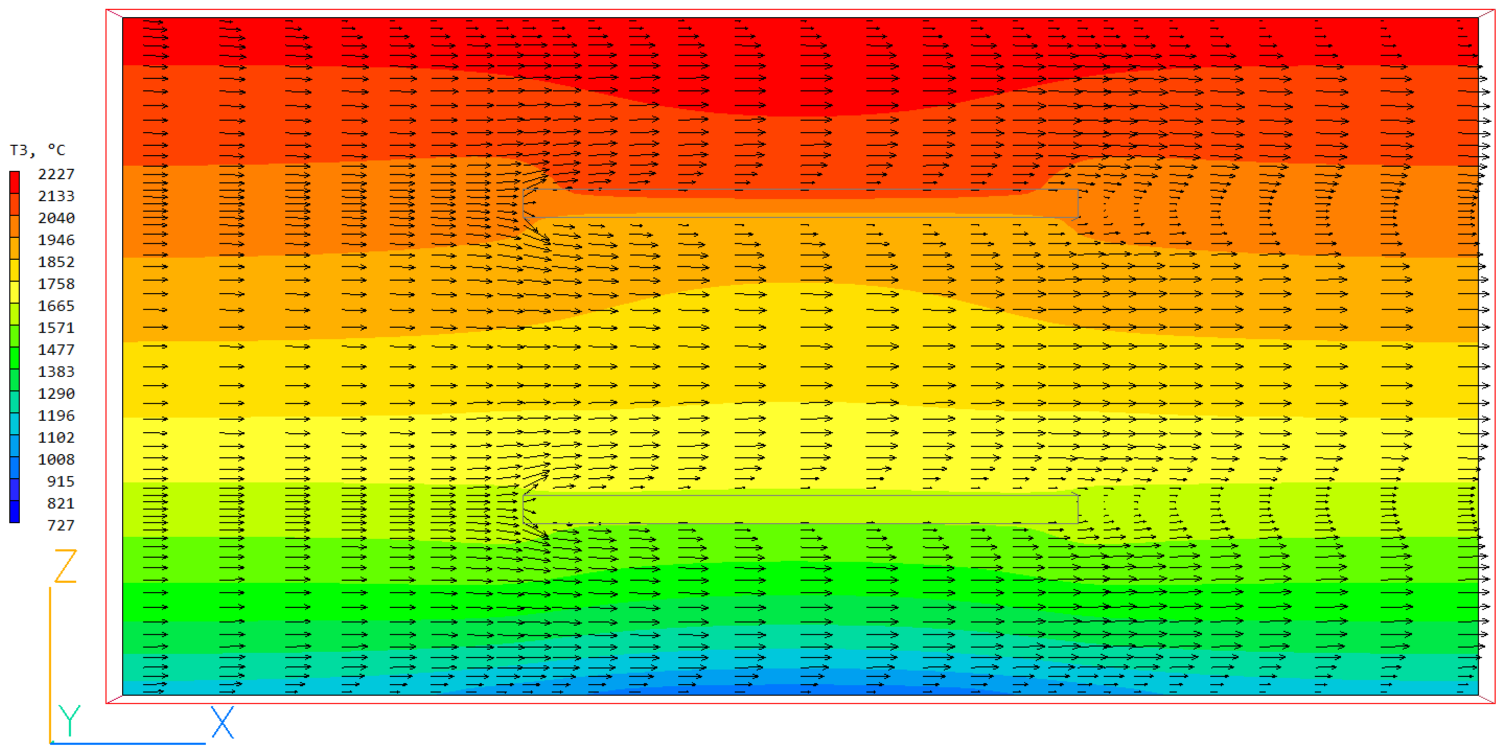
- Optically thin
- Radiant Temperature (T3)



Example – Duct Flow with Hot Wall

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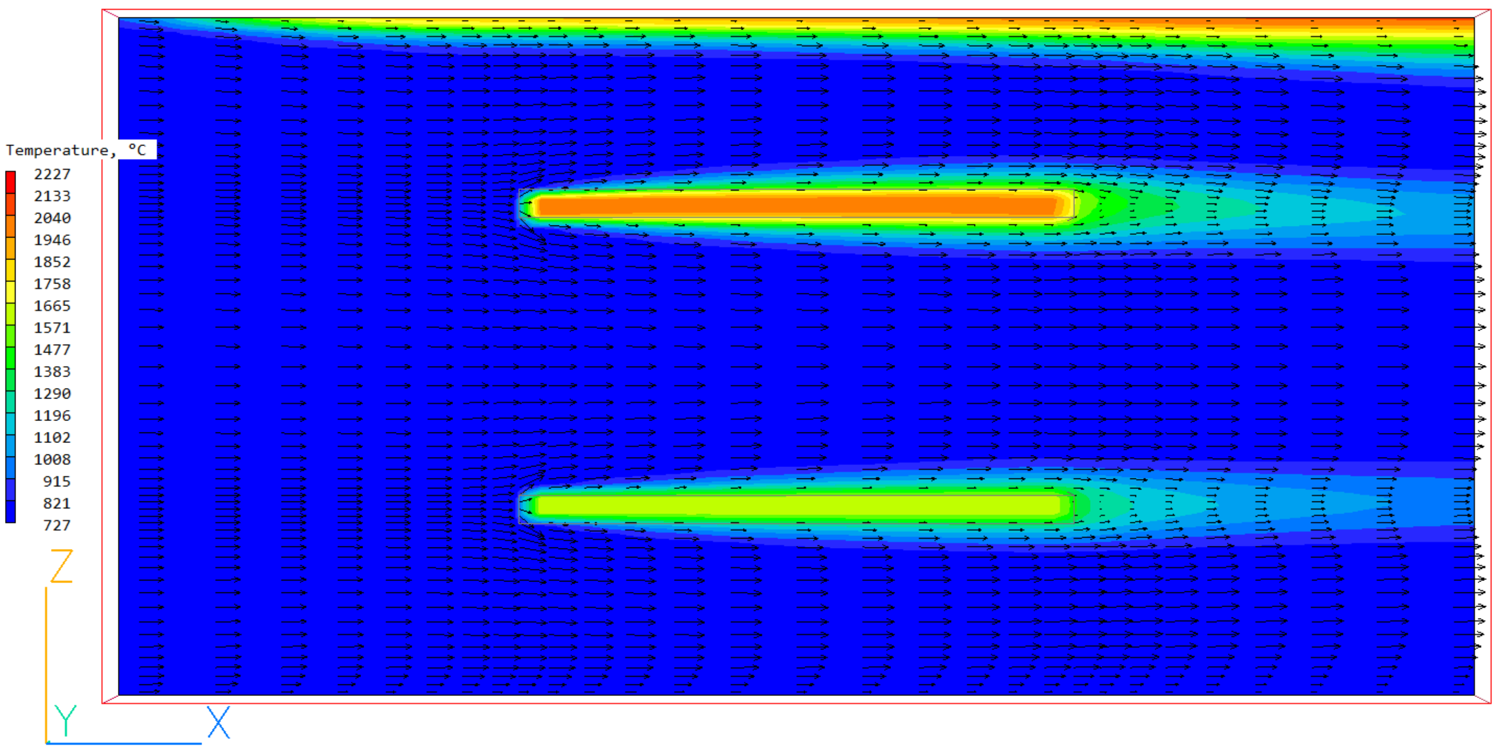
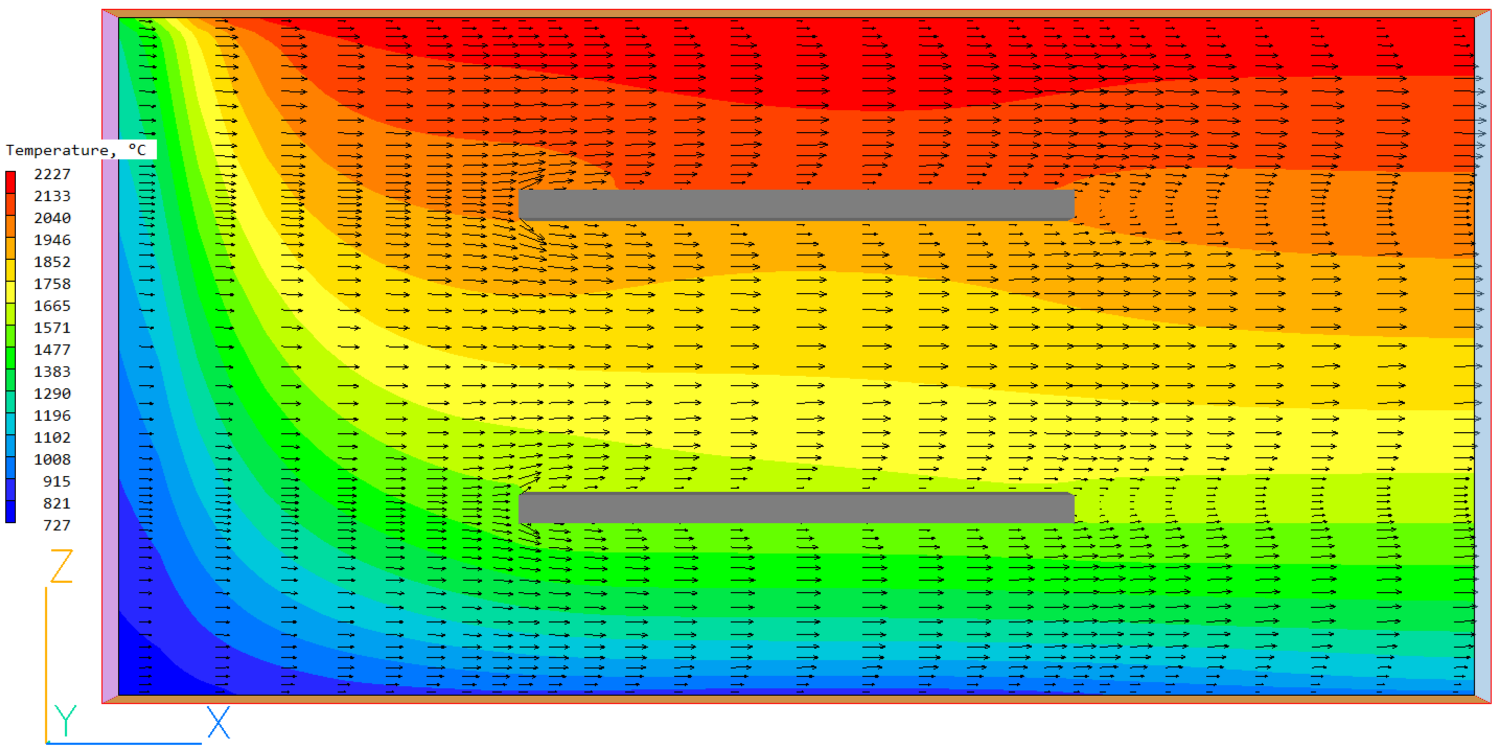
- Optically thin
- Temperature (TEM1)



Example –
Duct Flow with Hot Wall

- Optically thick (absorption coeff / unit length = 1)
- Temperature (TEM1)



Example –
Duct Flow with Hot Wall

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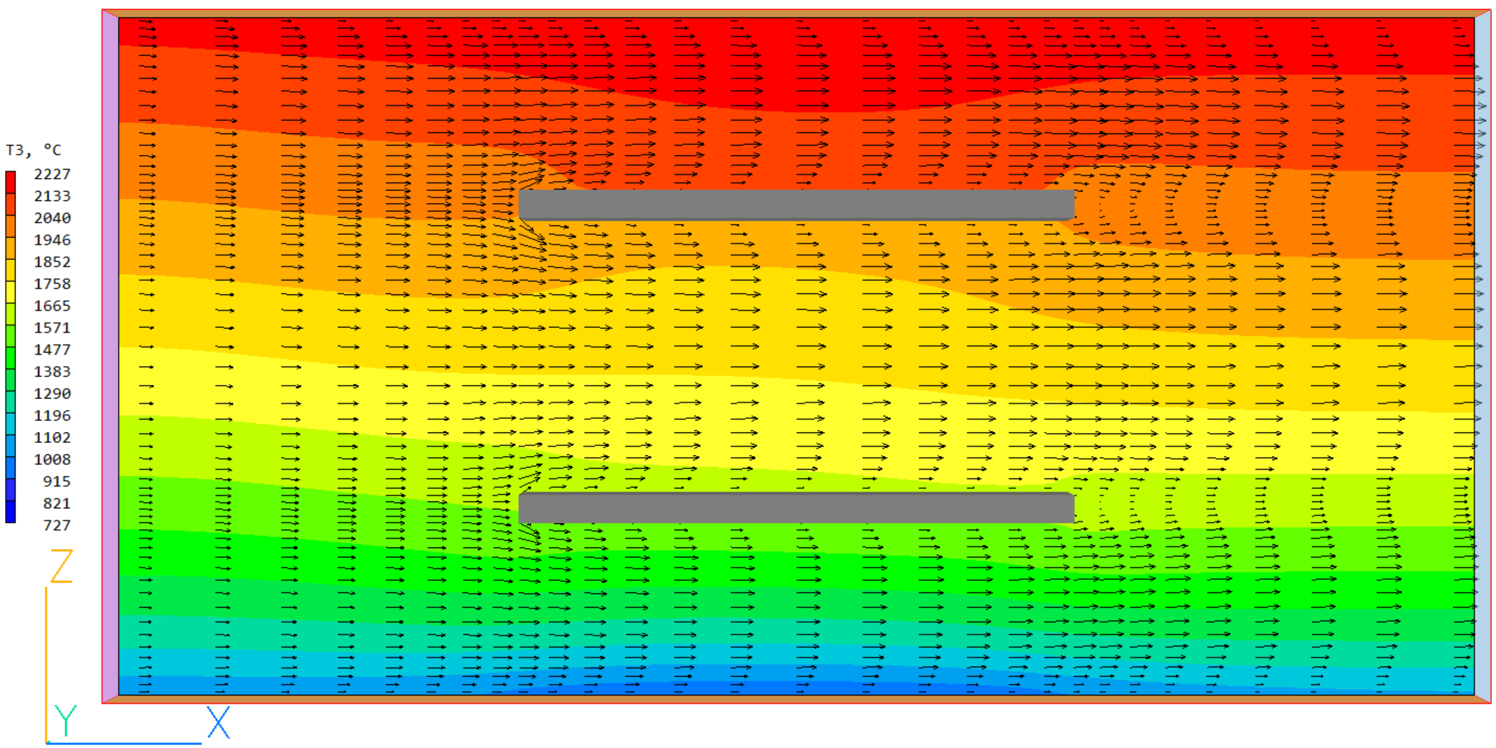
- Optically thick
- Radiant Temperature (T3)



Example –
Duct Flow with Hot Wall

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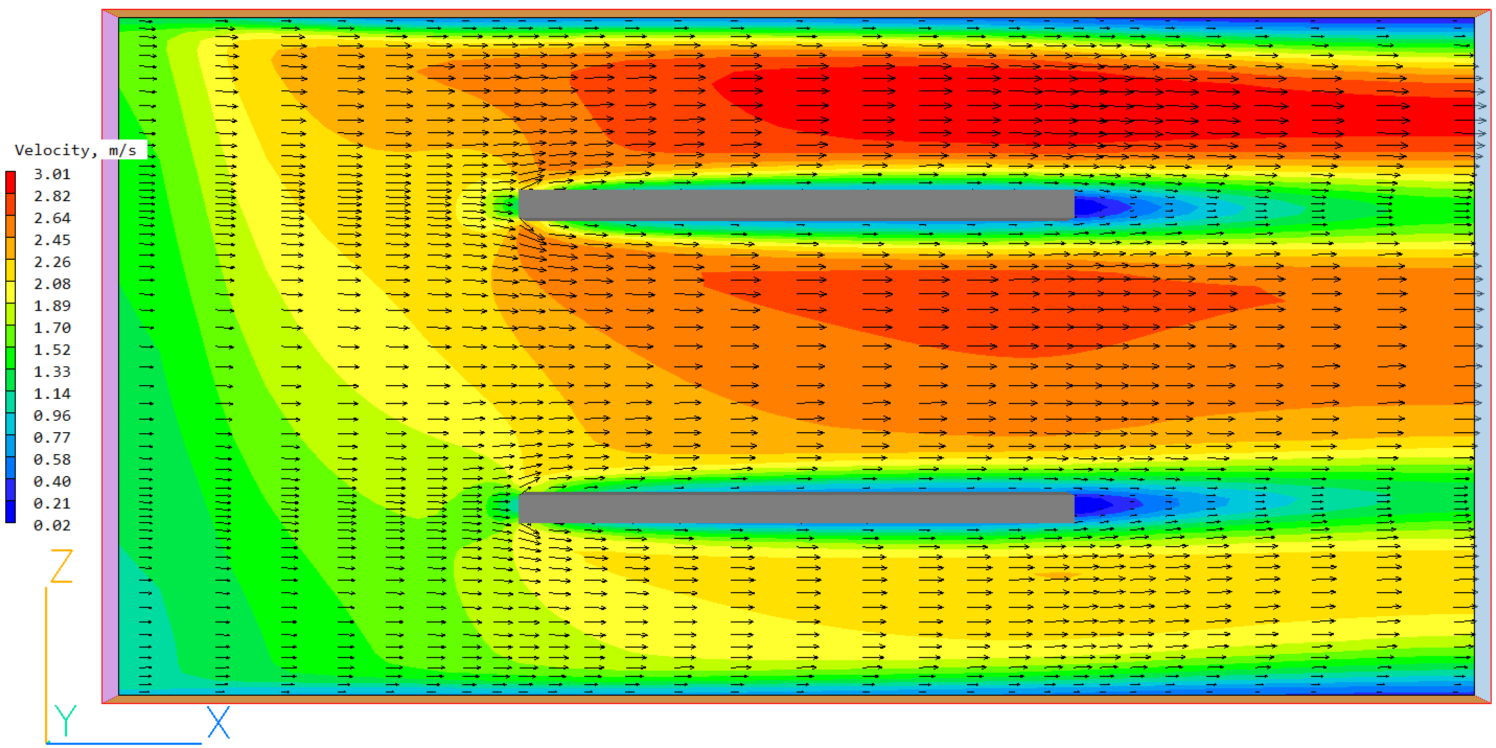
- Optically thick
- Velocity contours



Relaxation for T3

- For optically thin cases, setting Linear relaxation with amount 0.25 should be fine.

- For optically thick cases, either try the above, or use the same relaxation settings as for TEM1.

IMMERSOL and Wavelength

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Two important points

- The PHOENICS implementation of IMMERSOL has no wavelength dependence.

- Solar radiation (short wavelength) is NOT modelled in IMMERSOL.

IMMERSOL and Solar Radiation

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- The SUN object in FLAIR creates heat sources where the sun shines on solids.
- We do not model the solar radiation that creates these heat sources.
- Some of this heat is re-radiated (long wavelength).
- It is this long-wave infra-red radiation that is handled by IMMERSOL.

- An example follows – but we discuss Comfort Indices first.

Radiation Modelling and Comfort Indices

- Comfort indices measure degree of comfort, e.g.:

- Universal Thermal Climate Index (UTCI)

  UTCI is a function of air temperature, water vapour pressure, radiant temperature and wind speed

- Predicted Mean Vote (PMV)

  PMV measures comfort, based on air temp, water vapour pressure, radiant temp, wind speed, and various parameters measuring human metabolic rate and heat transfer

- These indices use the radiant temperature T3 …

- … which can be determined by using IMMERSOL

Radiation Modelling and Comfort Indices

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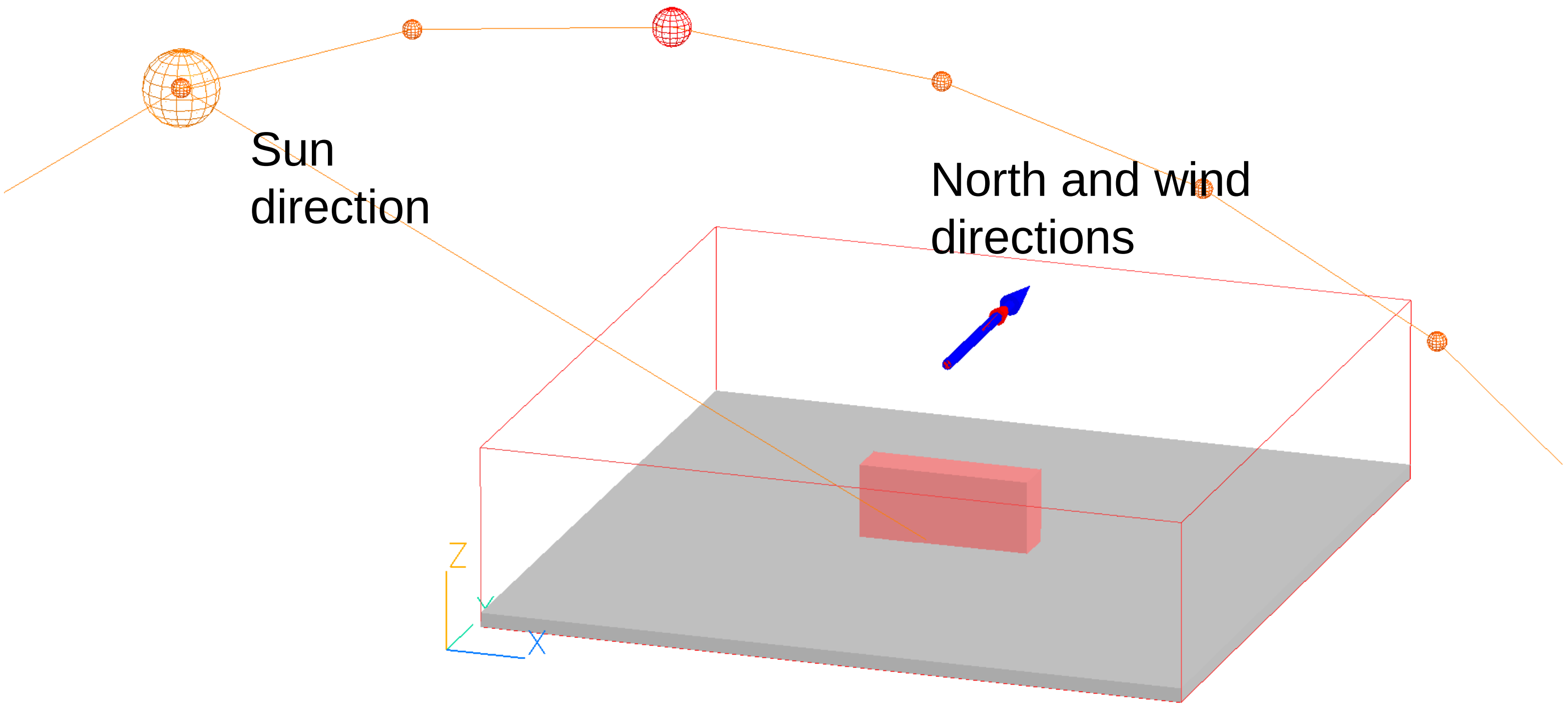
- Note: The comfort indices also use water vapour pressure.
- This can be determined by solving for humidity in FLAIR.

Example – Building in the Sun

- Wind 5 m/s from S, 20^{o}C
- RH 65%
- Building 120 x 30 x 51m
- Latitude of Hong Kong
- 21 December, 2.00 p.m.
- Sky temperature 0^{o}C
- Contour plots 1.75m above ground



Example – Building in the Sun

Lecture

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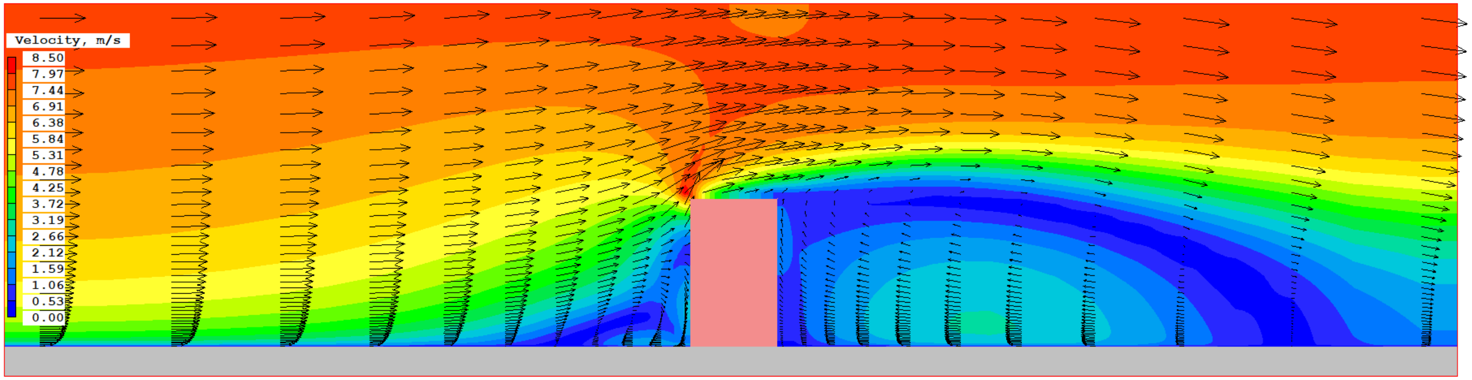
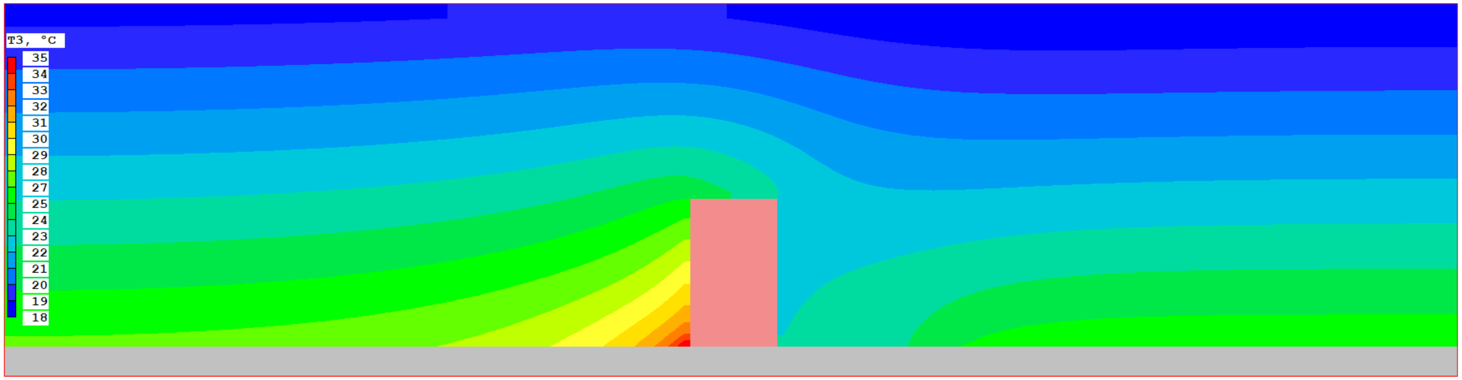
- Velocities in vertical plane

- Note the recirculation behind the building



Example – Building in the Sun

- Radiant Temperature (T3)
- If you stand in front of the sunlit building it feels warm



Example – Building in the Sun

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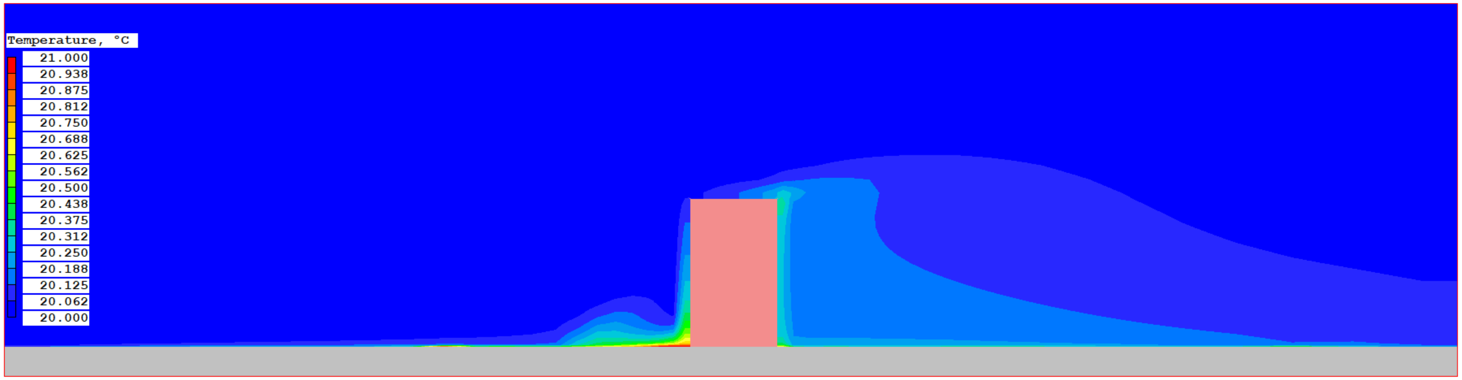
- Temperature (TEM1)

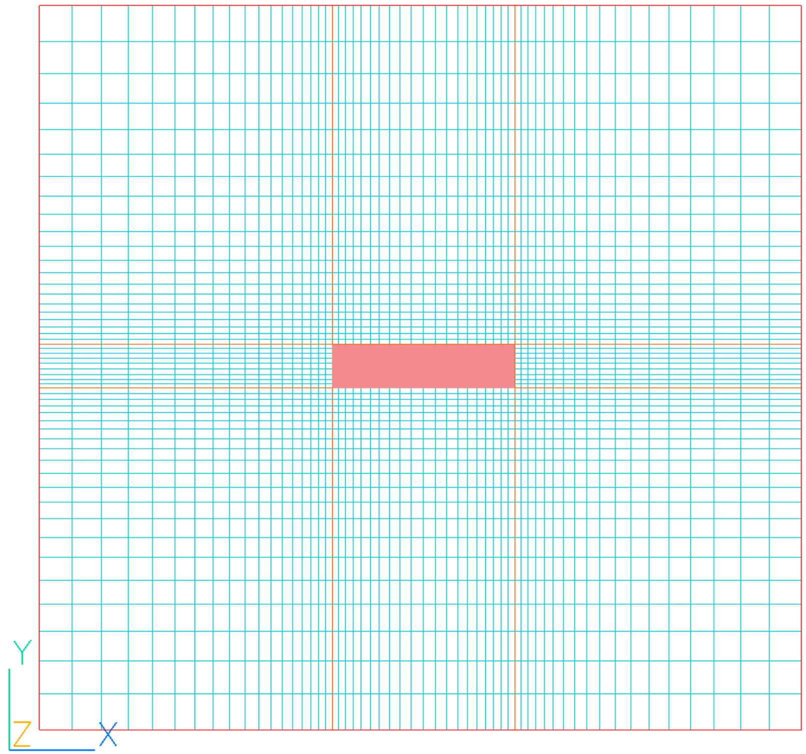
- The actual temperature varies by less than 1º, and only very close to the solid surfaces



- Observe how T3 is completely different from TEM1

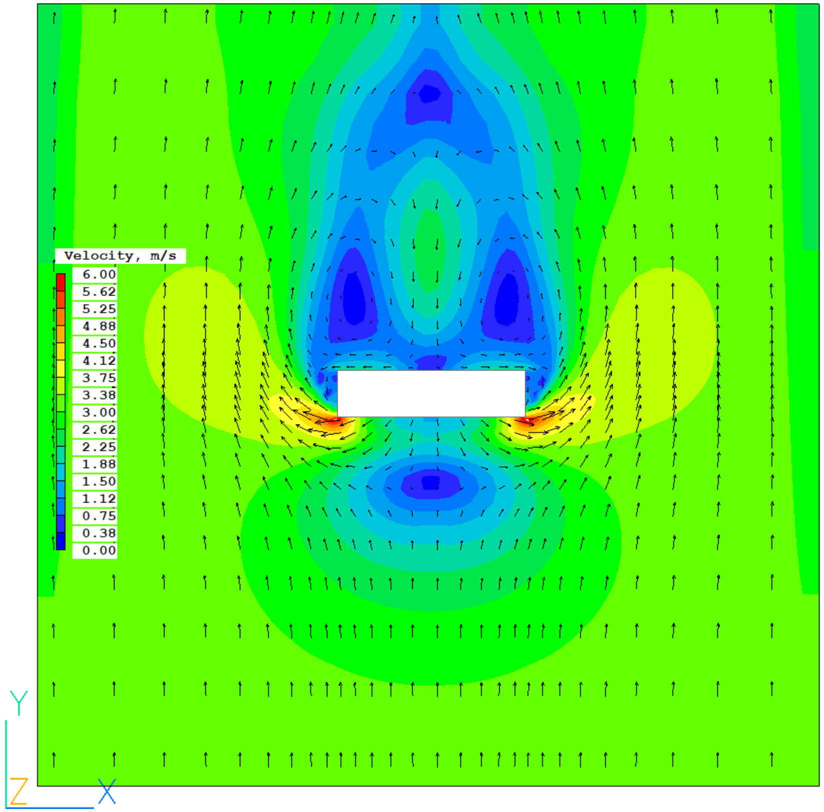
Example – Building in the Sun

- Mesh in horizontal plane



Example – Building in the Sun

- Velocities in horizontal plane 1.75 m from the ground



Example – Building in the Sun

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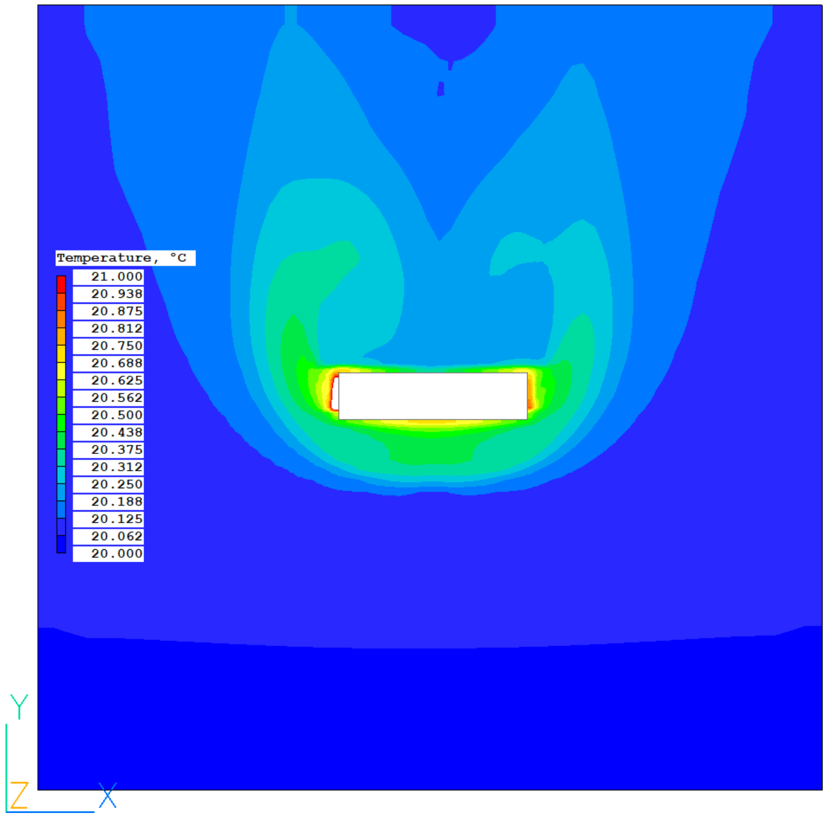
- Temperature (TEM1)



Example – Building in the Sun

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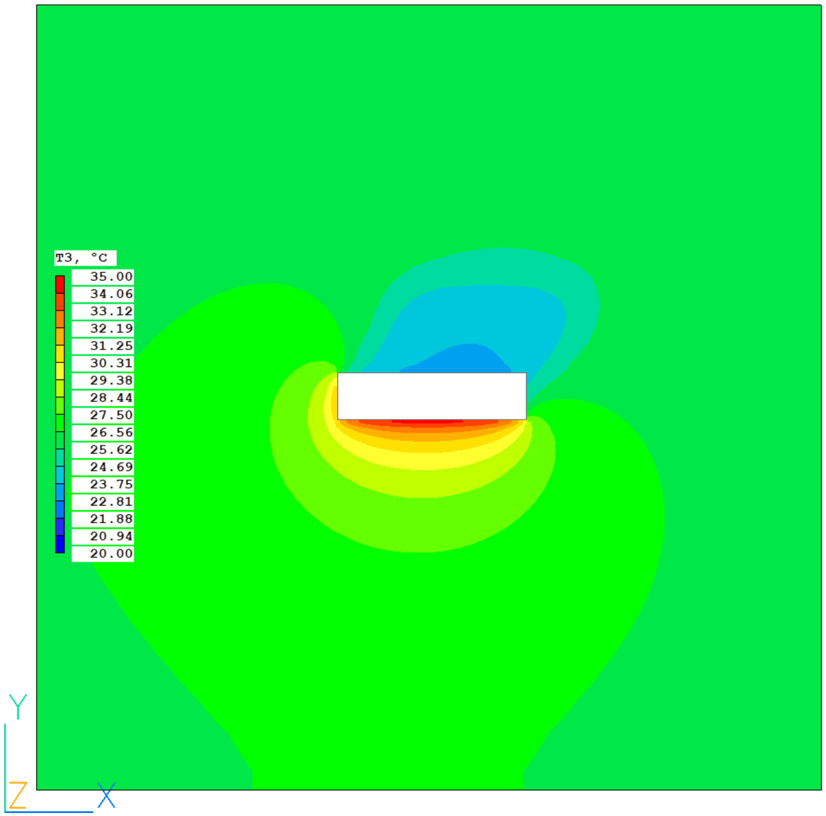
- Radiant Temperature (T3)
- It will feel hot in front of the building



Example – Building in the Sun

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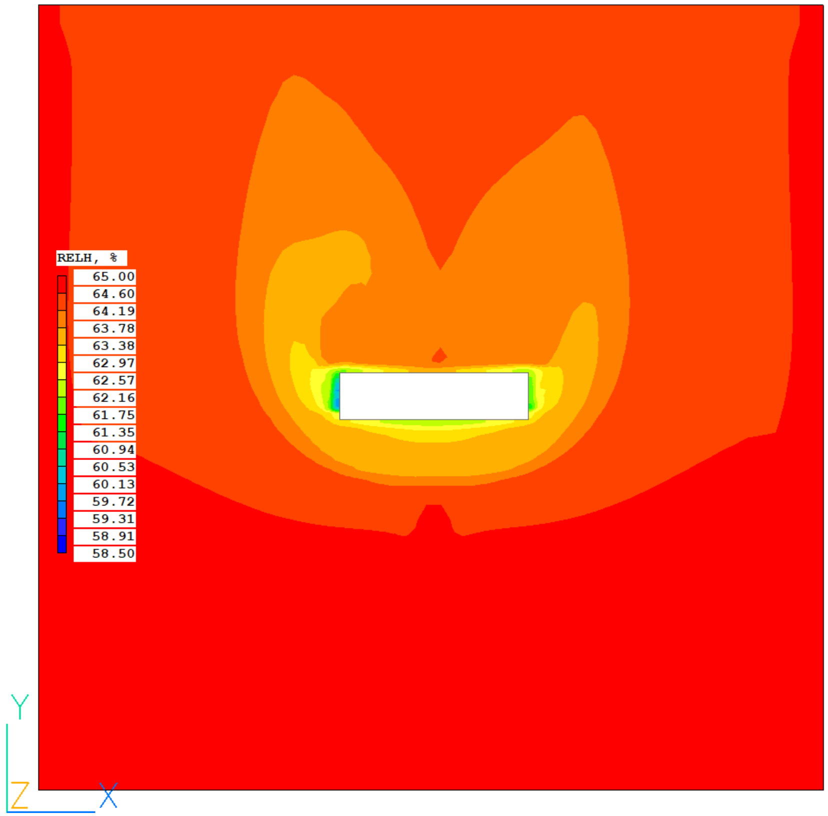
- Relative Humidity
- (Required for the comfort indices)



Example – Building in the Sun

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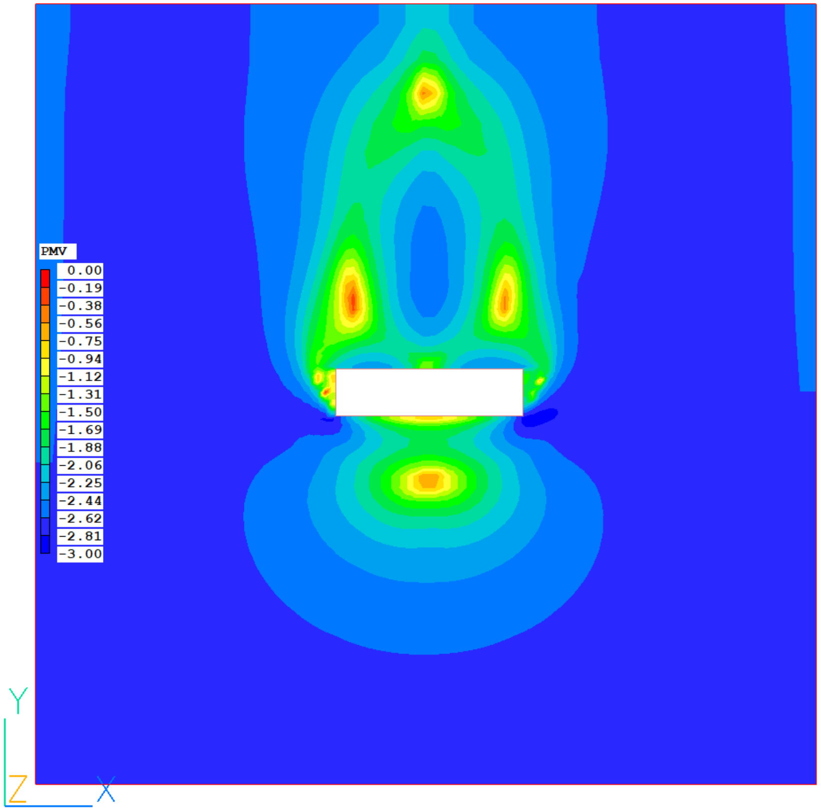
- Predicted Mean Vote (PMV)
- (0 feels “neutral”, -3 feels “cold”)



Example – Building in the Sun

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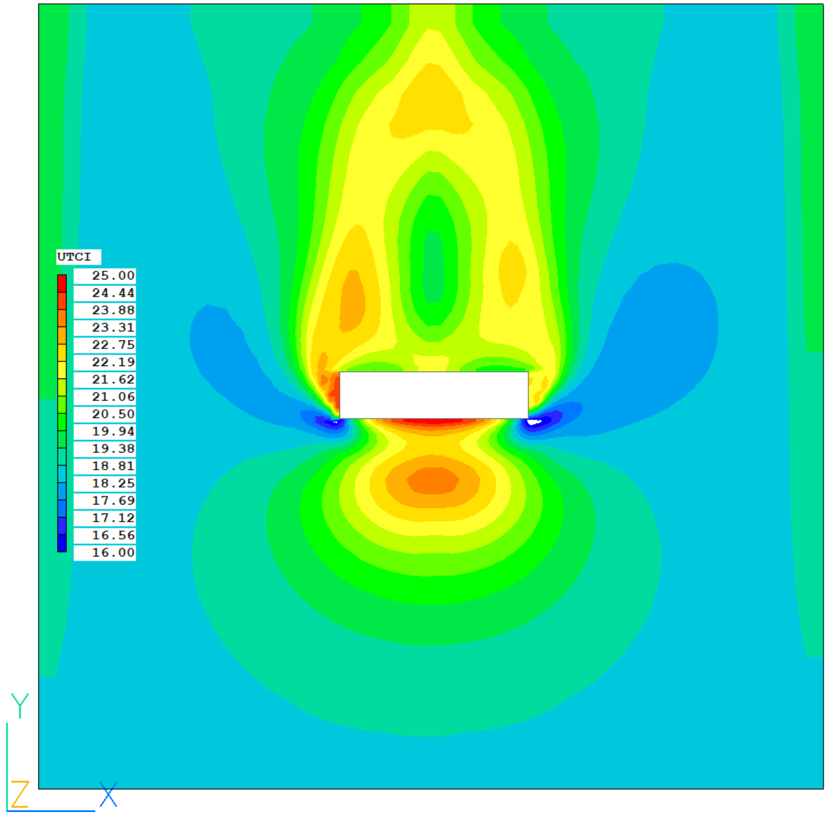
- Universal Thermal Comfort Index (UTCI)



Some Final Remarks…

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- IMMERSOL is activated from the "Models" Menu, via the "Radiation Models" button.
- The "Settings" button allows the absorption and scattering coefficients (per unit length) to be set.
- For a transparent medium, both should be zero.
- In fire simulations, the gas emissivity is often a function of smoke concentration (this requires InForm).
- Note – "absorptivity" and "emissivity" are basically the same.
- The "Settings" button also allows storage of the radiative heat fluxes in each direction. These can then be plotted as vectors in the Viewer.

Some Final Remarks…

- Before starting a run using IMMERSOL, check that:
  - You have set relaxation for T3 appropriately (see above).
  - All internal surfaces have sensible emissivities. The default value is 1. A suitable value for many materials is 0.9.
  - Inlets or outlets which allow radiation to pass through have “External radiative link” set.

- Remember to check the overall energy balance for TEM1 and T3 in the Result file – this appears just below the Nett Sources printout.

Some Final Remarks…

- IMMERSOL is the only radiation model to combine universal applicability with economic practicability for complex geometries.
- We have seen that IMMERSOL involves significant assumptions - the solutions are not exact.
- But wherever tested it has performed well, in respect of:
  - accuracy, where exact solutions are known;
  - plausibility, where they are not;
  - economy, in all circumstances.

*** THE END ***