Designing Retail Packages for Fruits for Uniform Cooling

R. Paul Singh and M. J. Ferrua

University of California, Davis.
Davis, California

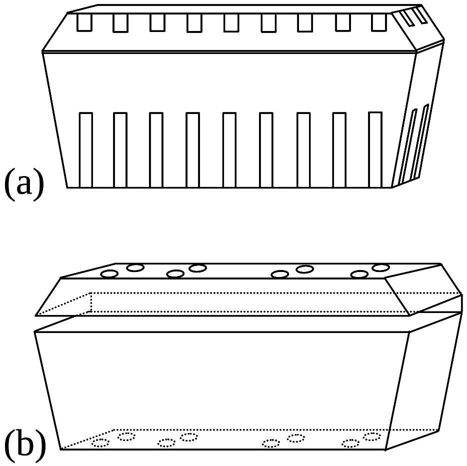
Overview

- Industrial practice in packaging of berry fruit
- Problem definition and rationale
- Engineering approach to address industrial problem
  - Fluid flow in complex systems
  - Use of a non-intrusive Particle Imaging Velocimetry (PIV) to determine flow field
  - Computational fluid dynamic modeling (CFD) and validation of flow field
  - Prediction and experimental validation of CFD models of heat transfer
- Use of CFD models to design next generation packaging systems

Industrial Practice

- Strawberries are field packed in individual containers.

Typical commercial clamshells used for strawberries

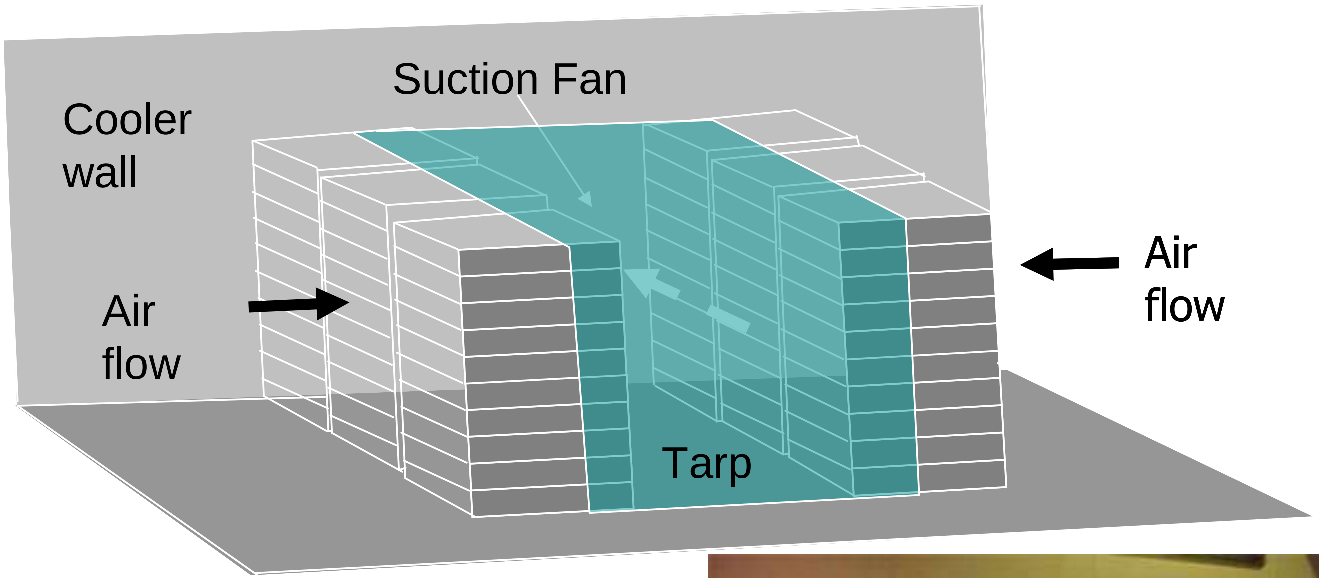


Clamshell packages in cardboard trays

- Clamshells are placed into open-top cardboard trays, and trays are stacked onto each other.

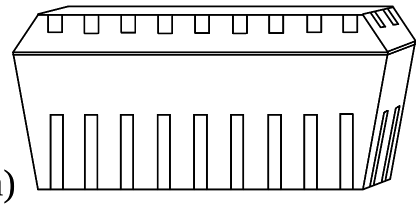
- Finally, they are rushed to the cooling facility.

Forced air cooling of pallet loads

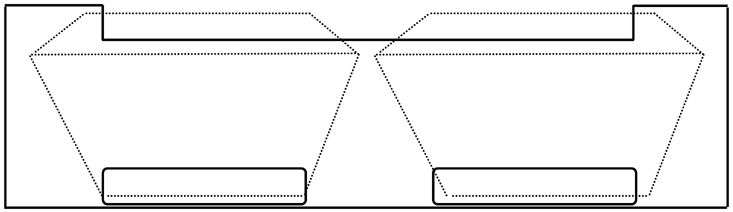


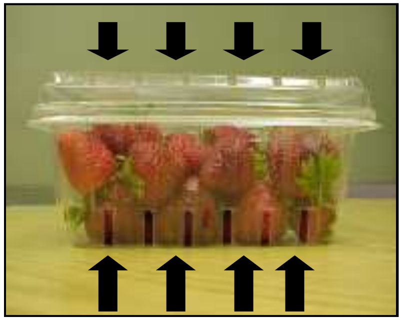
Airflow in Clamshells and Cardboard Trays

(a)



(c)





Industrial Needs

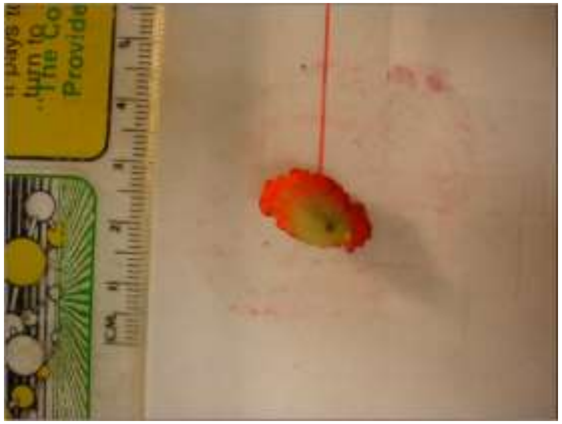
- Develop a scientific basis for the design of clamshells and cardboard trays, as a system, to promote optimum cooling and energy efficiency.
- The design of the system should include size and location of vent openings in walls of clamshells and cardboard trays, and related issues such as pallet load assembly in creating cooling tunnels.

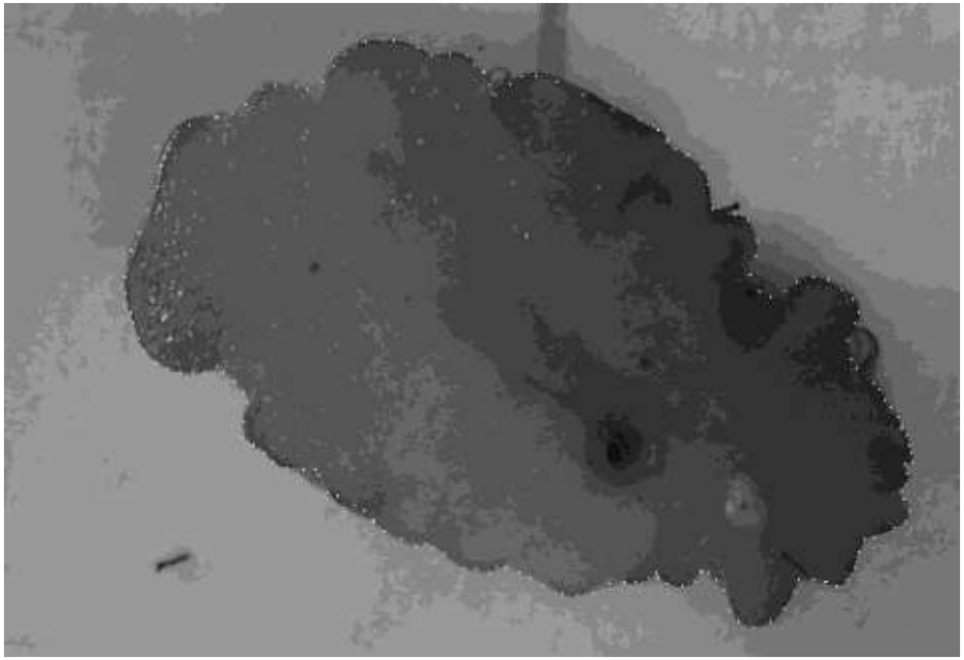
A computational model of the physical system

Model

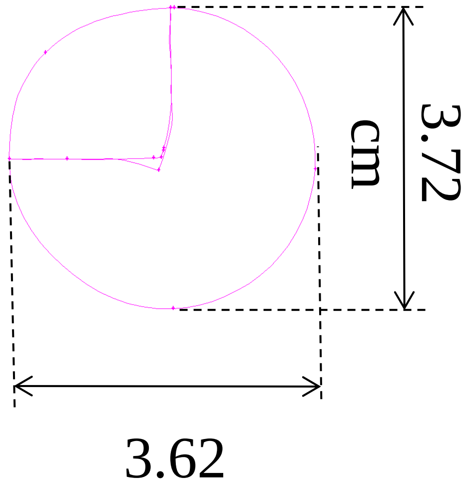
- System:
  - Strawberries,
  - clamshell,
  - tray package,
  - clamshells in a tray,
  - trays organized on a pallet.

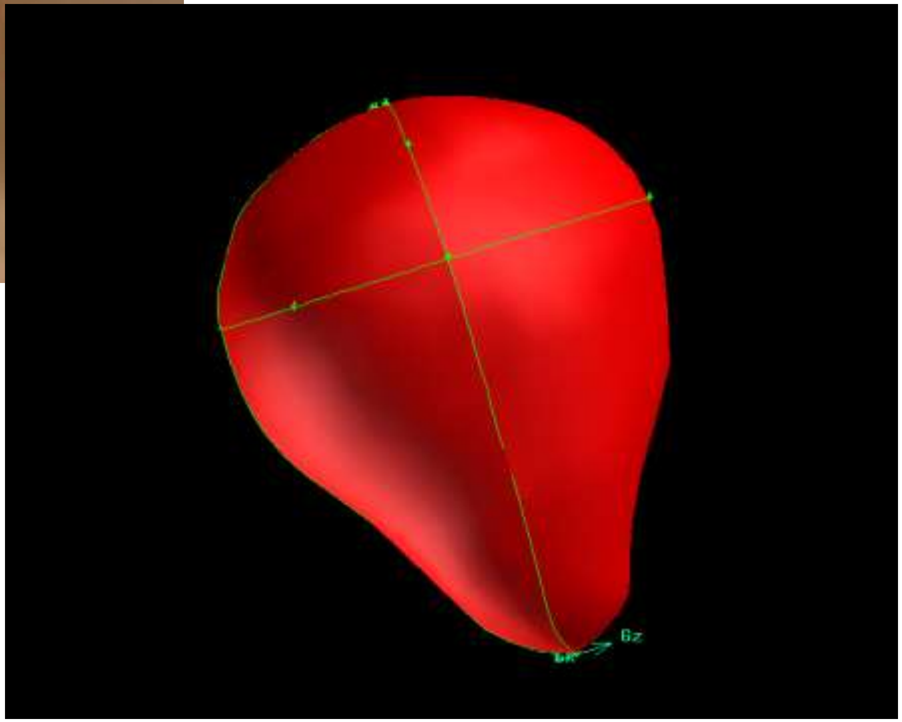
Strawberry model

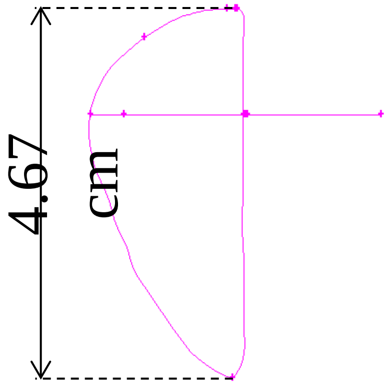




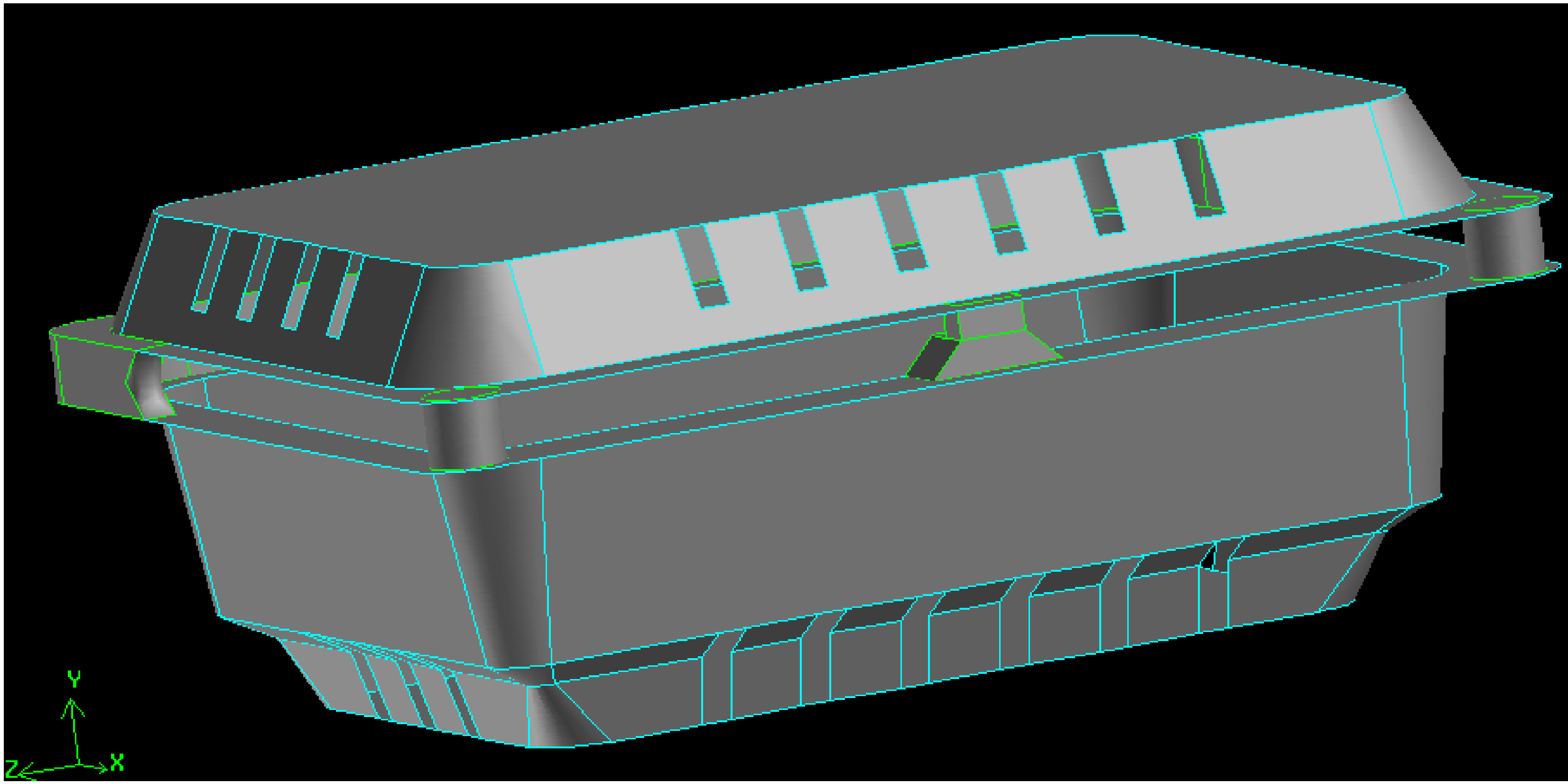
Model of a real strawberry



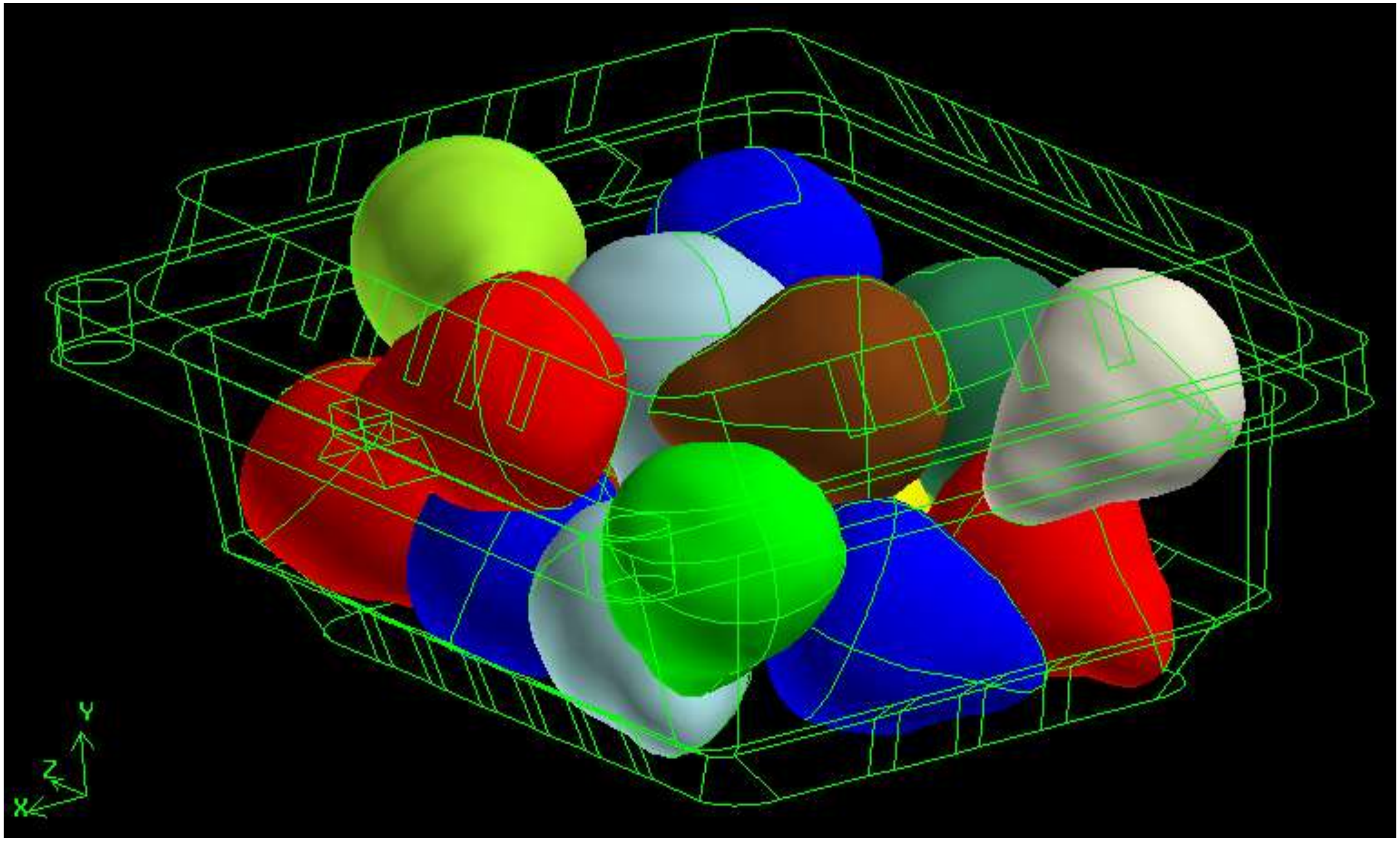




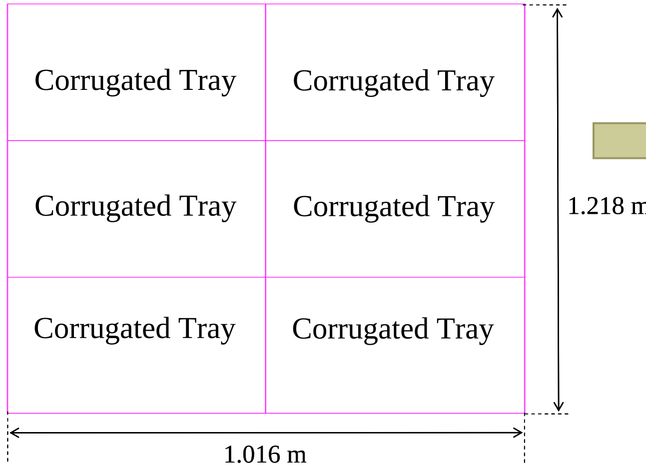
Clamshell

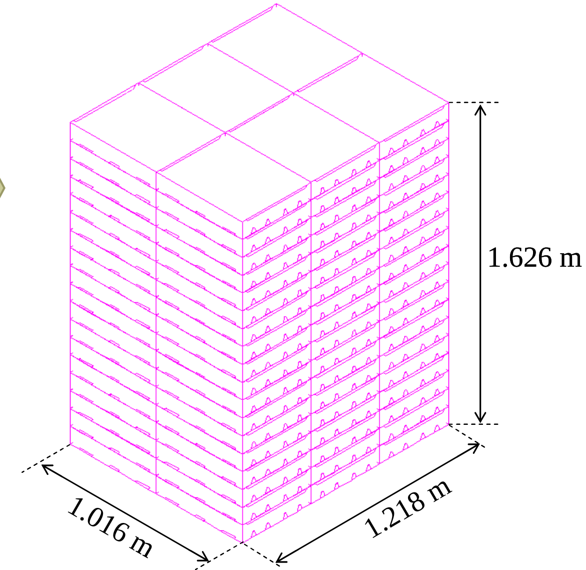


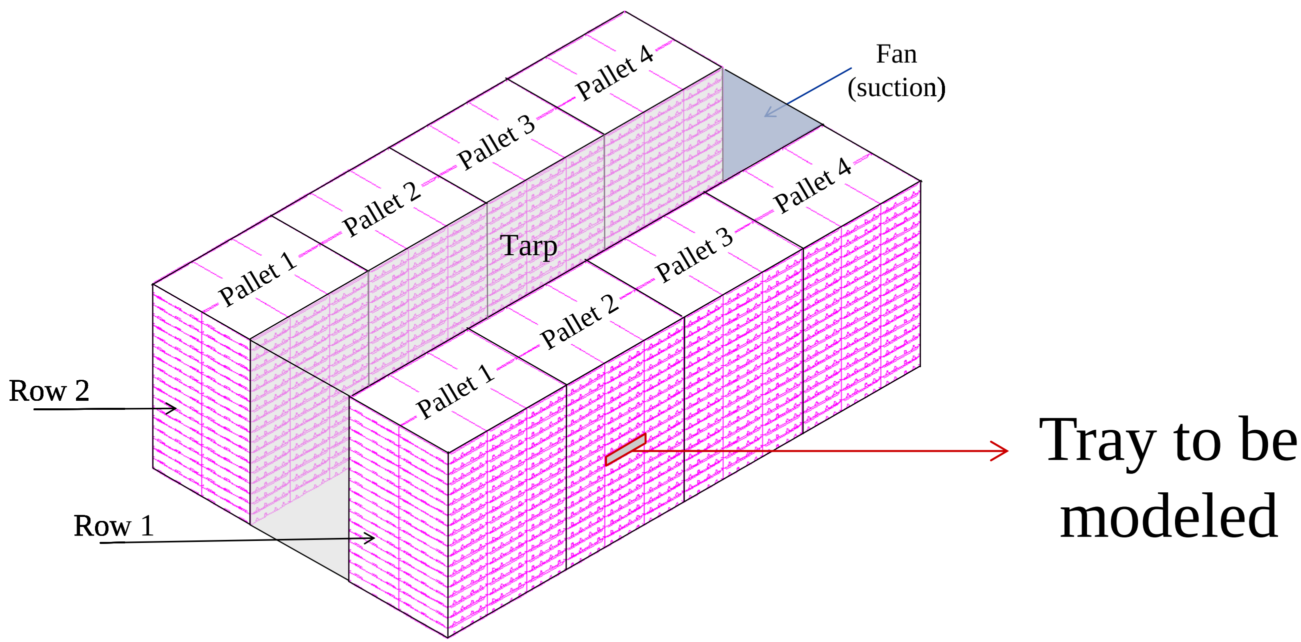
Strawberry package



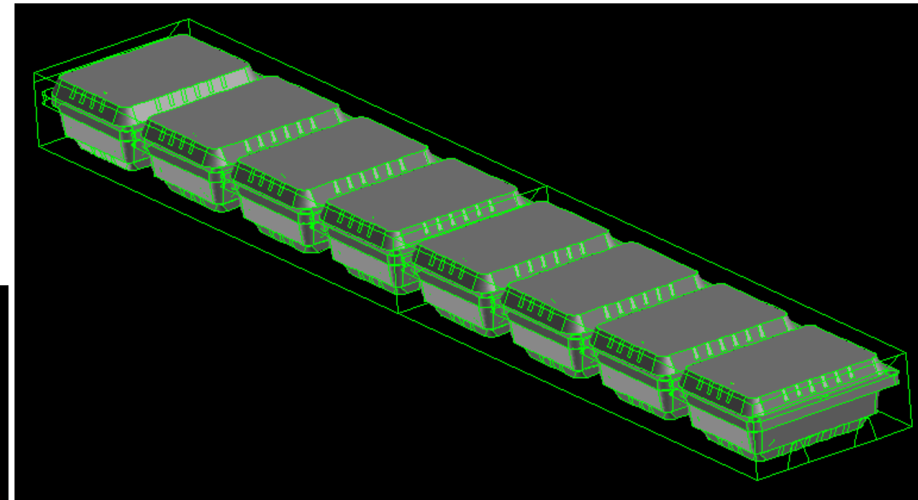
Pallet structure

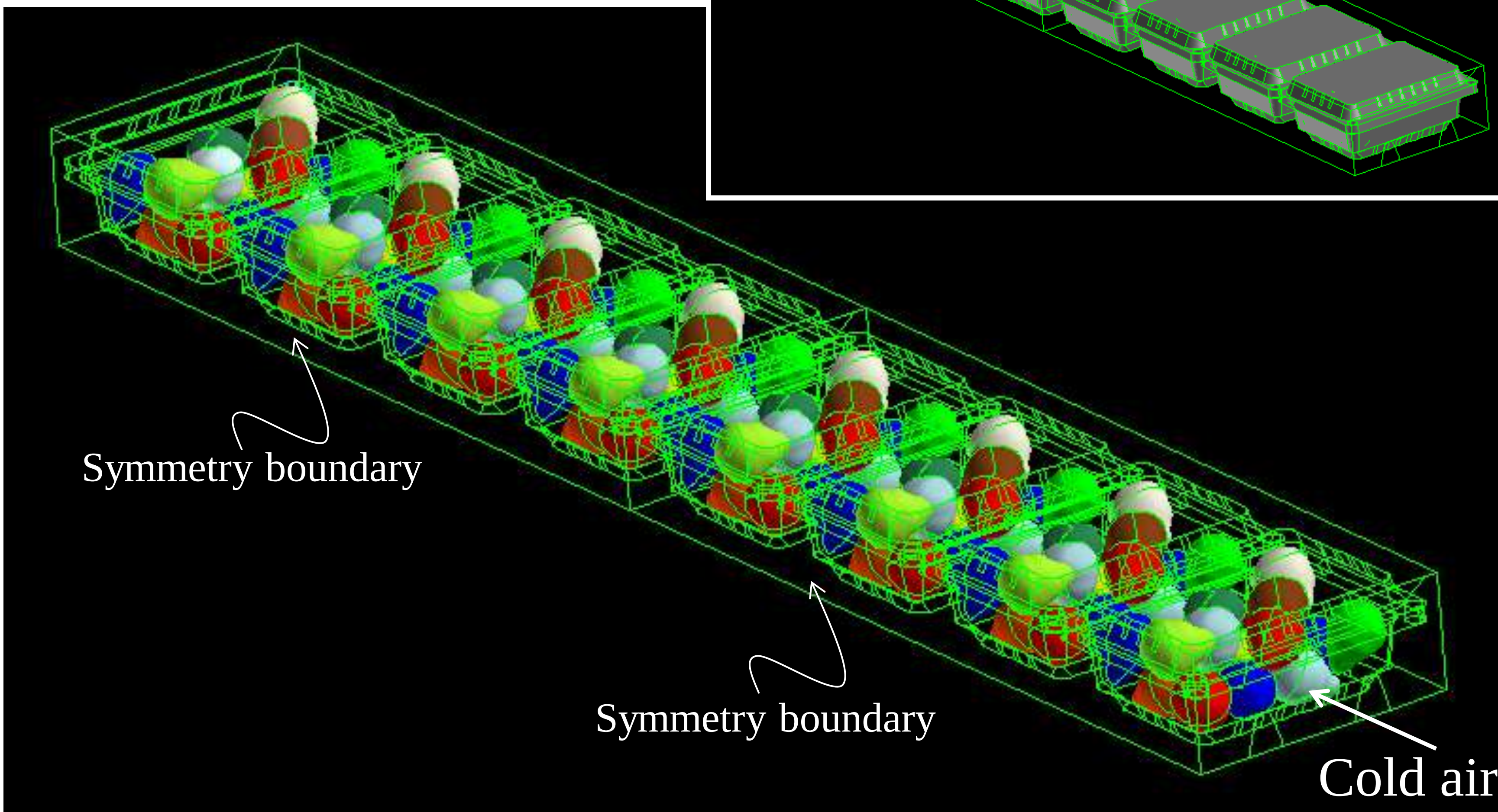






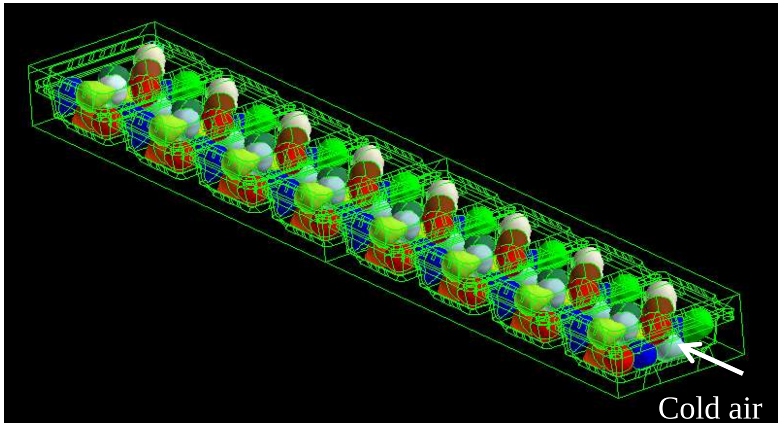
Final model



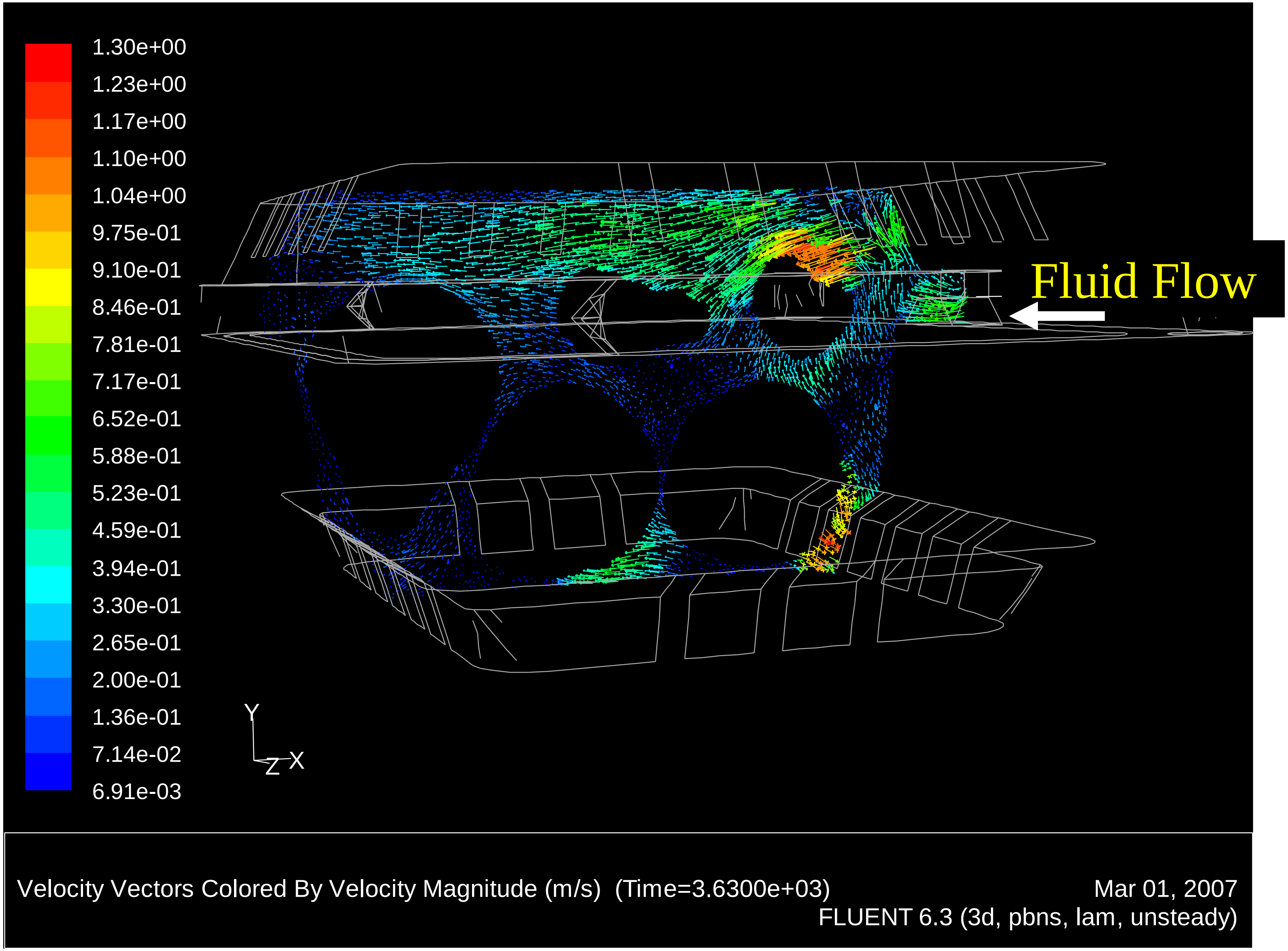


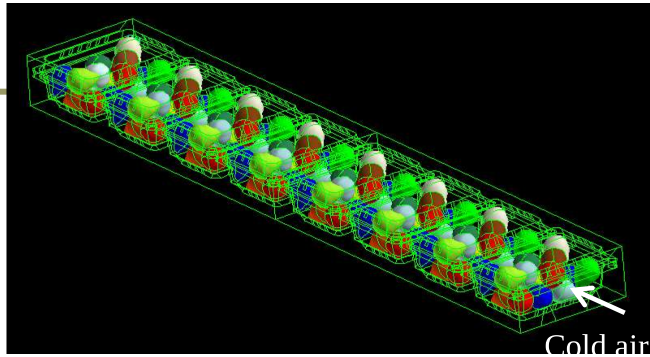
Predicted Air flow inside the system using CFD model

Simulation of the airflow through the palletized structure

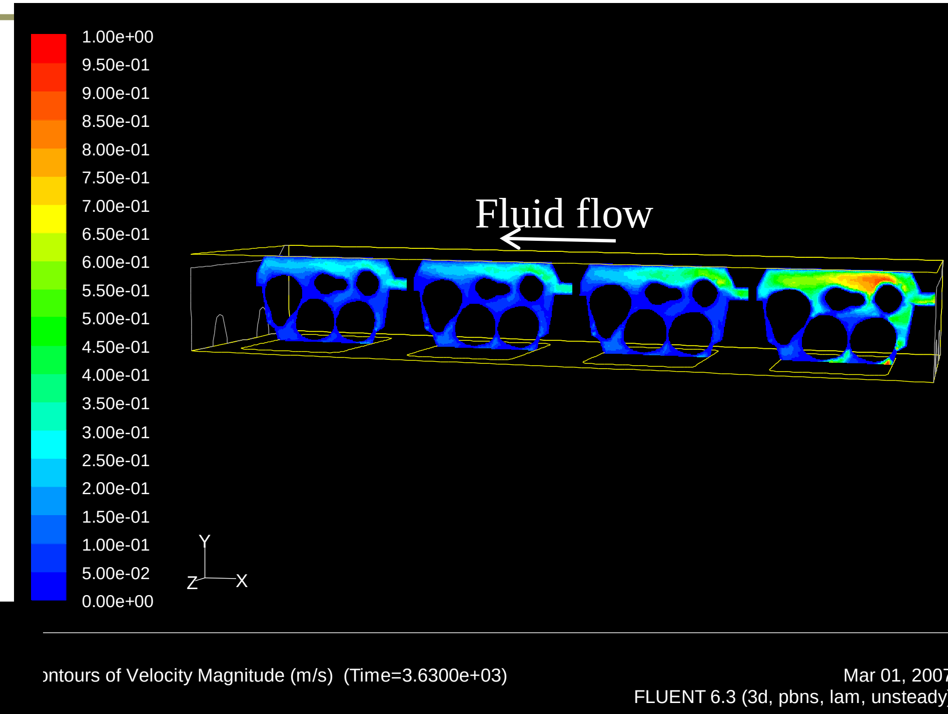


Clamshell 1

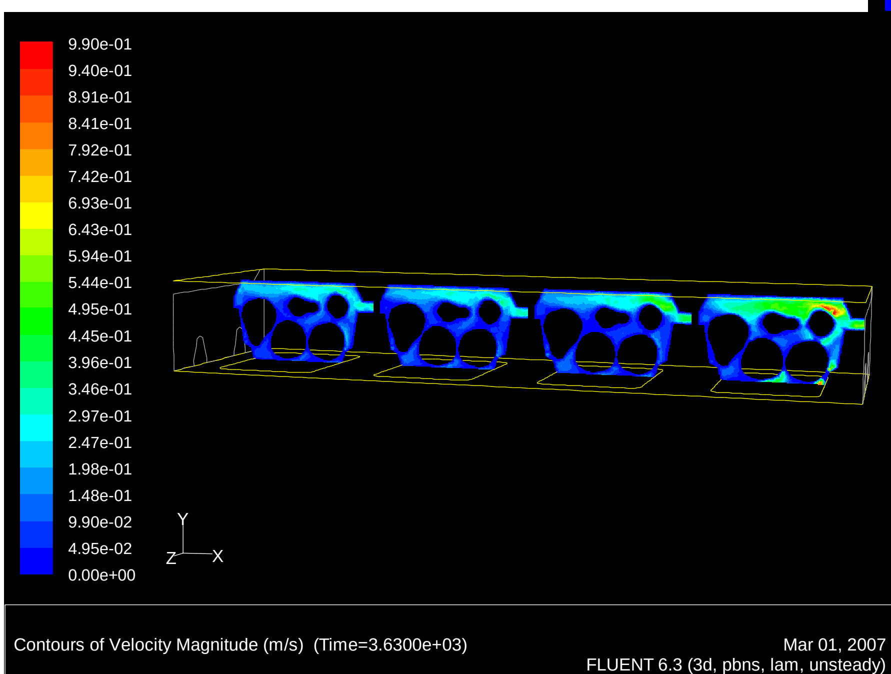

1.30e+00
1.23e+00
1.17e+00
1.10e+00
1.04e+00
9.75e-01
9.10e-01
8.46e-01
7.81e-01
7.17e-01
6.52e-01
5.88e-01
5.23e-01
4.59e-01
3.94e-01
3.30e-01
2.65e-01
2.00e-01
1.36e-01
7.14e-02
6.91e-03
Fluid Flow
Y
Z
X
Velocity Vectors Colored By Velocity Magnitude (m/s) (Time=3.6300e+03)
Mar 01, 2007
FLUENT 6.3 (3d, pbns, lam, unsteady)



Vertical plane (first tray)



Vertical plane (second tray)

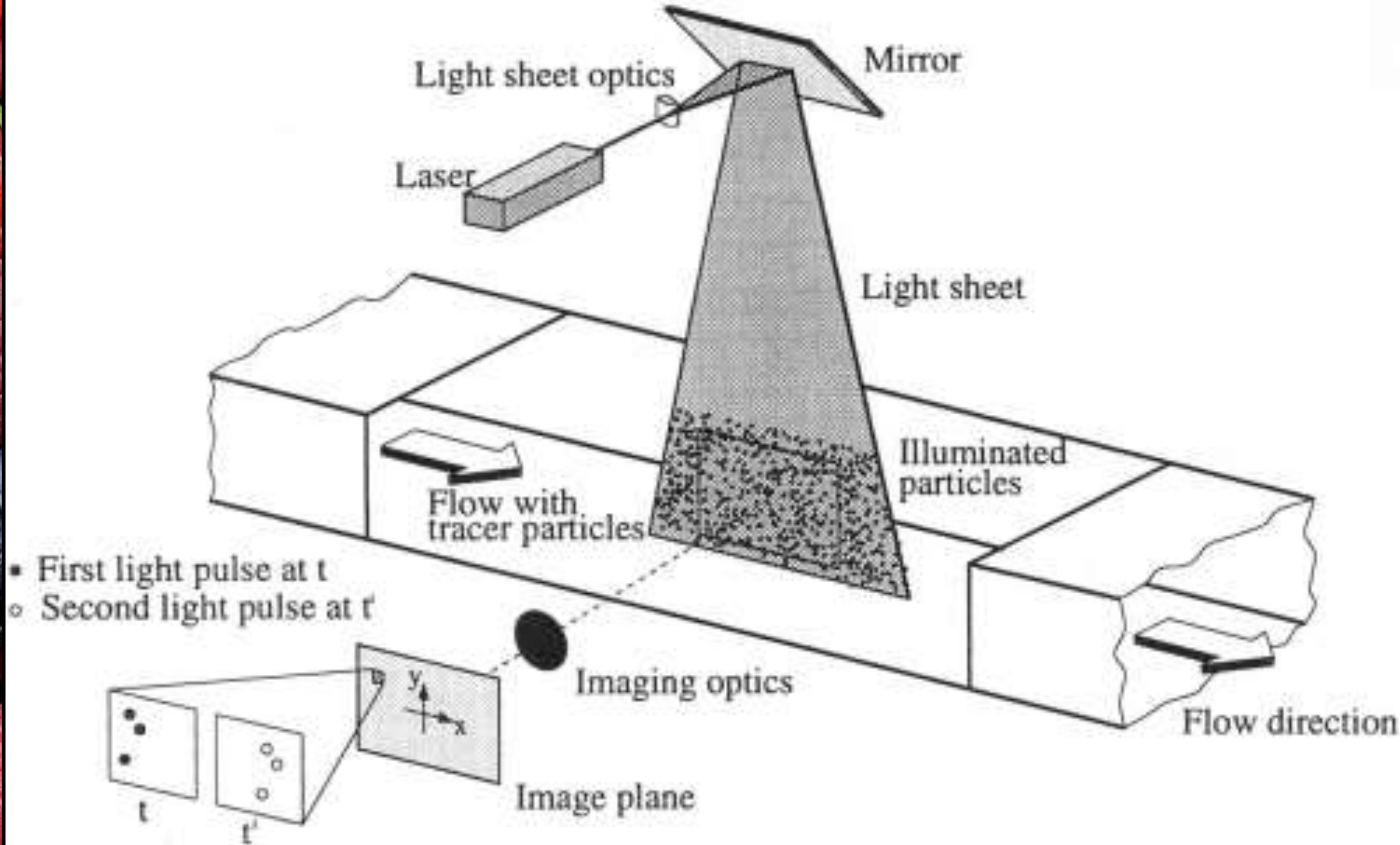


Experimental Setup
Flow Field Studies

PARTICLE IMAGE VELOCIMETRY (PIV)

PARTICLE IMAGE VELOCIMETRY (PIV)

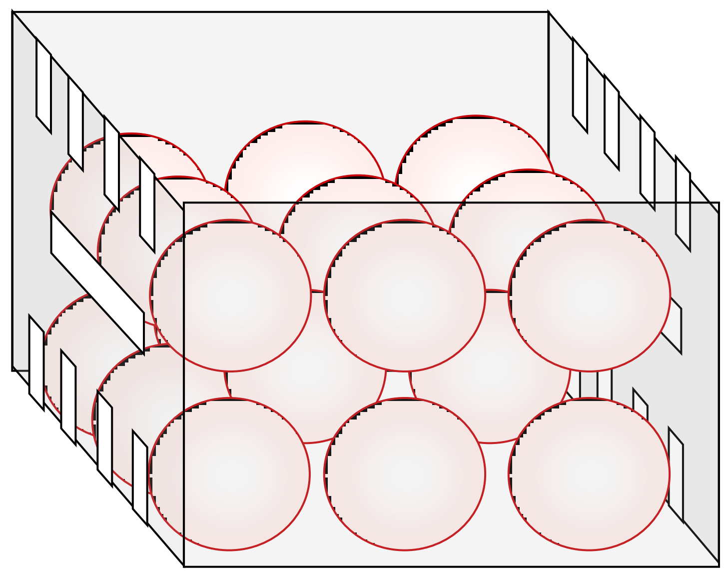
- PIV determines the flow fields over global domains by optically measuring the motion of small markers seeded in the flow.
  - A pulsed sheet of laser light illuminates the flow domain at different instants of time.
  - The location of the markers at the time of each pulse is recorded by the light scattered by them into a camera lens.



The requirement of <u>optical access to the flow</u> has limited PIV application to simple geometries.

A transparent model for PIV validation

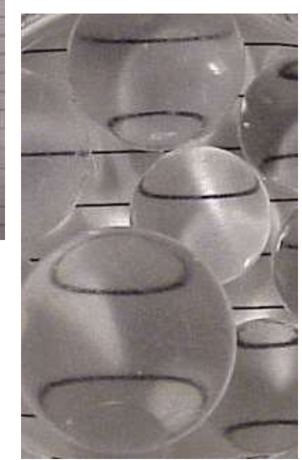
- PIV requires optical access to the flow field.
- Need a transparent model of the packed structure.



MODEL FOR PIV APPLICATIONS

- The optical access to the flow domain requires:
  - Transparent setup of the individual package of produce.

  - Perfect refractive index (η) match between the transparent model setup and the working fluid (to avoid distortions of both the laser sheet and the scattered light as they pass through the system).



Air cannot be used as a model fluid, its η is of different order of magnitude than solids' η.

Transparent model

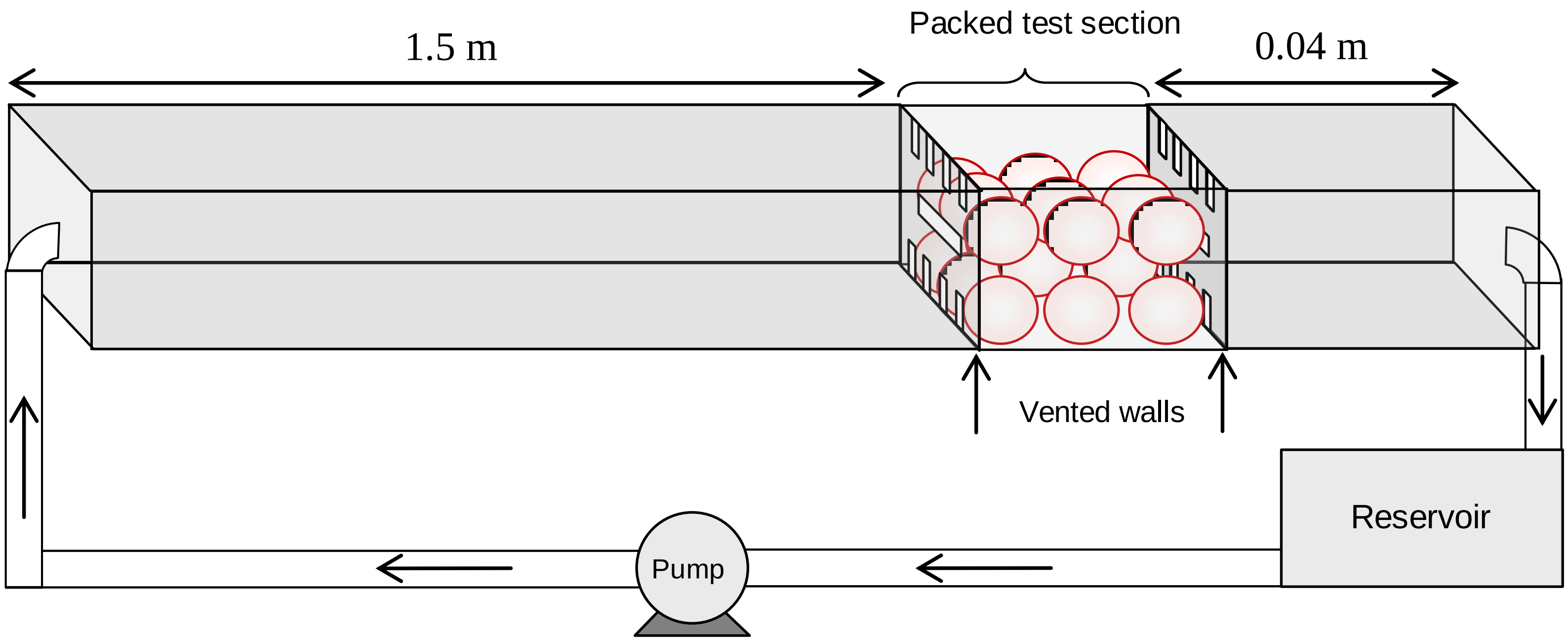
- An appropriate combination of solid/liquid.
  - Refractive index matching.
  - Low Fluid viscosity (easily pumped).
  - Cost.

Fused silica spheres.
Air

Fused silica spheres.
Johnson & Johnson baby oil-Drakesol 260 oil mixture.

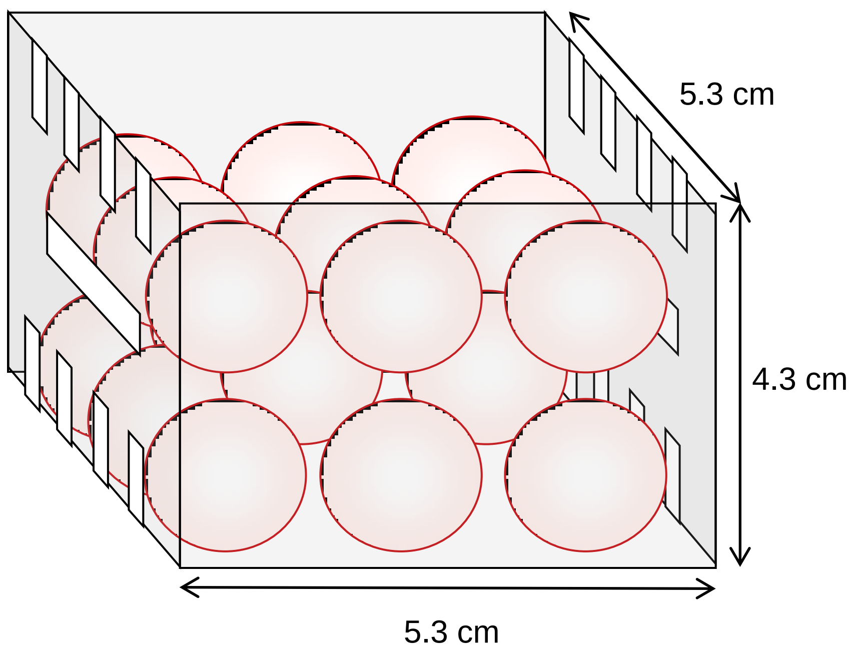
Transparent model

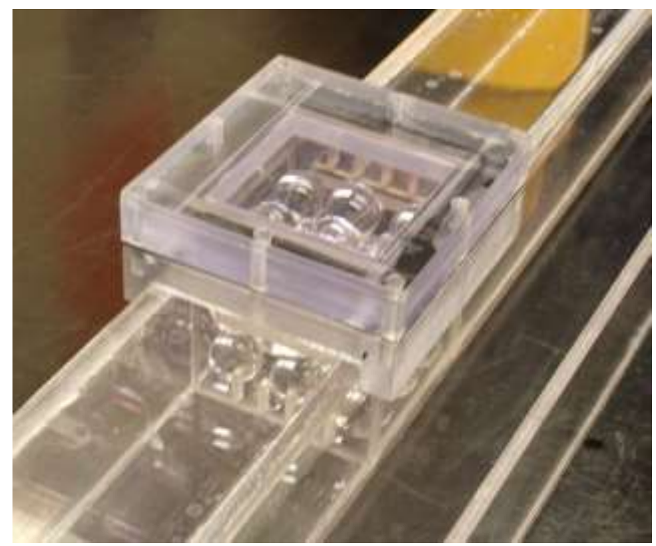
- Transparent experimental set up.



Transparent model

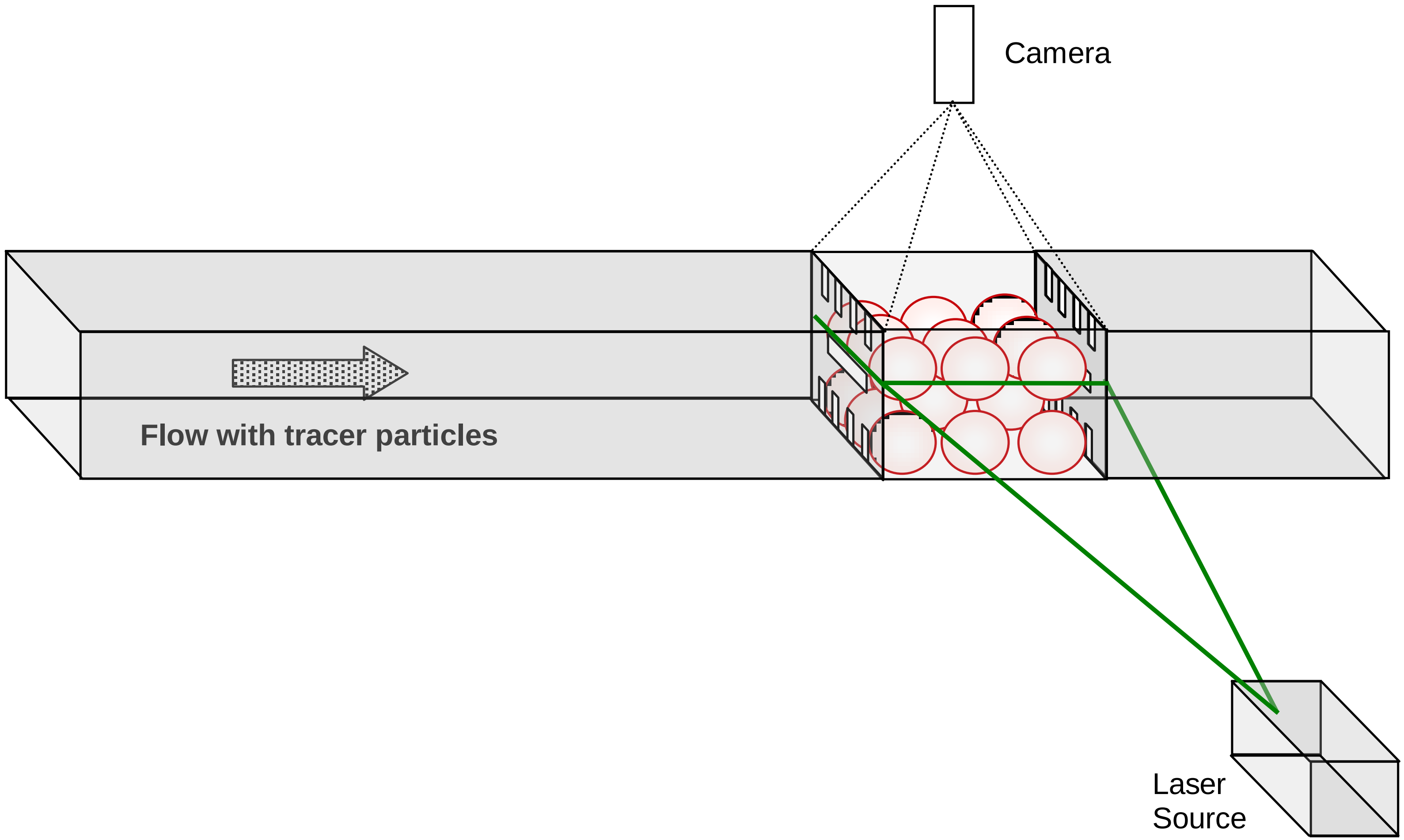
- The packed test section design was based on the packed structure and the smaller cross-section dimensions of a typical 0.5 kg strawberry package.
  - Berries were modeled by spheres whose volume represent the average volume of the fruit.



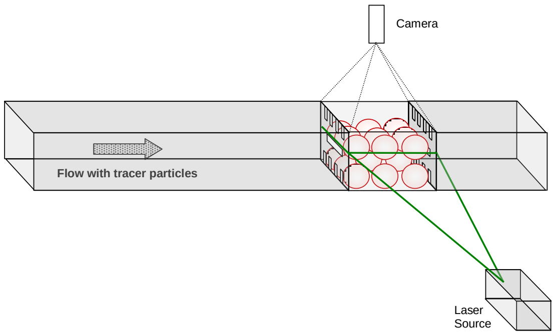


PIV MEASUREMENTS

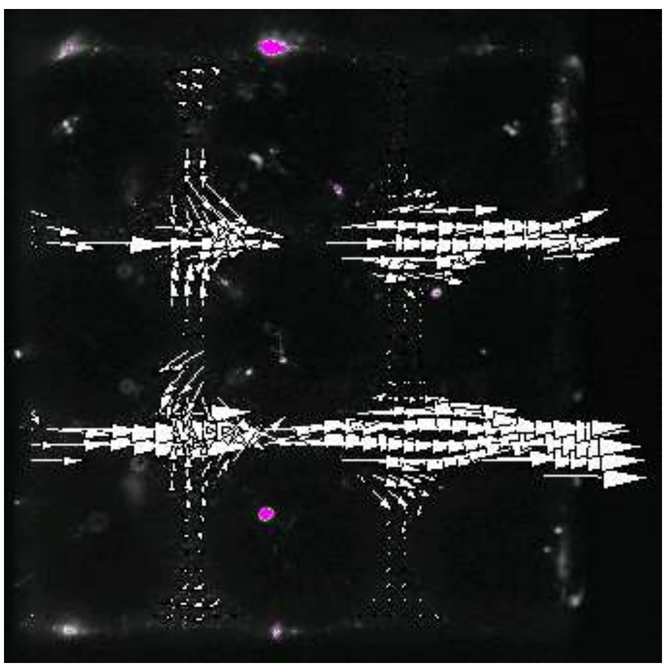
- The flow field in four horizontal planes within the system was measured.

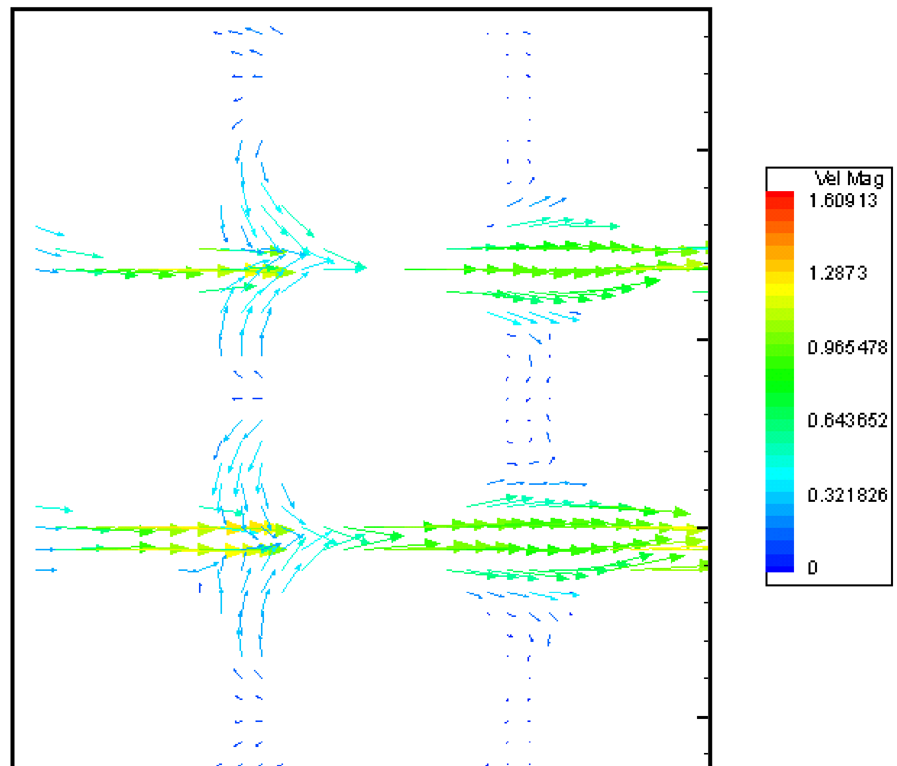


Level 1

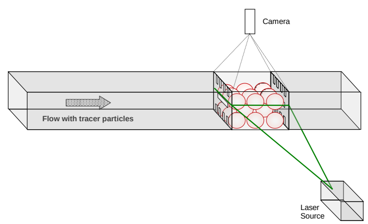


Fluid flow direction





RESULTS

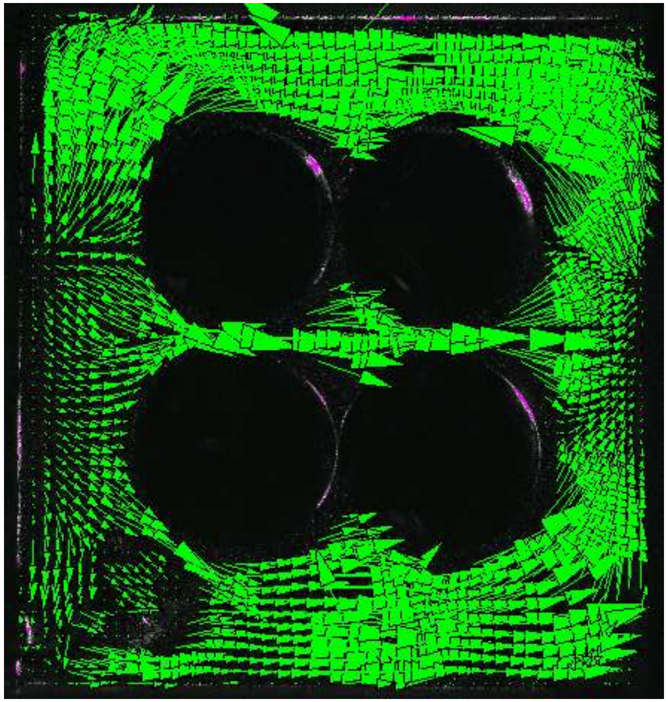


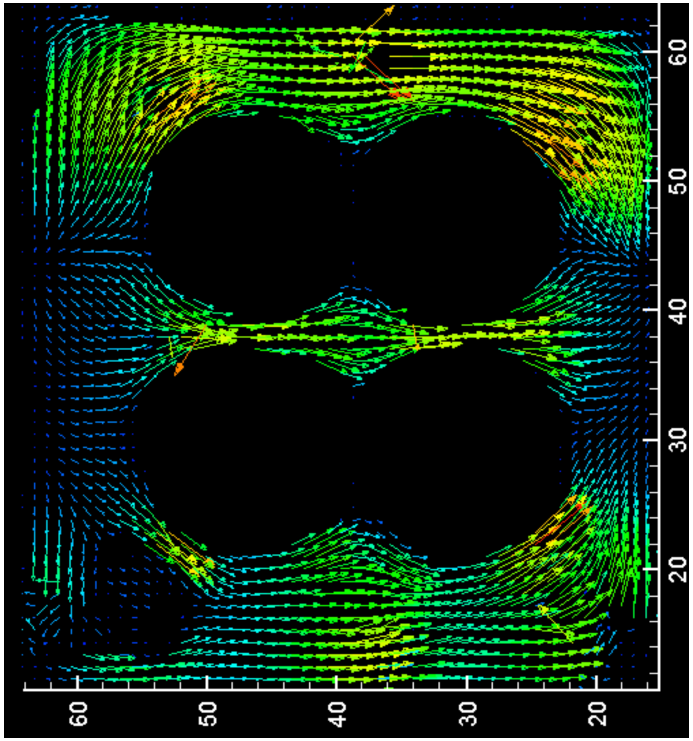
Fluid flow direction

Side view

Top view

Fluid flow





Computational Model (for transparent system using quartz)

MATHEMATICAL MODEL

- Steady laminar flow of an incompressible, Newtonian fluid with constant fluid viscosity.

Navier-Stokes equations:

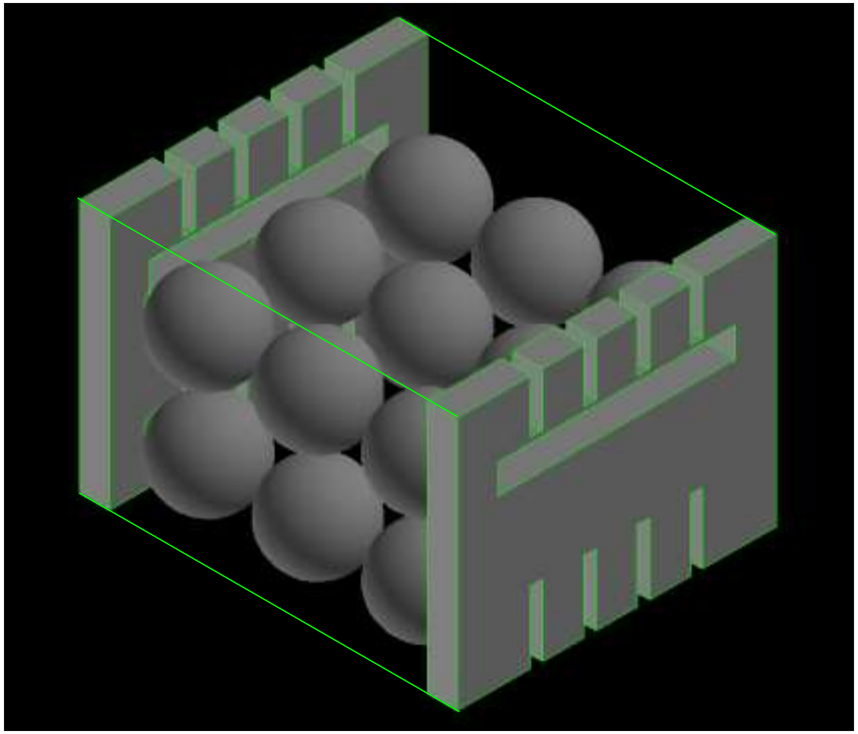
$$\frac{\partial U_i}{\partial x_i} = 0$$

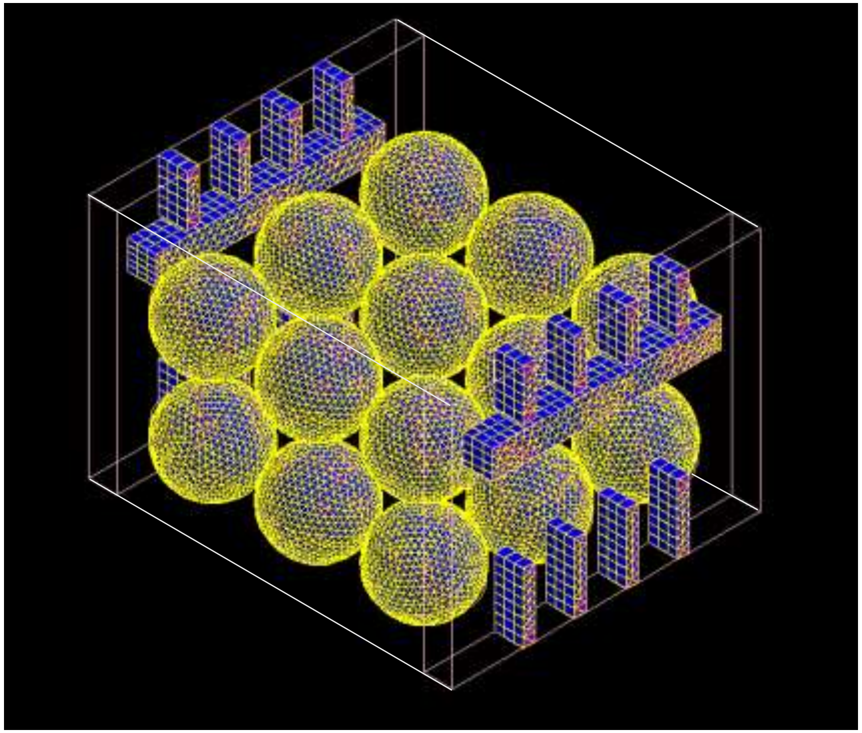
$$U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j} + g_i$$

Where: U_i: velocity component in x_i direction, m/s.
P: static pressure, Pa.
ρ: density of the fluid, kg/m^3.
ν: kinematic viscosity of the fluid, m^2/s.
g_i: volume force per unit of mass, m/s^2.

COMPUTATIONAL MODEL

- The first step in any CFD simulation is the creation of a computational model that accurately reproduces the experimental domain under study.

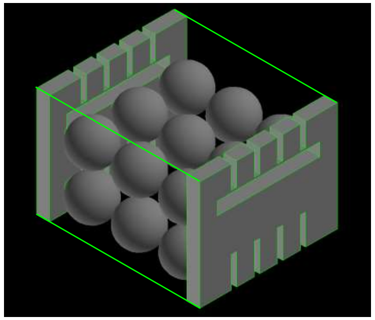


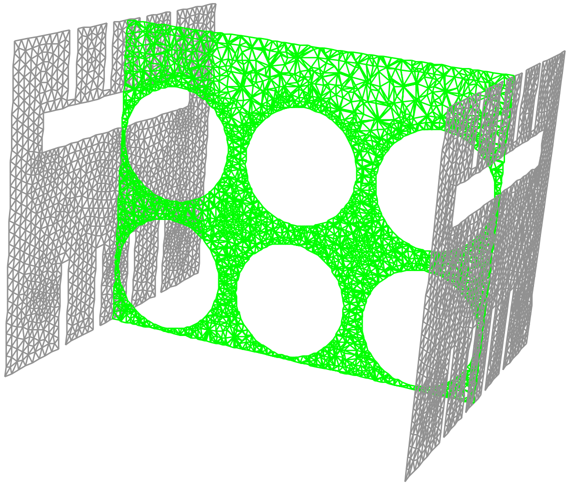


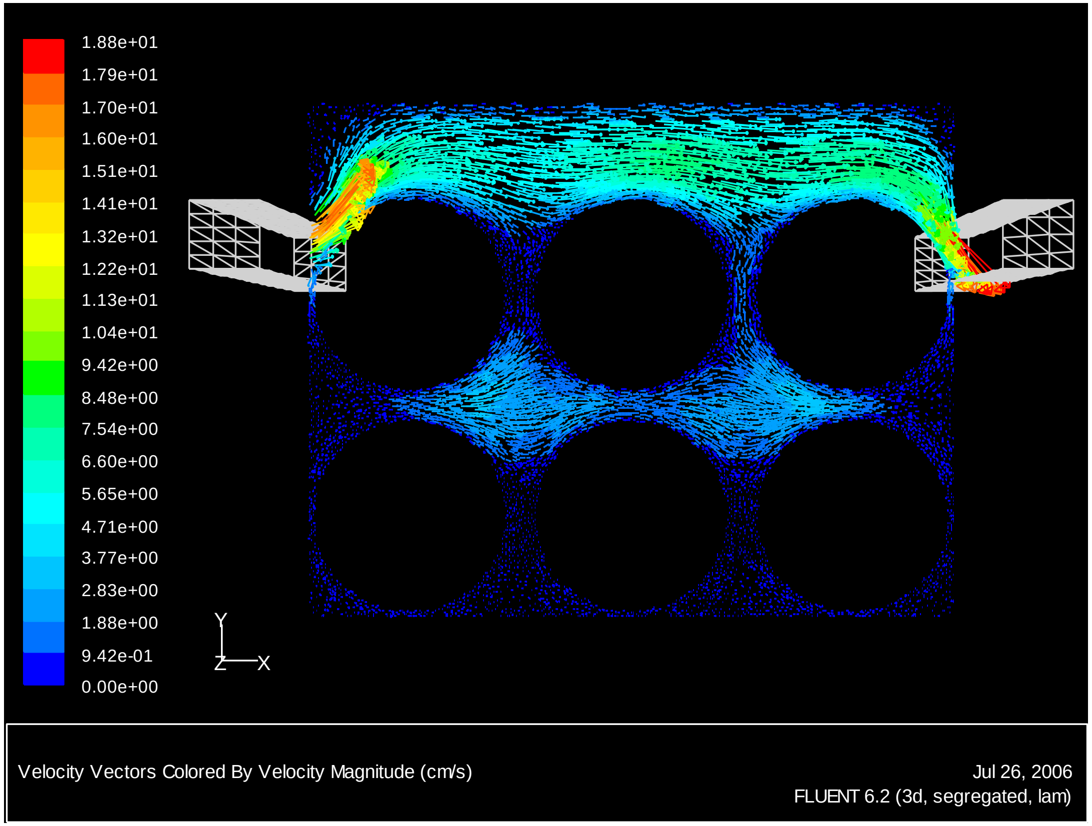
NUMERICAL RESULTS

- CFD analysis provide a detailed flow field description.

  1. Velocity field within different planes



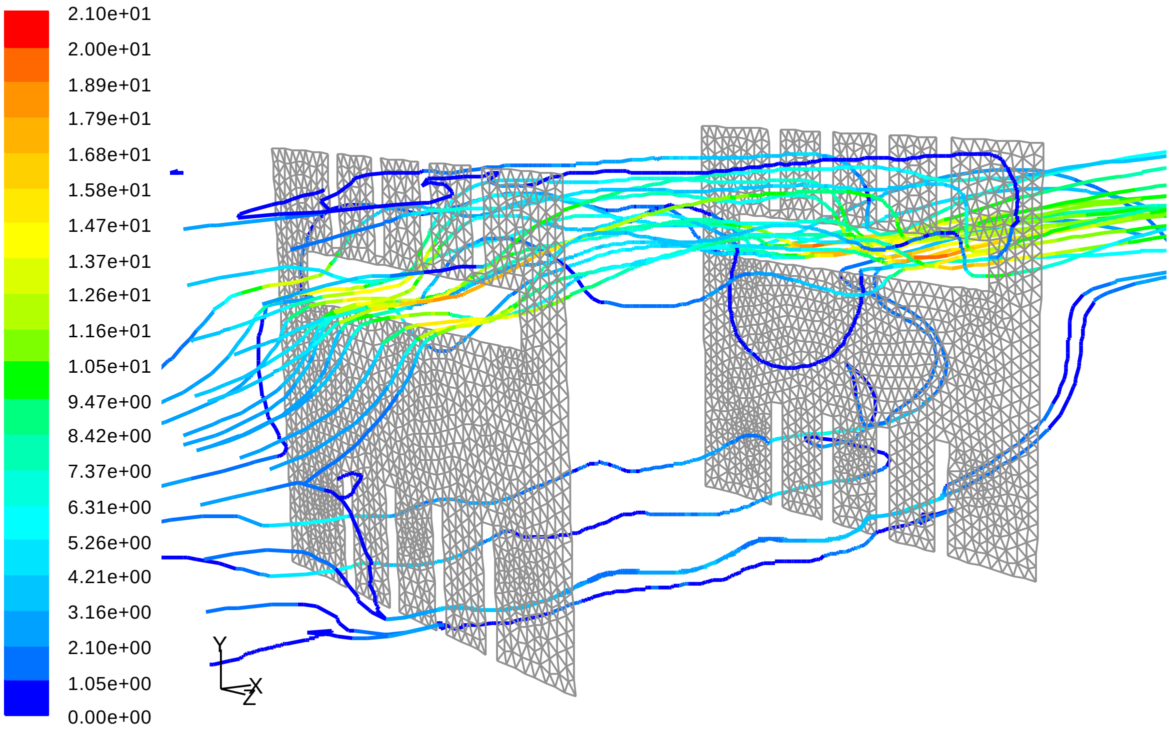




NUMERICAL RESULTS

- CFD analysis provide a detailed flow field description.

  3. Particle tracking.



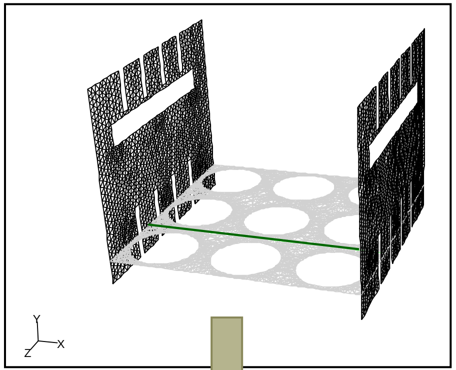
Path Lines Colored by Velocity Magnitude (cm/s)

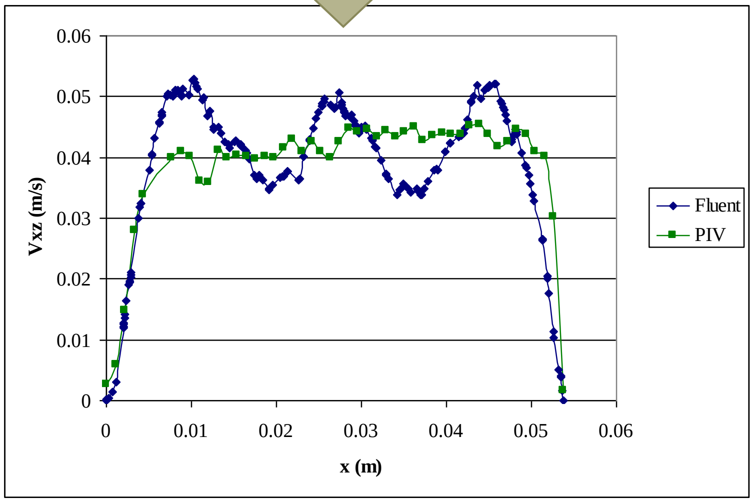
Aug 04, 2006
FLUENT 6.2 (3d, segregated, lam)

Validation of CFD model (of flow around quartz spheres)

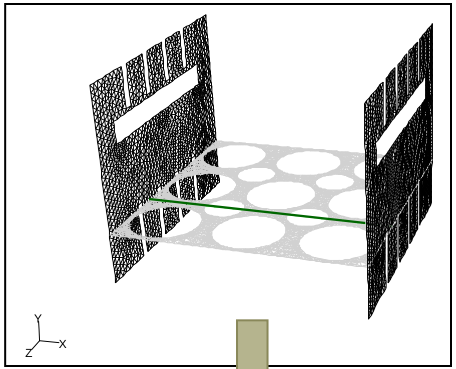
VALIDATION USING PIV MEASUREMENTS

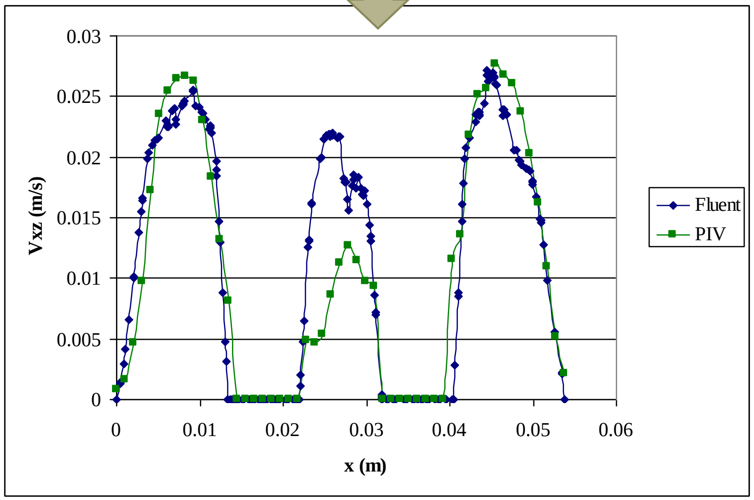
- Plane through the bottom layer of spheres.



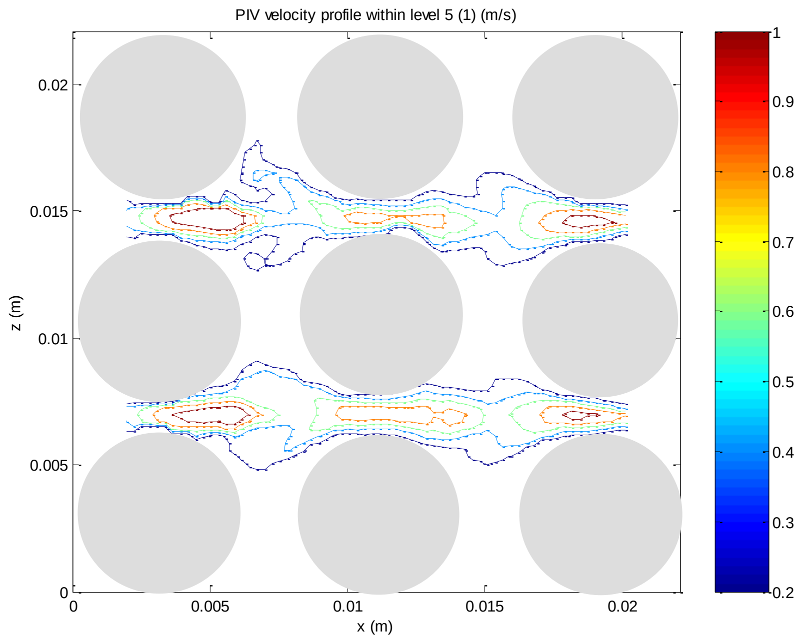


- Plane through the bottom and middle layer of spheres.

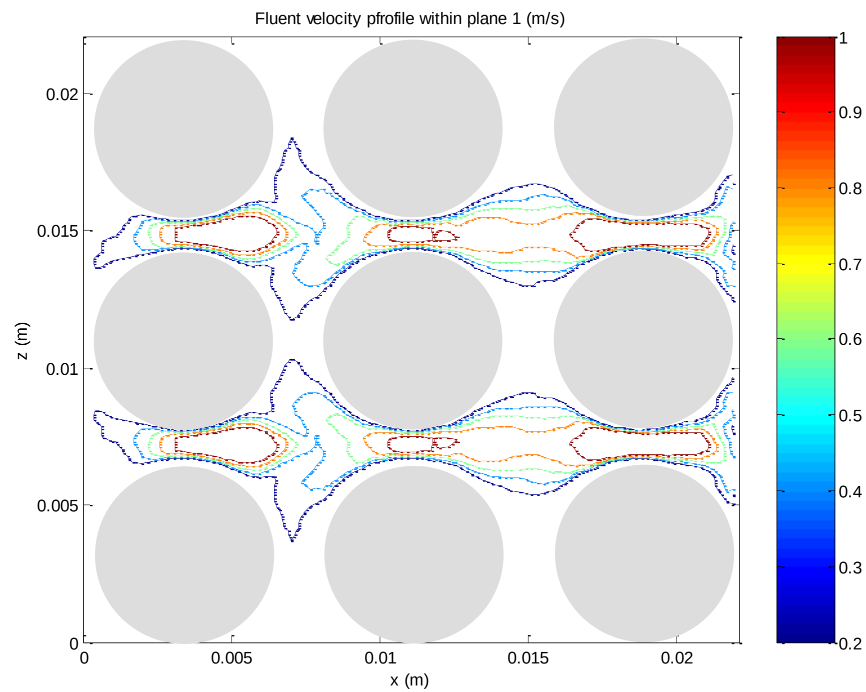




Level 1

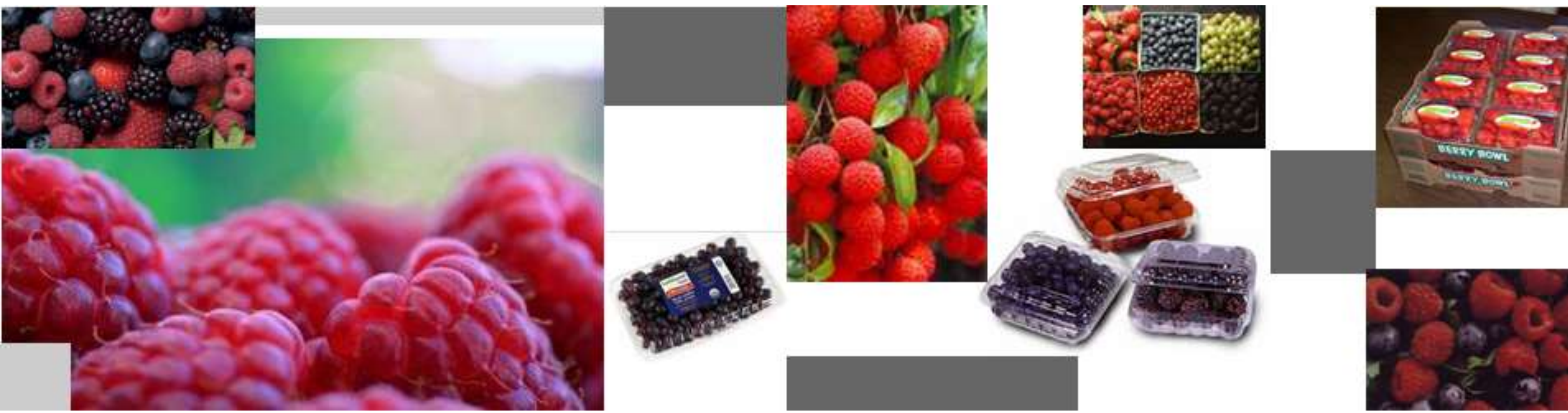


PIV measurements



CFD Predictions

Heat Transfer in Clamshell/Tray System



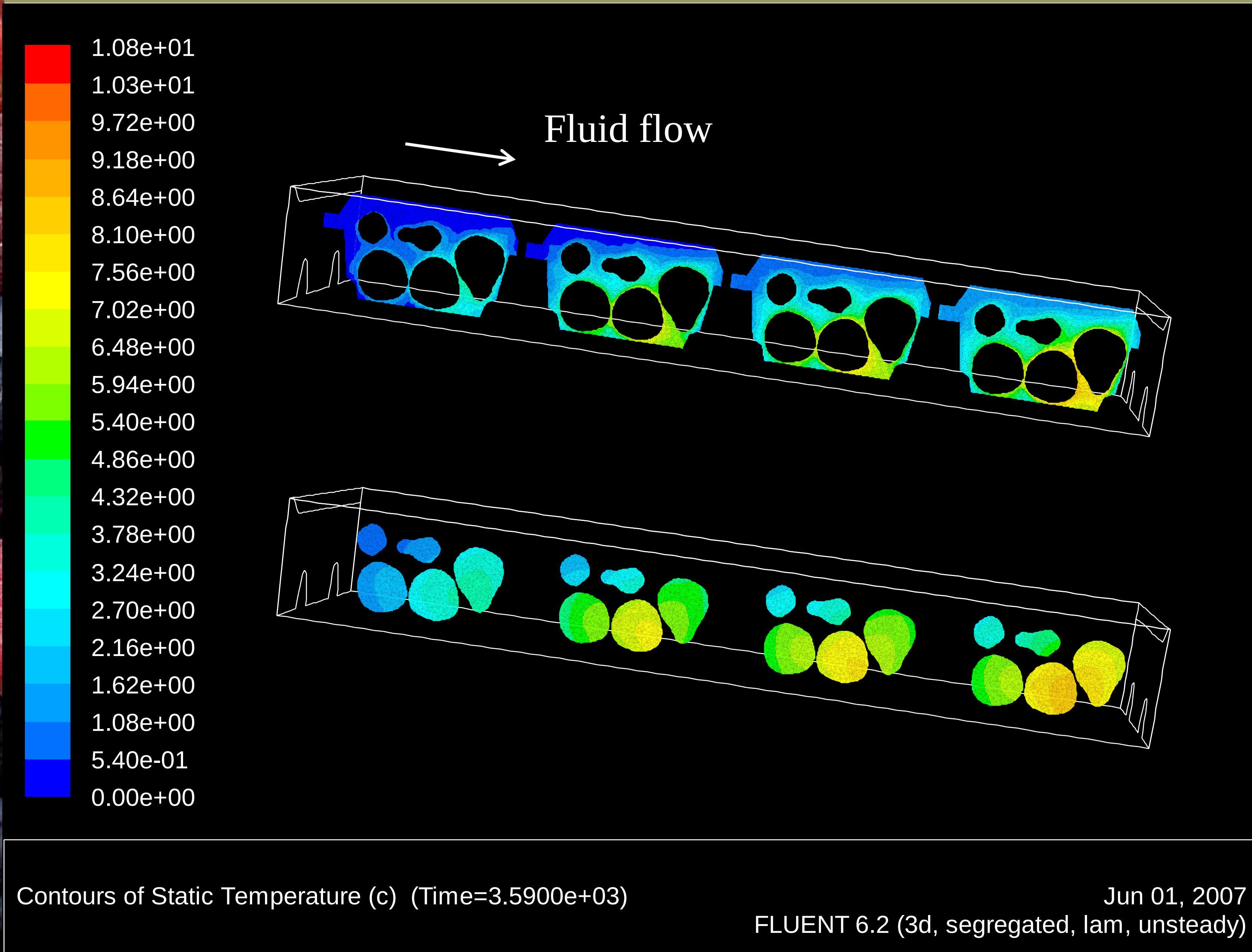
MATHEMATICAL MODEL

- Energy equations for the fluid and solid regions.
  - Fluid phase: $\left(\rho C_p\right)_f \left[\frac{\partial T_f}{\partial t} + \nabla \cdot \mathbf{u} T_f\right] = \nabla \cdot \left(k_f \nabla T_f\right)$
  - Solid phase: $\left(\rho C_p\right)_s \frac{\partial T_s}{\partial t} = \nabla \cdot k_s \nabla T_s$
- Boundary conditions at the fluid-solid interfacial area A_{fs} are given by the continuity of temperature and heat flux

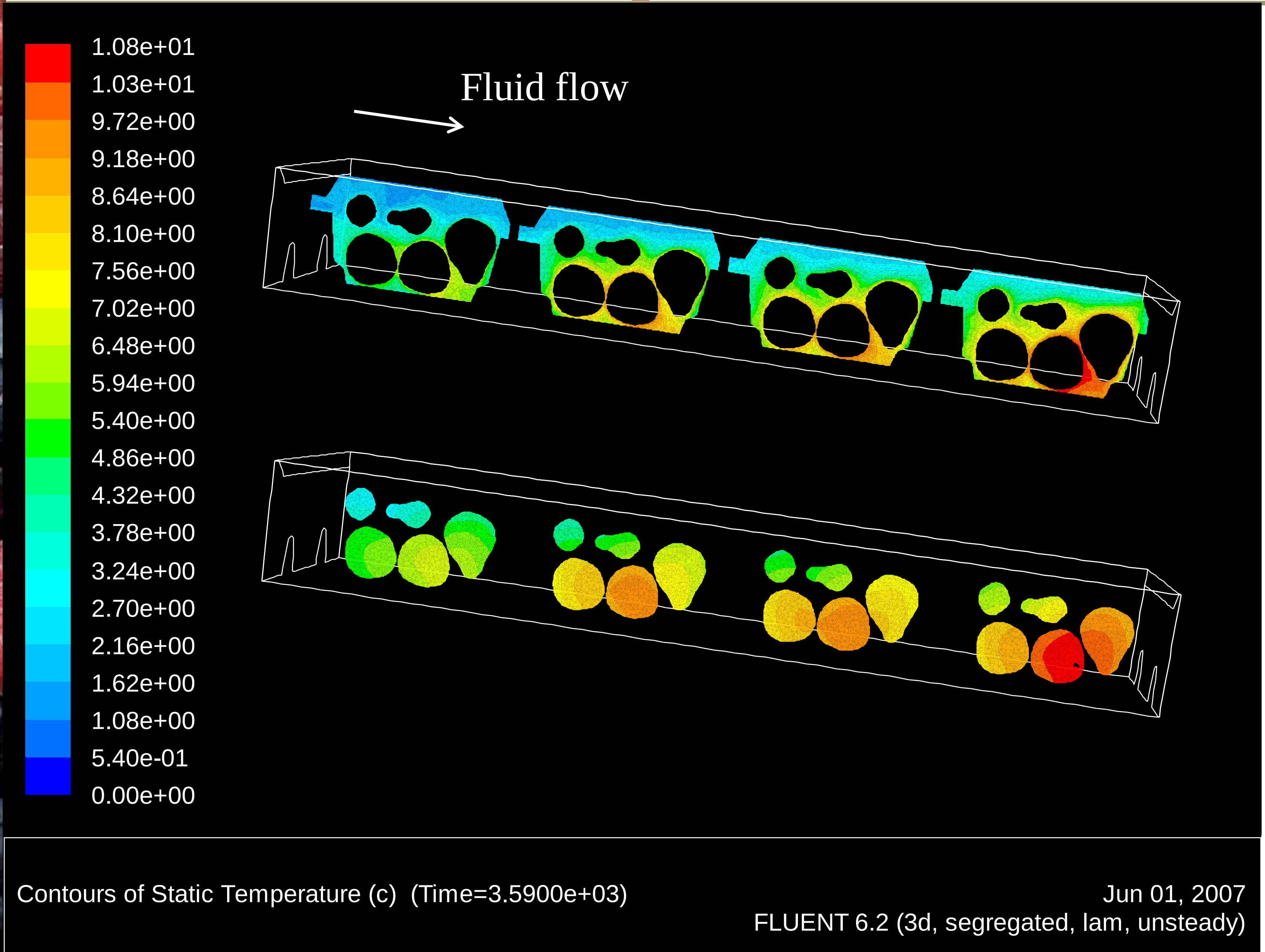
$$T_f = T_s \quad \text{on} \;\; \mathrm{A_{fs}}$$

$$\mathbf{n_{fs}} \cdot k_f \nabla T_f = \mathbf{n_{fs}} \cdot k_s \nabla T_s \quad \text{on} \;\; \mathrm{A_{fs}}$$

Air and Product Temperature in Tray 1

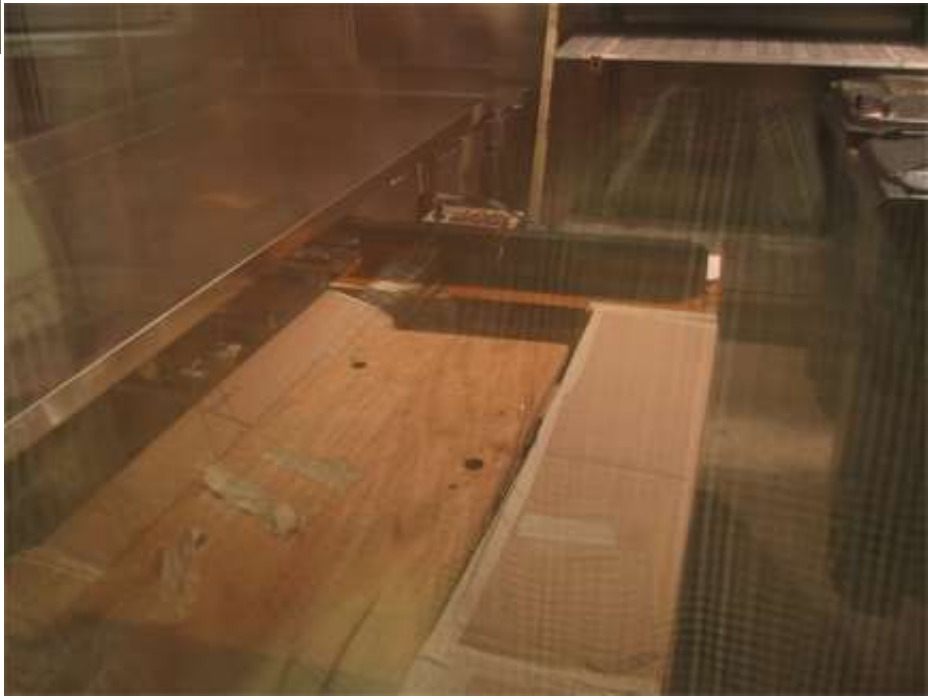


Air and Product Temperature Profile in Tray 2

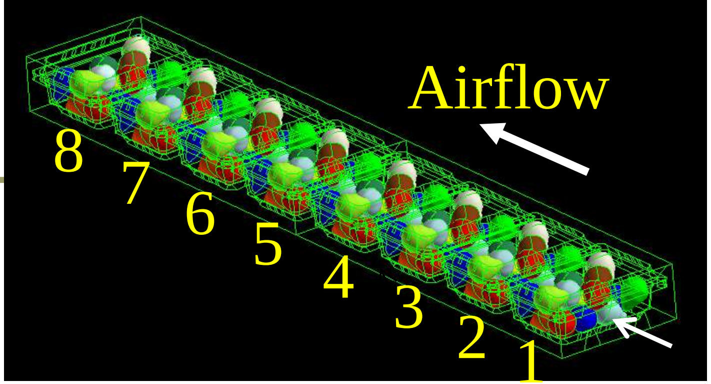


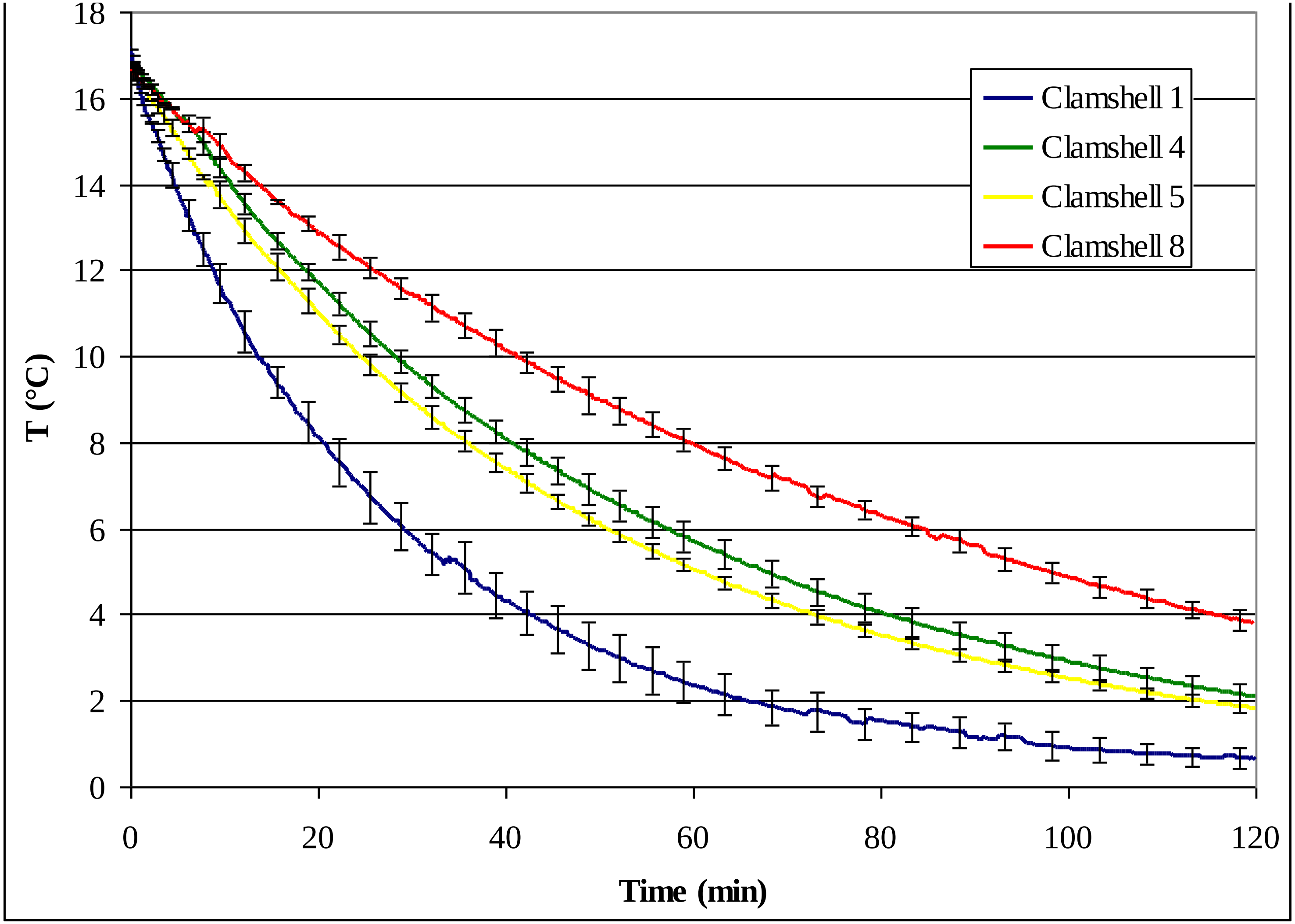
Validation of Heat Transfer in Clamshell/Tray System



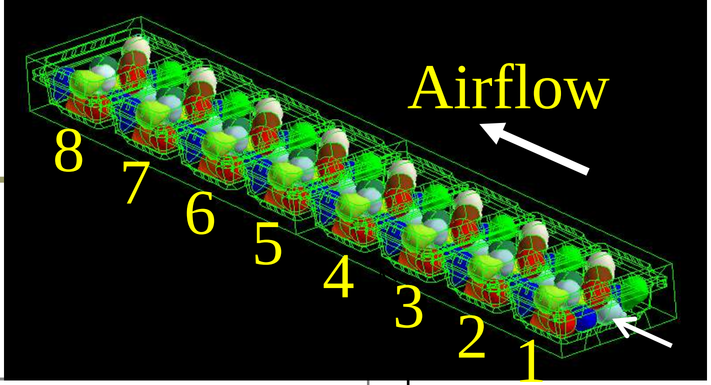


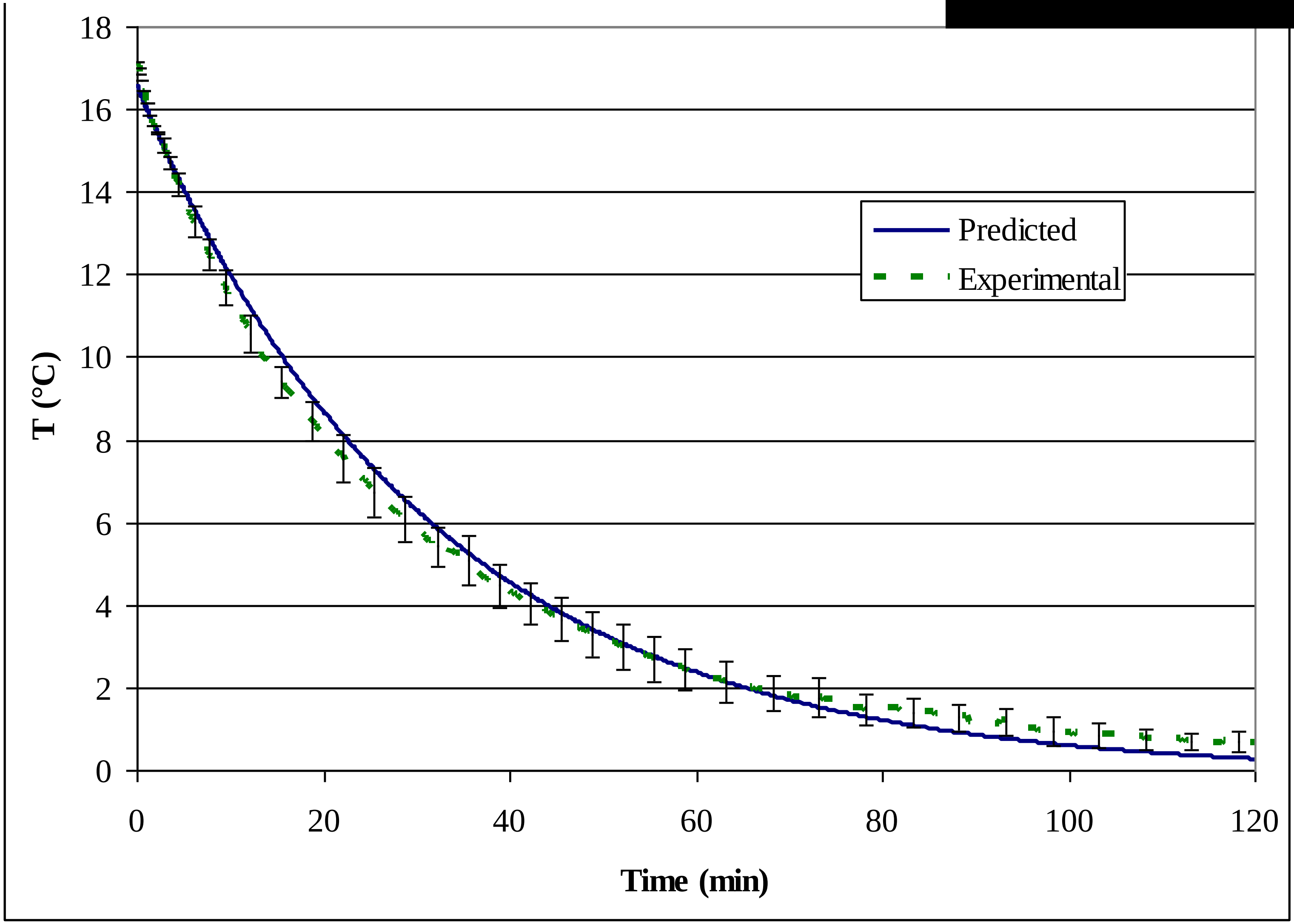
Average fruit temperature in Clamshells - measured



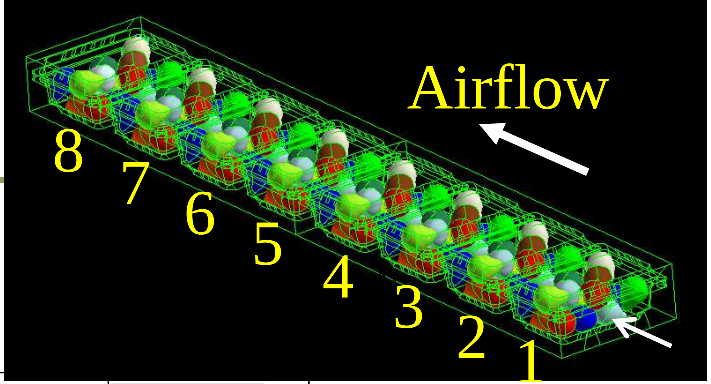


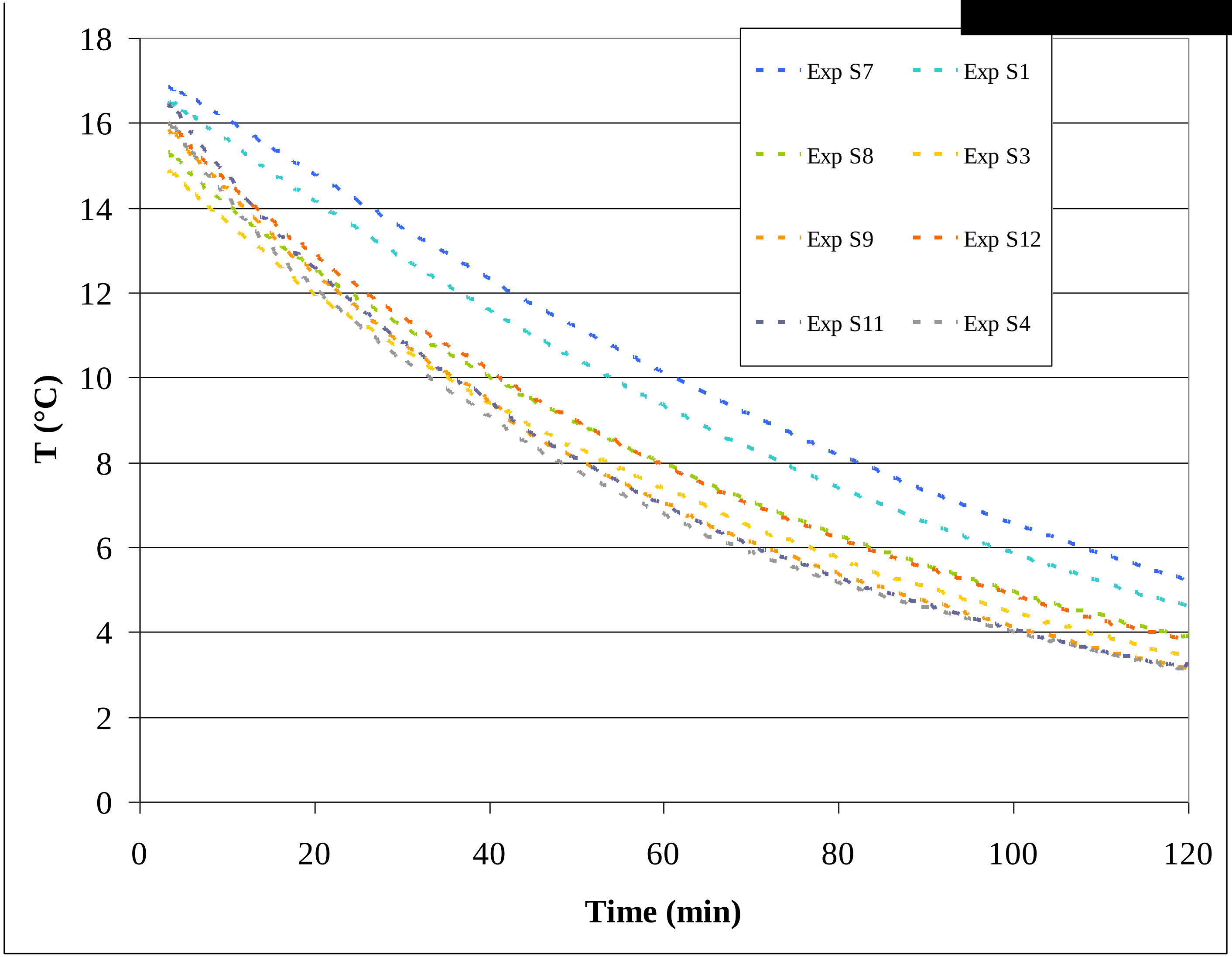
Average fruit temperature in Clamshell 1 – measured and predicted





Strawberry temperatures in Clamshell 8





Strawberry temperatures in Clamshell 1 – measured and predicted