A Benchmark Study on the Effect of Simplified Representation of Human Figures in Computational Fluid Dynamics (CFD) Simulation

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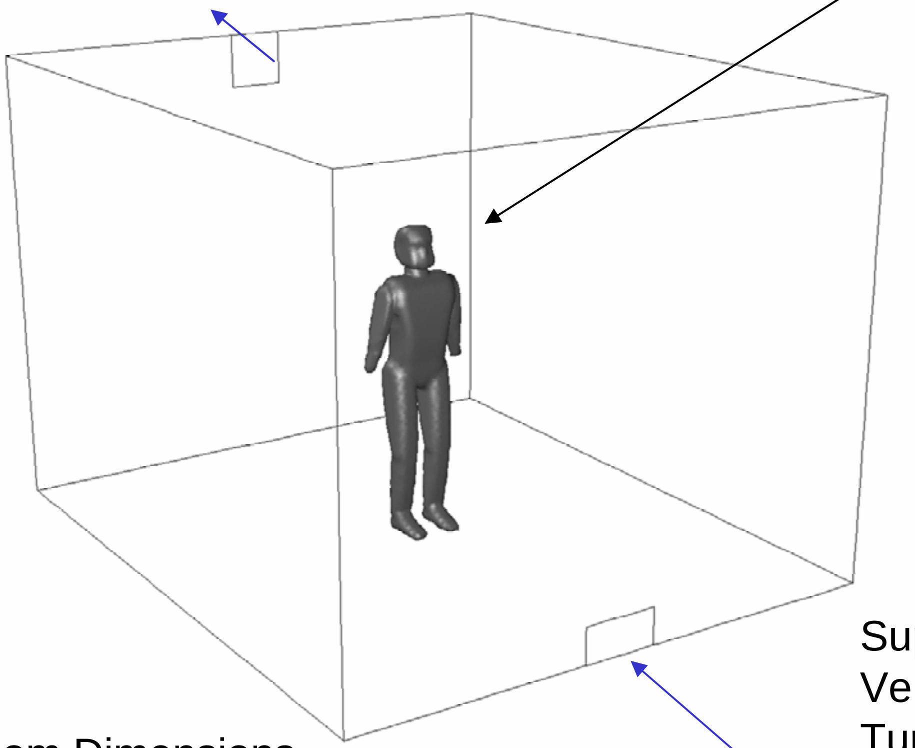
Motivation and Objectives

- Motivation and previous work
  - Perform CFD benchmark testing on displacement ventilation case available through Aalborg University (www.cfd-benchmarks.com) web site
  - Validation study results presented at previous ASHRAE meeting (Sideroff and Dang, 2005)
- Objectives of present work
  - Evaluate accuracy that can be obtained using wall function modeling approach for turbulent flow
    - Is there an advantage to using more realistic human figure?
    - What effect does the choice of turbulence model have?

Experimental Conditions

Exhaust Opening (0.3 m x 0.3 m)

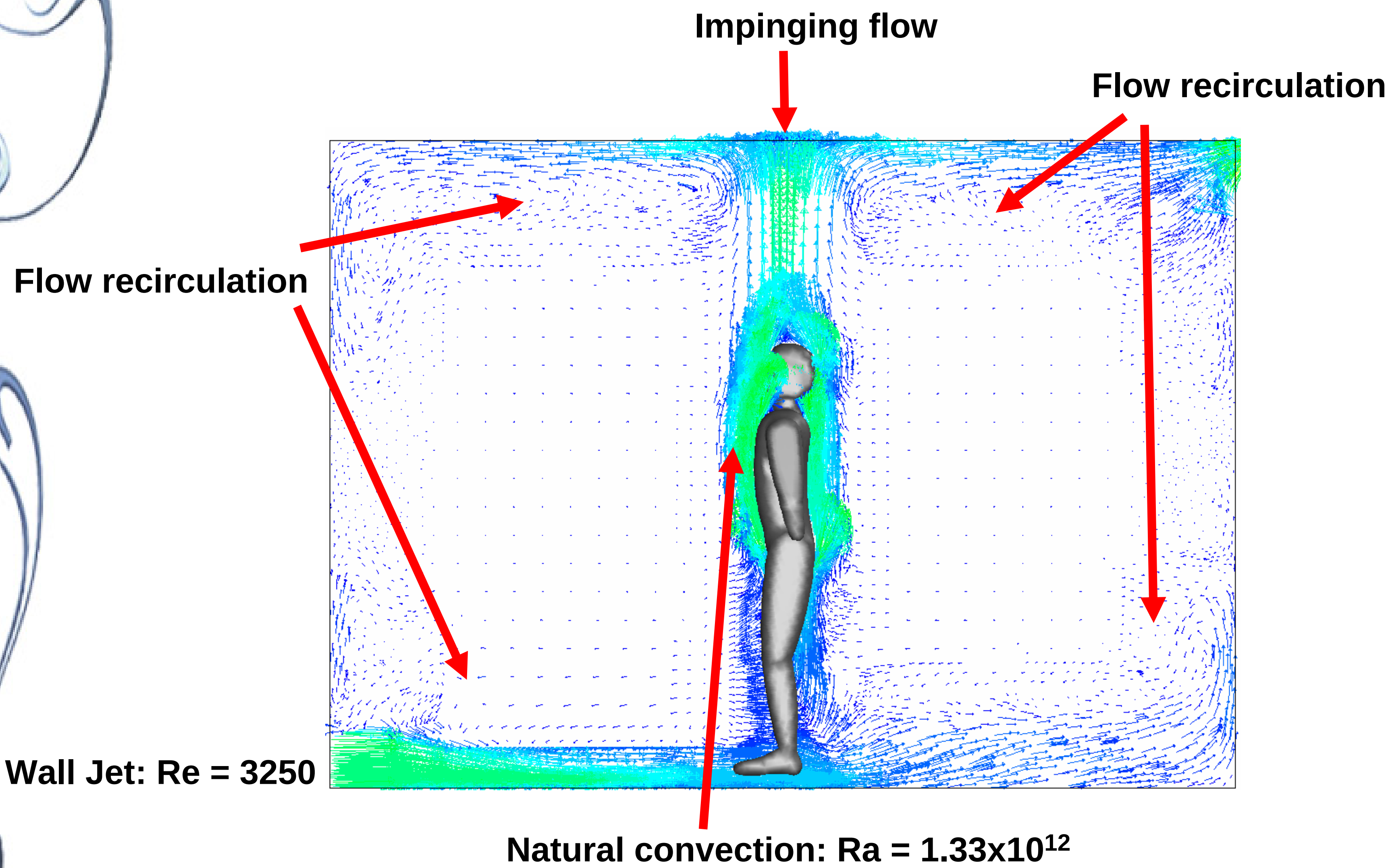
Mannikin:
1.67 m tall, ~ 0.4 m wide, located 5 cm above floor in center of room.
Heat output: 76 W



Supply Opening (0.4 m x 0.2 m)
Velocity: 0.182 m/s (30.85 cfm, ~2 ACH)
Turbulence intensity: 30%
Turbulence length scale: 0.1 m
Temperature: 21.8 ºC

Room Dimensions
3.5 m (L) x 3.0 m (W) x 2.5 m (H)

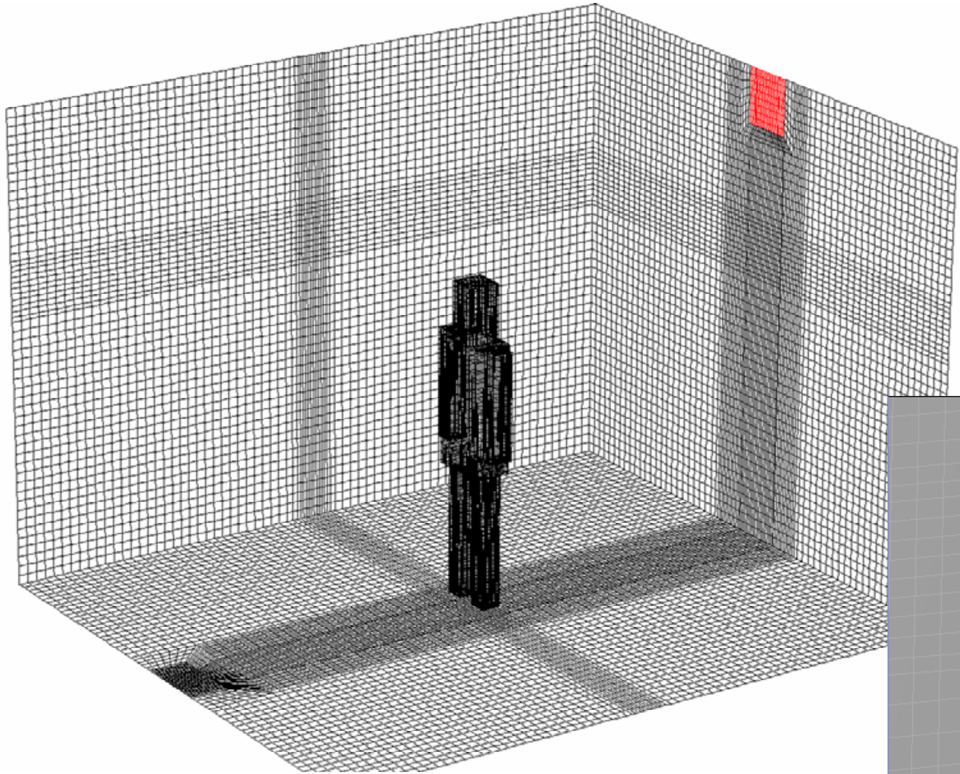
Flow Features



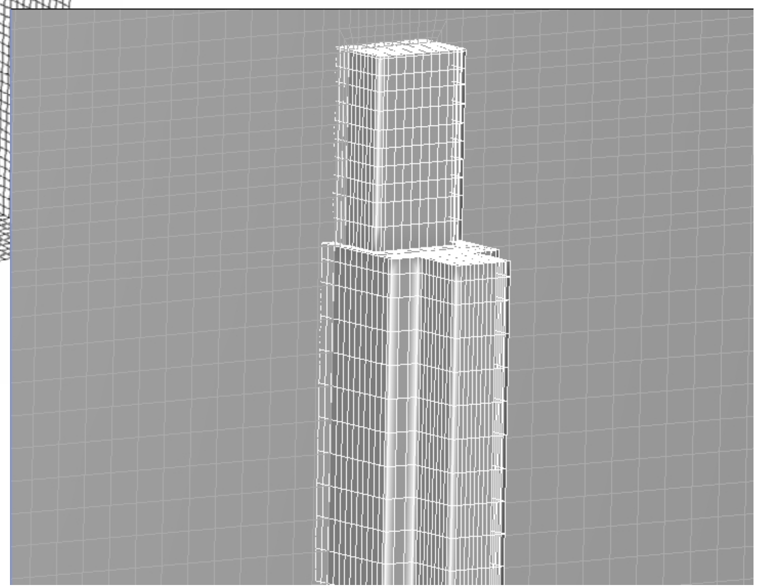
Numerical Method

- Transient calculation with large time step size
  - Often difficult to impose a steady state solution on flows with buoyant plumes
  - In this case, allows solution to converge with little or no intervention from user
  - Solutions run until time-averaged data does not show significant variation with Δt = 1 sec. – 5 sec. depending on case
- All transport equations solved with second order upwind discretization
- Density: $P_{ref} = \rho R T$
- Radiation: Discrete ordinates model
- Turbulence
  - Several different RANS models

Geometry and Grid for Simplified Figure

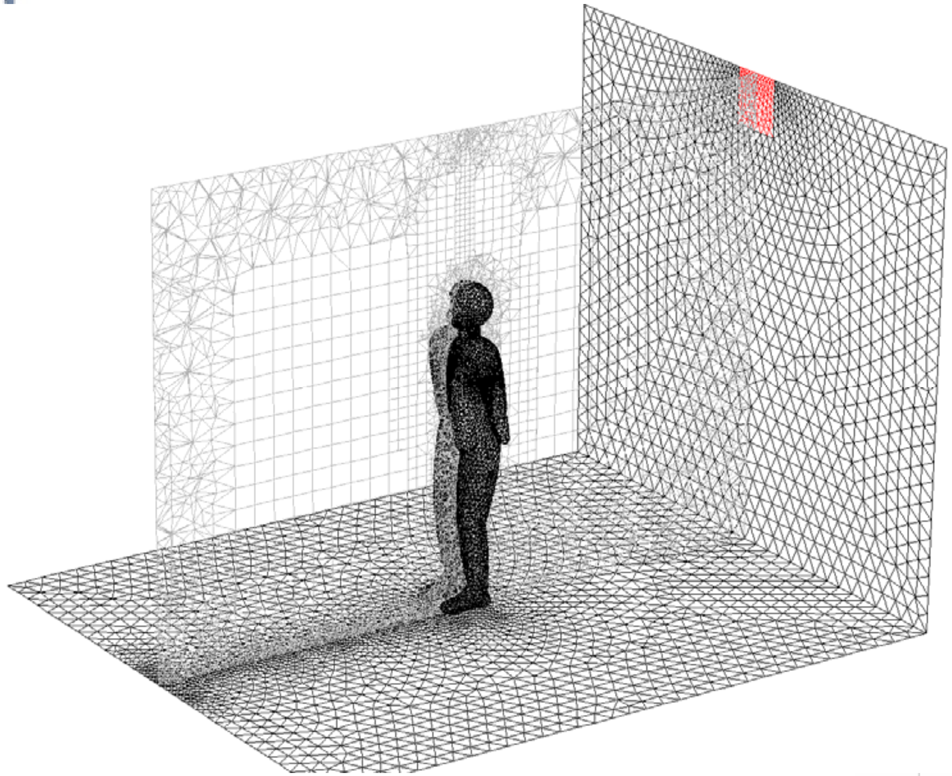


410,500 hexahedral cells

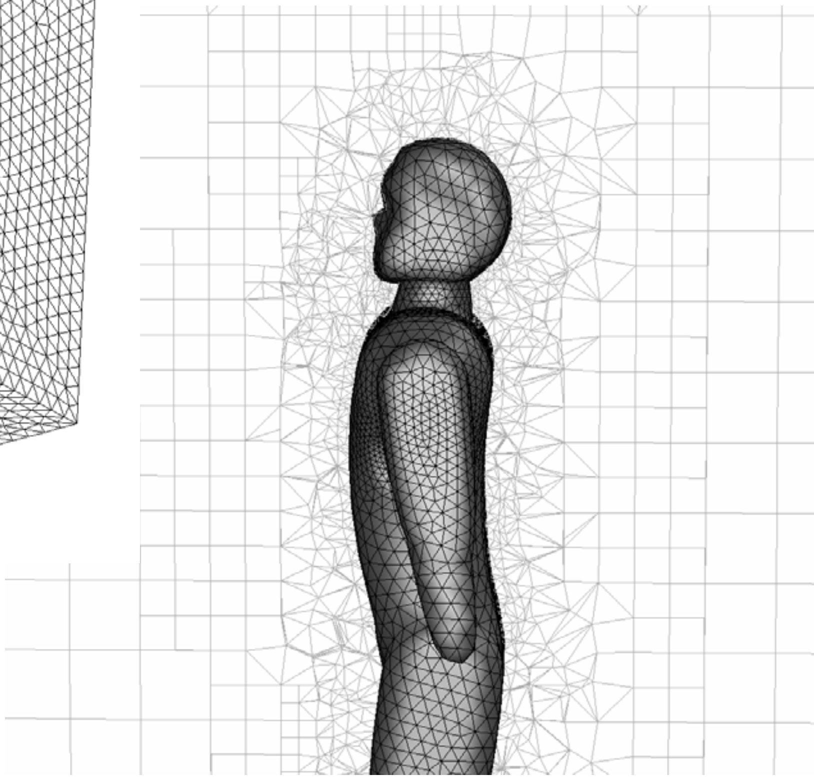


Detail of mesh on mannikin surface

Geometry and Grid for Realistic Figure



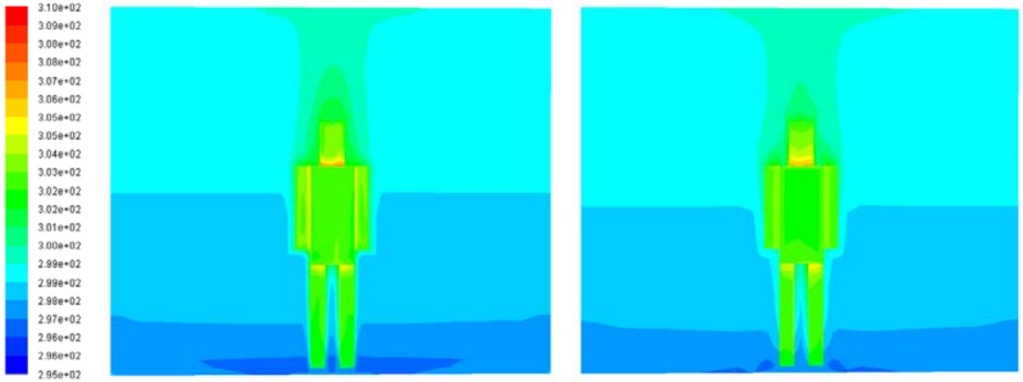
Combination of hexahedral and tetrahedral cells: 194,726 total cells



Detail of mesh on mannikin surface

Grid Study for Square Figure

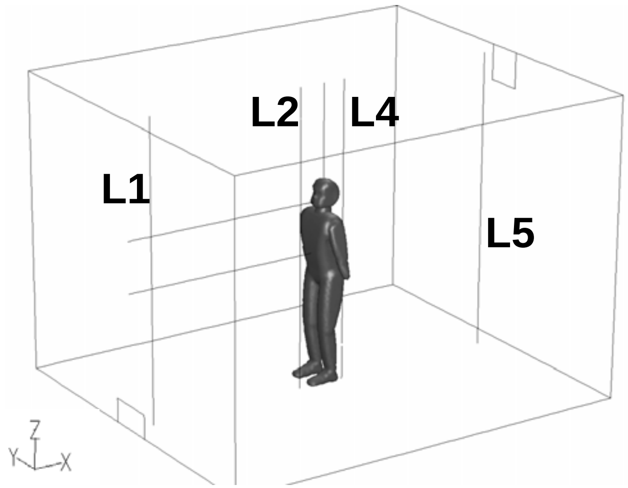
Indoor zero-equation turbulence model (Chen & Wu, 1988)
- does not employ wall functions

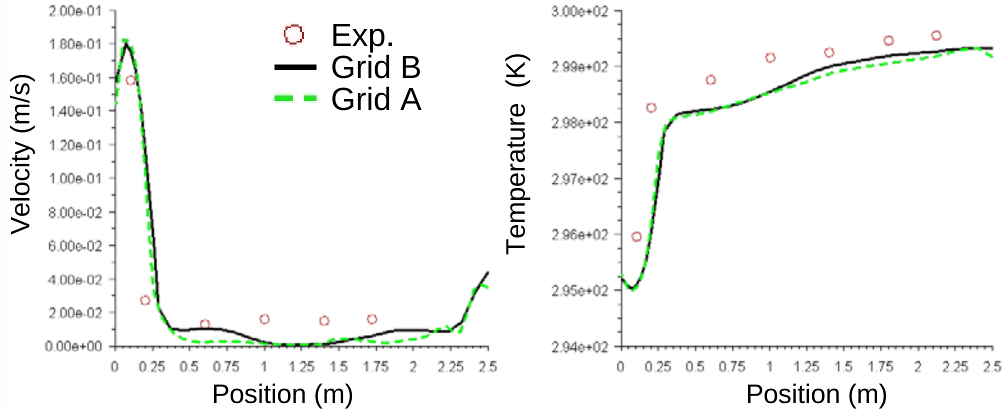


Grid A (shown previously) **Grid B (36,268 cells)**

Grid A
Average mannikin surface temperature = 303.30 K
Radiative heat flux = 43.1 W (57% of total)

Grid B
Average mannikin surface temperature = 303.26 K
Radiative heat flux = 42.9 W (56% of total)

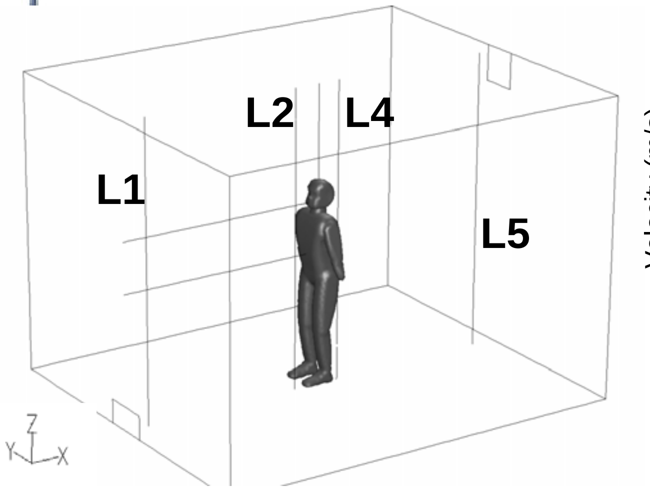


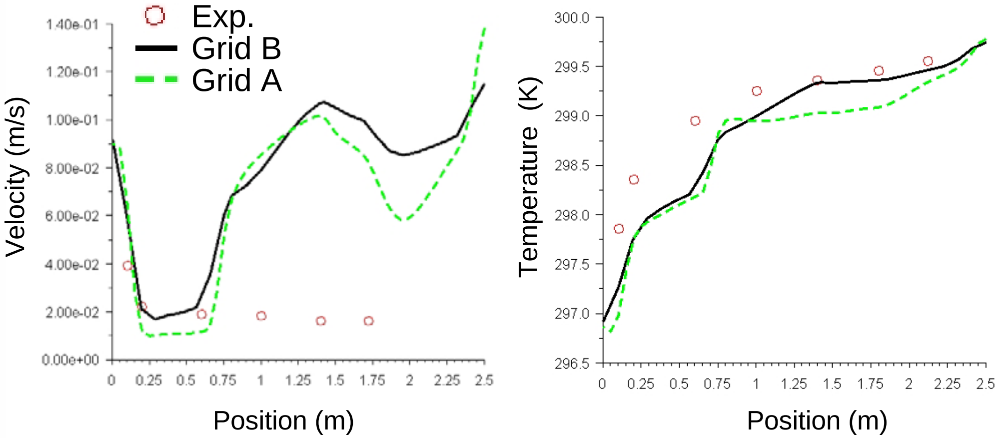


Velocity and temperature profiles at L1

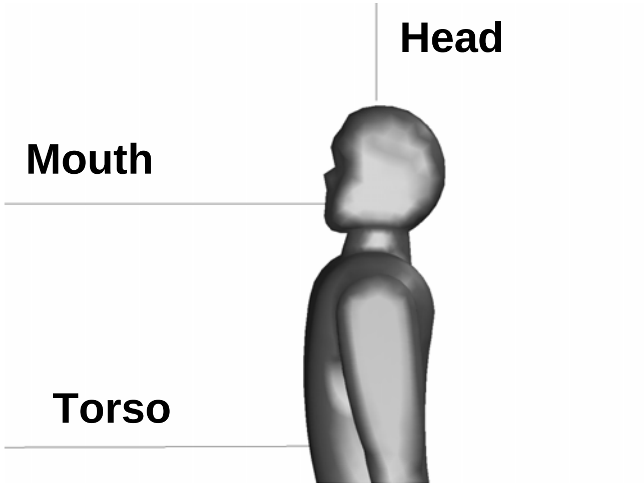
Grid Study for Square Figure

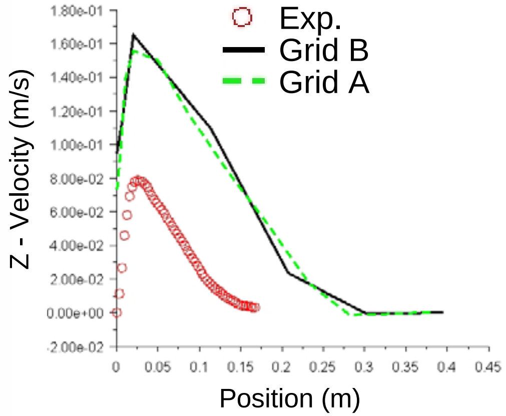
Indoor zero-equation turbulence model





Velocity and temperature profiles at L2

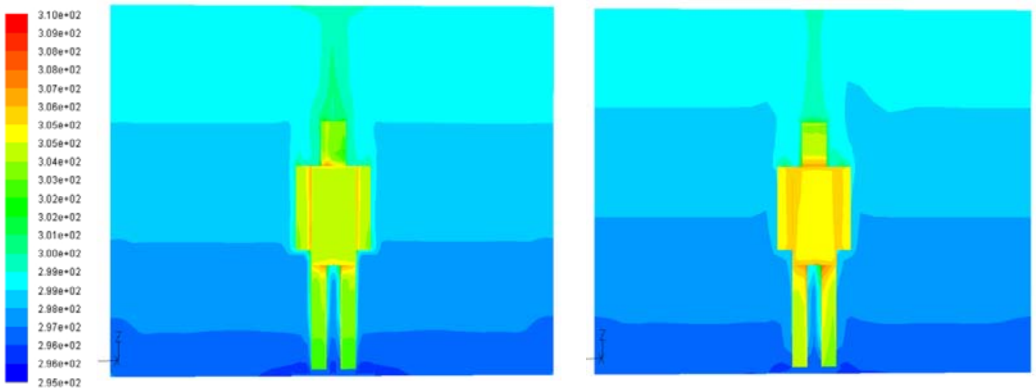




Z-velocity profile at Mouth

Grid Study for Square Figure

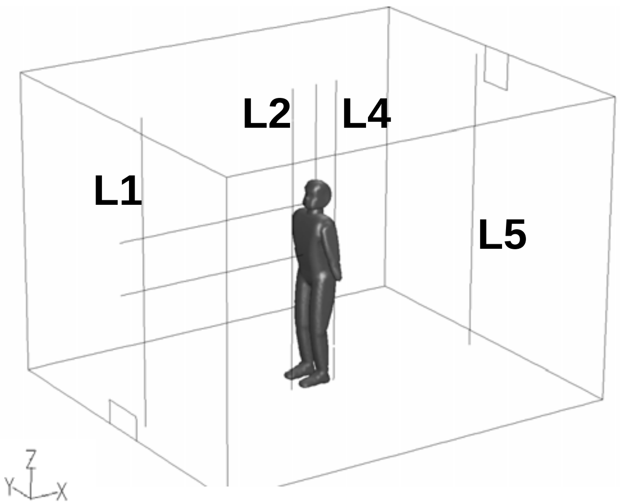
Results with RNG k-epsilon turbulence model

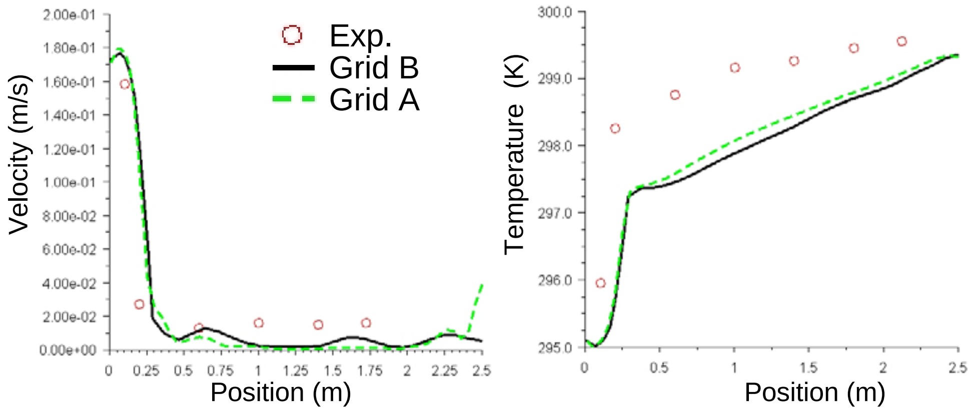


Grid A (shown previously) Grid B (36,268 cells)

Grid A
Average mannikin surface temperature = 304.5 K
Radiative heat flux = 52.6 W (69% of total)

Grid B
Average mannikin surface temperature = 305.4 K
Radiative heat flux = 57.25 W (75% of total)

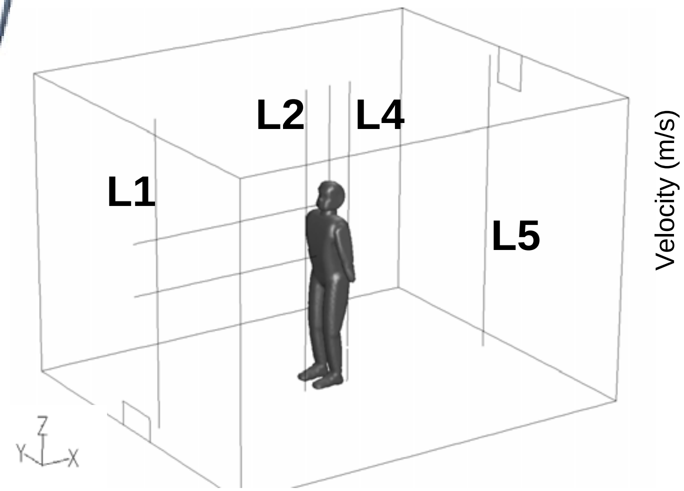


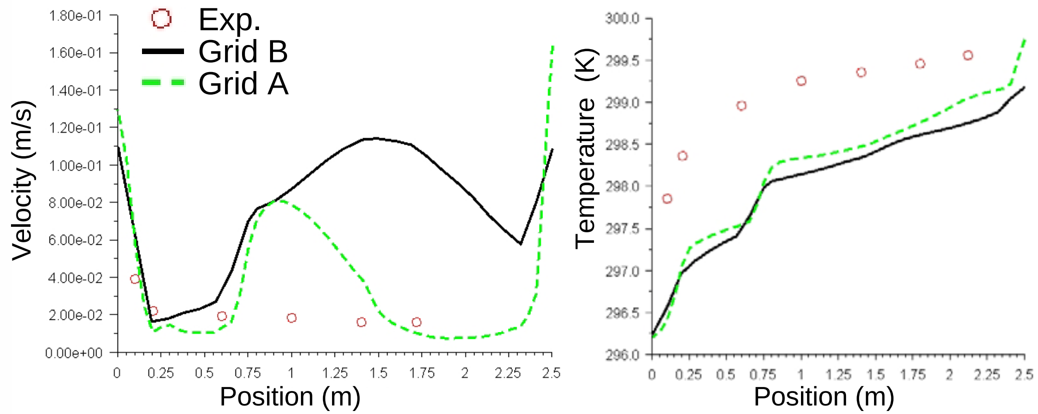


Velocity and temperature profiles at L1

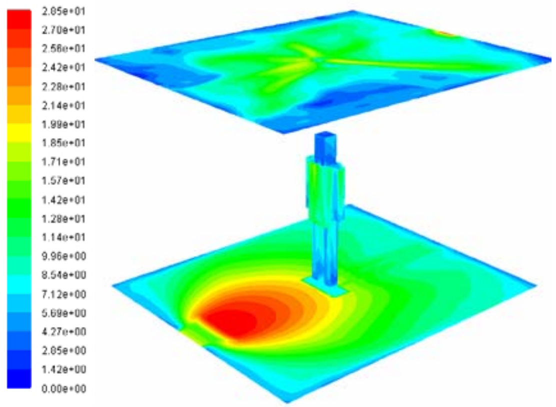
Grid Study for Square Figure

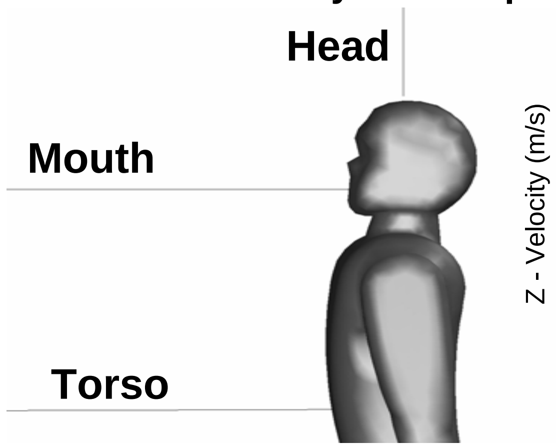
Results with RNG k-epsilon turbulence model

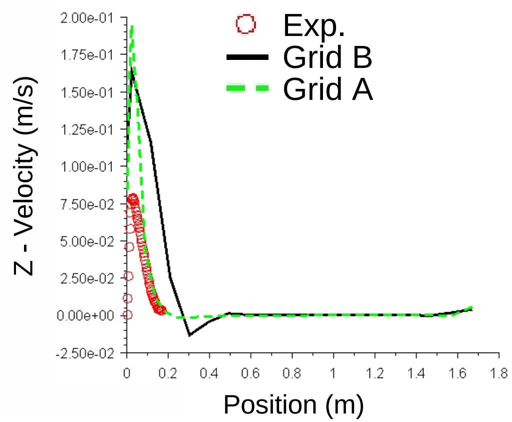




Velocity and temperature profiles at L1







Wall Y+ Distribution

Z-velocity profile at Mouth

Grid Study Summary

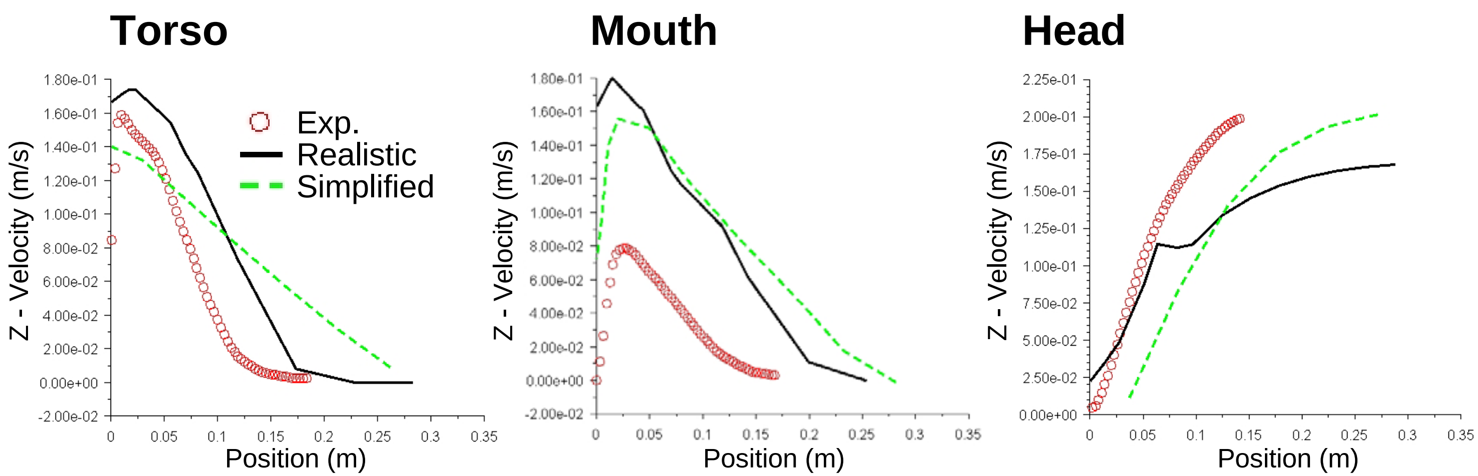
- Similar grid dependency observed on all additional cases with simplified figure

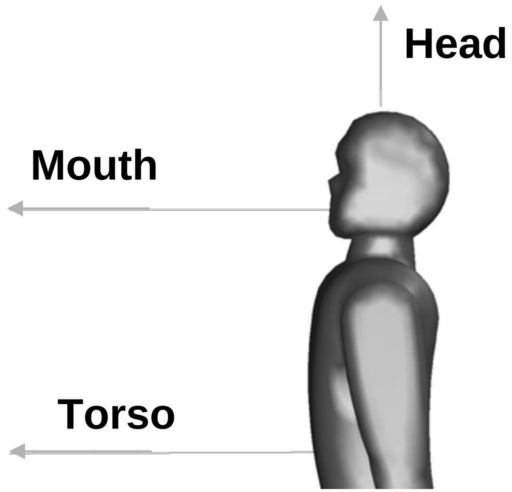
Predicted total radiative flux from mannikin (W)

	Grid A	Grid B
SKE	50.85	55.99
RNG	52.61	57.25
SKW	49.24	54.32
RSM	51.59	56.61
I0E	43.11	42.93

  - Problematic as y+ should ideally have lower bound of ~30 for wall functions but with Grid A already much lower on most of mannikin surface
- Similar results observed for indoor zero equation on realistic figure
- Similar grid dependency observed for all additional turbulence models on realistic figure

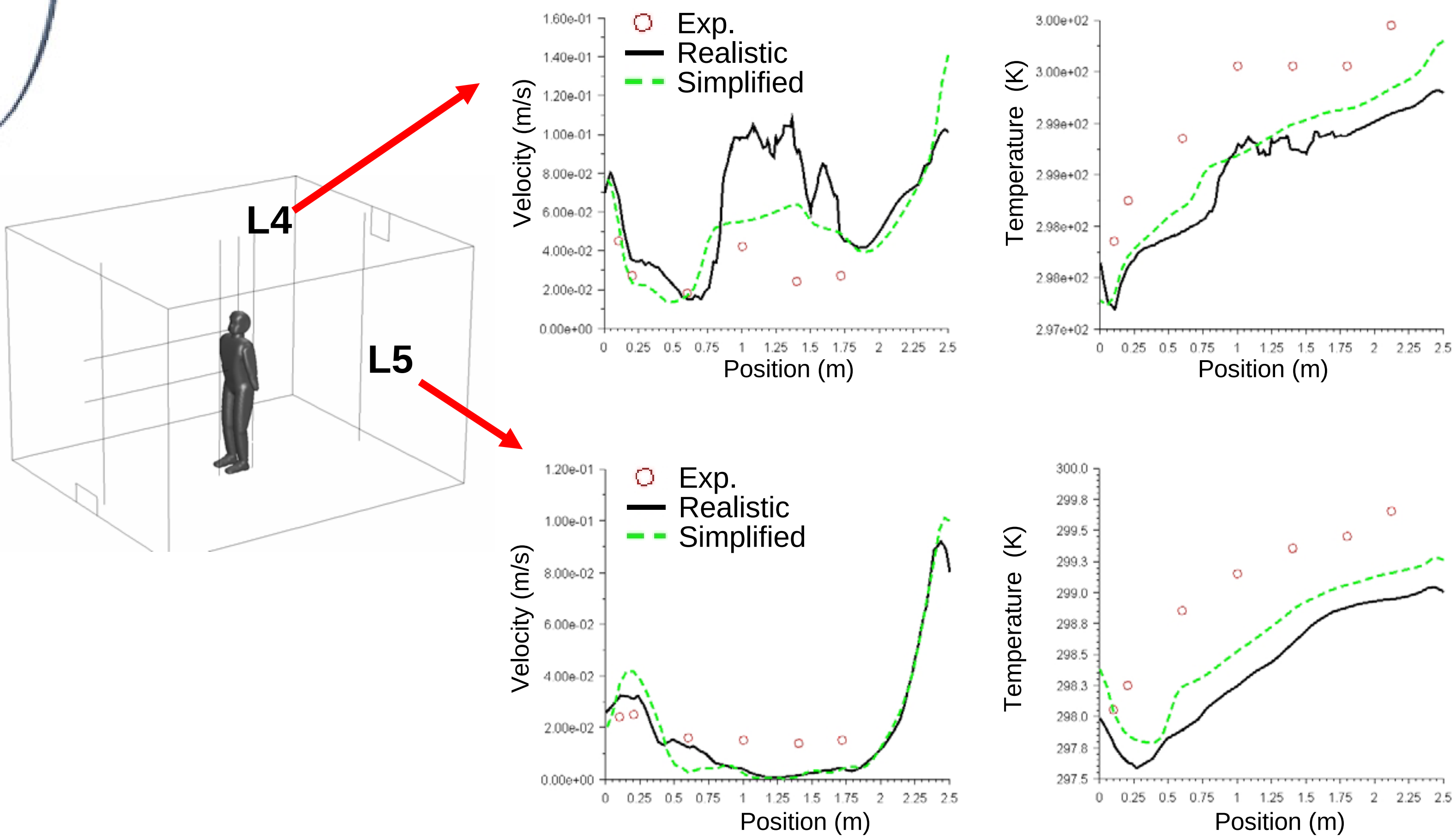
Effect of Geometry: Z-Velocity Profiles in Proximity of Mannikin





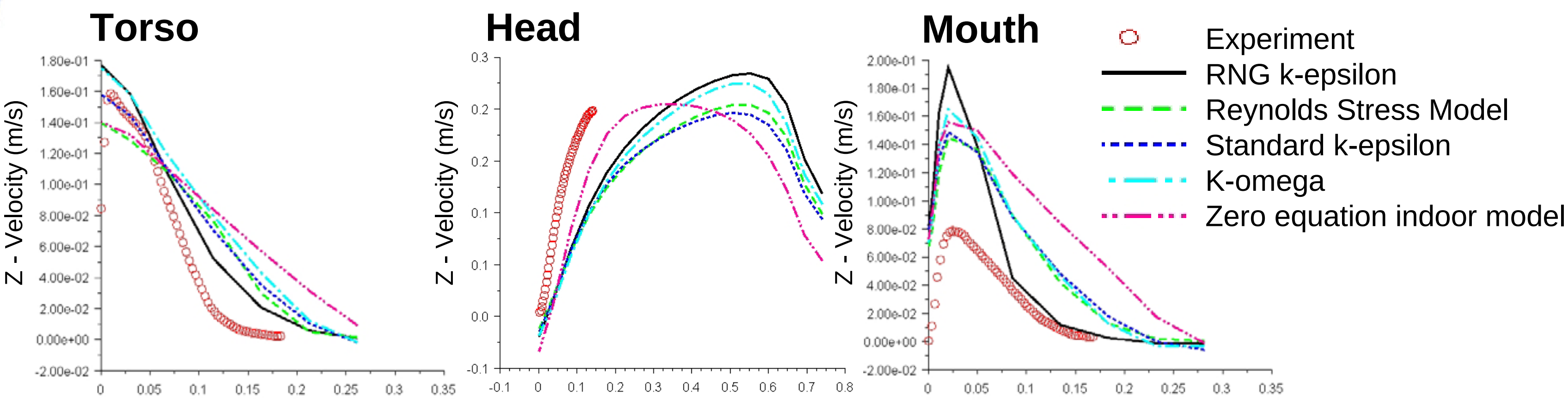
- Realistic geometry does not result in dramatic improvement
  - Slight improvement – especially in boundary layer thickness
  - Would identical geometry help?

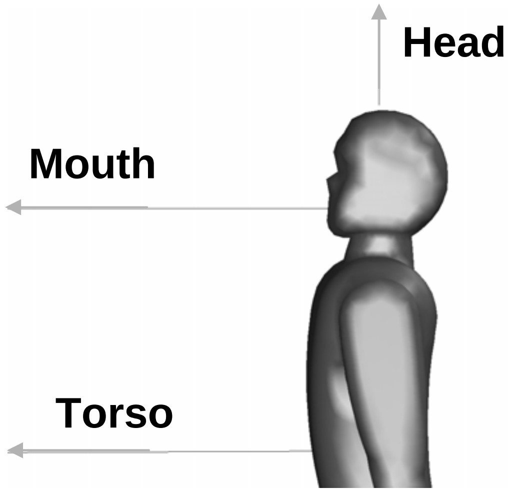
Effect of Geometry: Temperature and Velocity Profiles Behind Mannikin



Turbulence Model Comparison

Comparison of turbulence models on Grid A for simplified geometry





- RNG k-epsilon model appears promising if grid independent solution can be achieved

Summary and Conclusions

- For the case under consideration, it is difficult to avoid grid dependency in 2-equation and Reynolds Stress turbulence models when attempting to use wall functions
  - Of five turbulence models considered, all except the indoor zero equation turbulence model demonstrated unacceptable grid dependency
- Where resolution of profiles within viscous sublayer is unnecessary or too expensive, the indoor zero equation model appears to be an attractive option
  - Boundary layer width on mannikin surface appears to be slightly overpredicted in this case
  - Temperature and velocity predictions within room appear satisfactory
- Highly accurate results in proximity of mannikin require sufficient resolution of viscous sublayer and appropriate near wall modeling approach
- Use of a more realistic geometry results only in a slight improvement
  - Additional pre-processing effort compared to simplified geometry may not be justified unless near-wall modeling approach used
- Possibilities for further work
  - Investigate further geometry simplifications
  - Investigate experimental mannikin geometry