DEVELOPING DESIGN CRITERIA FOR RAPID AND UNIFORM COOLING OF PRODUCE IN CONSUMER PACKAGES

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POSTHARVEST CONTROLS

- Postharvest losses of fresh horticultural products are estimated to be between 25% and 40% of the total world production[1].
- A rapid post harvest cooling to ~3°C is the most important factor in maintaining the quality and extending the shelf life of fresh produce.

The forced-air cooling method is one of the most common and recommended one.

[1] Radbound University Nijmegen (http://www.bharatbook.com/detail.asp?id=11009)

FORCED AIR COOLING

- Most berries are field packed in individual containers.

Typical commercial <u>clamshells</u> of berries.

FORCED AIR COOLING

- Clamshells are placed into open-top corrugated trays.
- Trays are stacked onto each other in pallets.

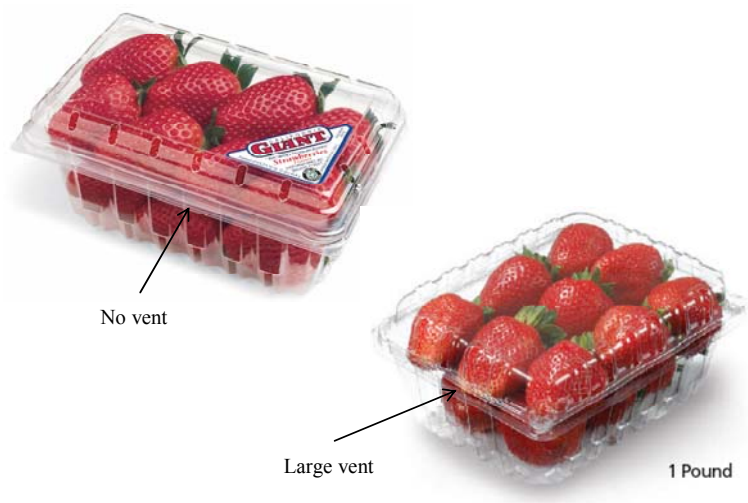
Strawberry Pallet

FORCED AIR COOLING

- Pallets are arranged in commercial cooling tunnels.
  - Cold air at 0 ºC is forced through them.

INDUSTRIAL PROBLEM

- Although the forced-air cooling process is routinely used, quality loss prevails due to non-uniform cooling.
- The vent design of clamshells and trays is largely based on the package mechanical strength.
  - Their ability to promote a rapid and uniform cooling is often deficient.



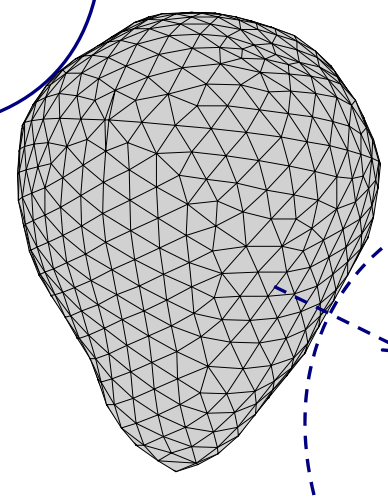
SPECIFIC OBJECTIVES

- To develop a mathematical model of the transport phenomena during forced-air cooling processes.
  - To use computational fluid dynamic (CFD) to numerically predict the flow field and cooling rate of individual berries within packages.
- To validate the flow model using a non-intrusive flow measurement technique (Particle Image Velocimetry, PIV).
- To validate the energy model using experimental information of the temperature history of packed produce.

MATHEMATICAL MODEL

TRANSPORT PHENOMENA

Convective heat transfer process (energy transport) $= f\left(T_s, T_f, \underline{u}\right)$



Removal of latent heat due to the product moisture loss (sink of energy)

Rate of moisture loss (convective mass transport) $= f\left(\underline{u}, P_{w,s}, P_{w,f}\right)$

Momentum transport $\left(\underline{u}, P_{w,f}, P_{Total}\right)$

Mass transport $\left(\underline{u}, P_{w,s}, P_{w,f}\right)$ $\Longleftrightarrow$ Energy transport $\left(\underline{u}, T_f, T_s\right)$

MATHEMATICAL MODEL

- Decoupling of momentum transport from:
  - Mass transport
  - Energy transport

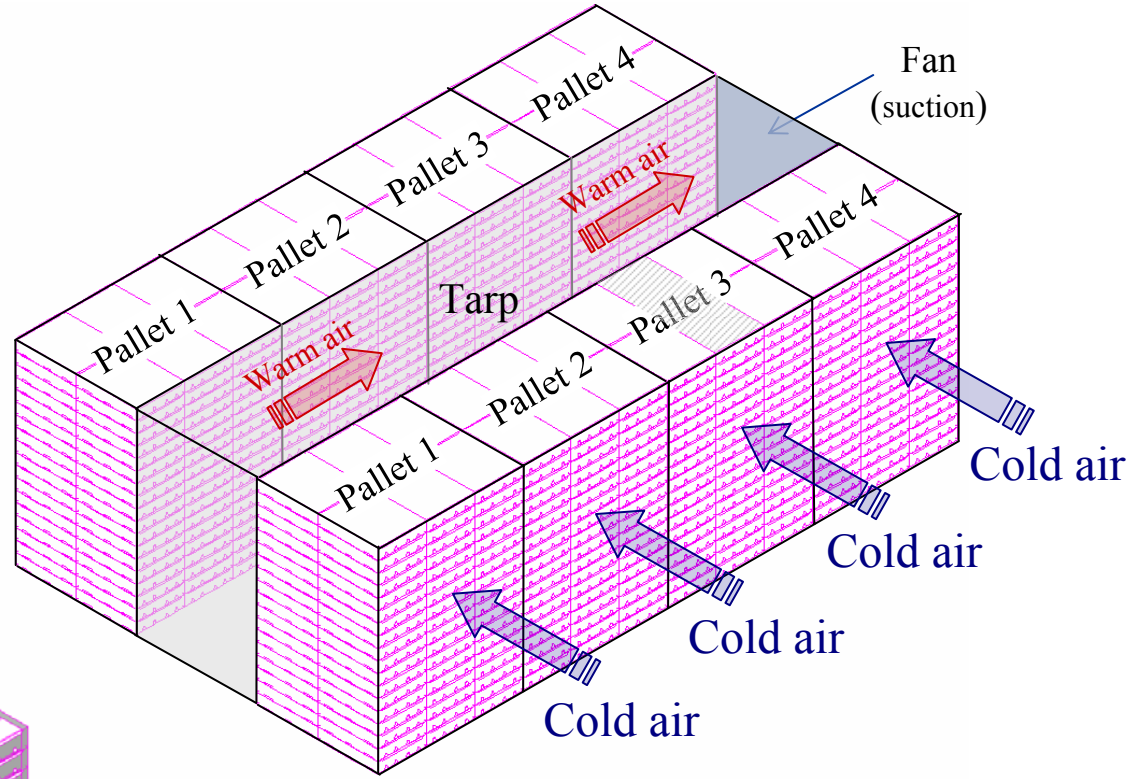
  → Dynamics of vapor-air mixture can not be modeled.

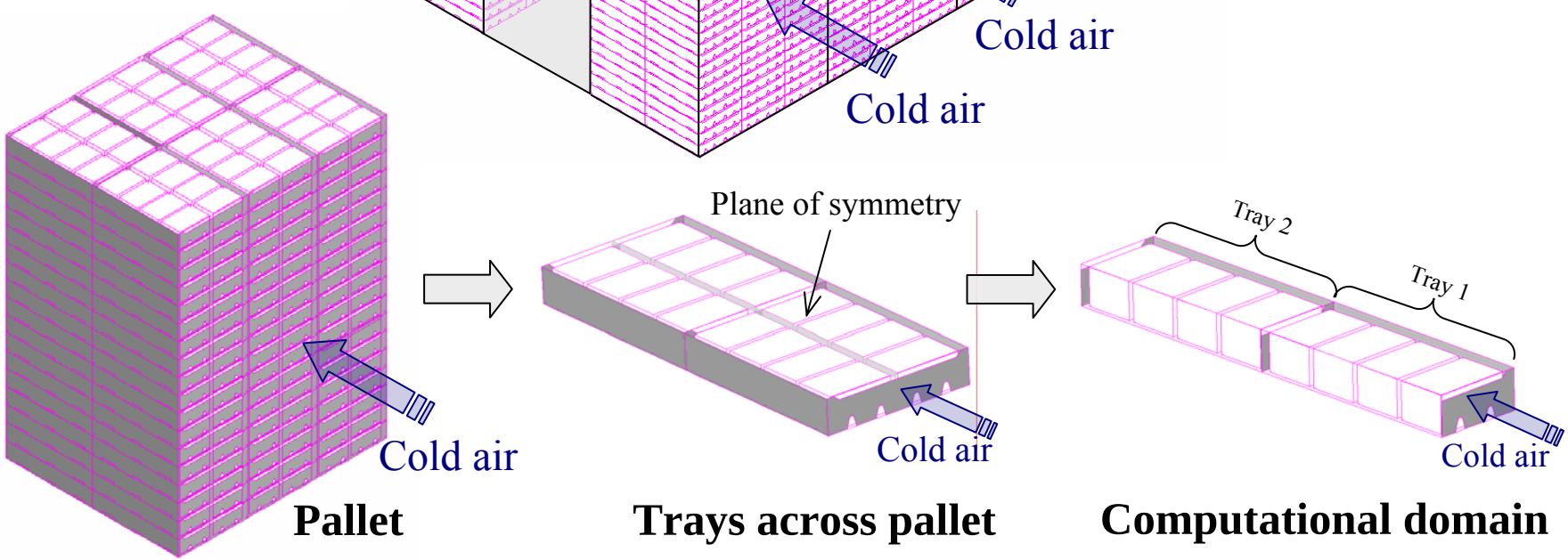
Momentum transport $(\underline{u}, P_{Total})$

Use of Fick's law to predict the rate of moisture evaporation ⟷ Energy transport $(\underline{u}, T_f, T_s)$

CFD ANALYSIS

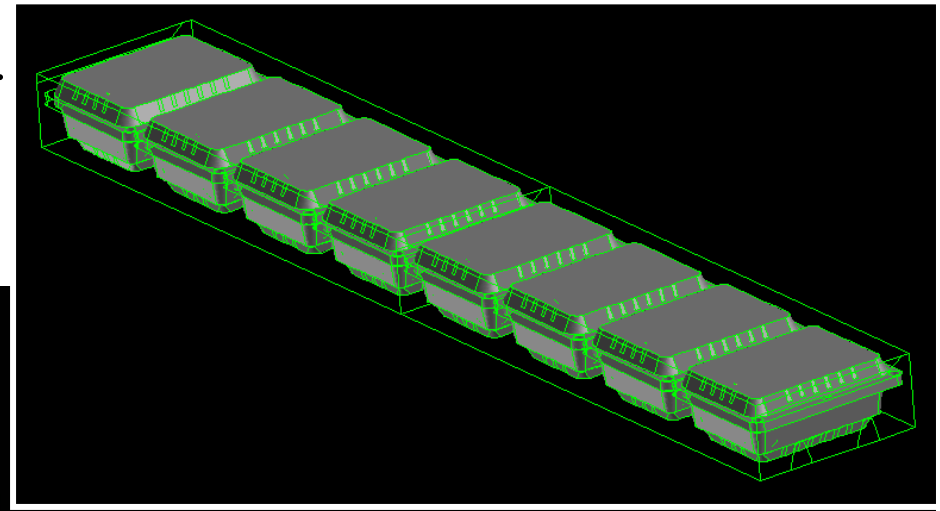
COMPUTATIONAL DOMAIN

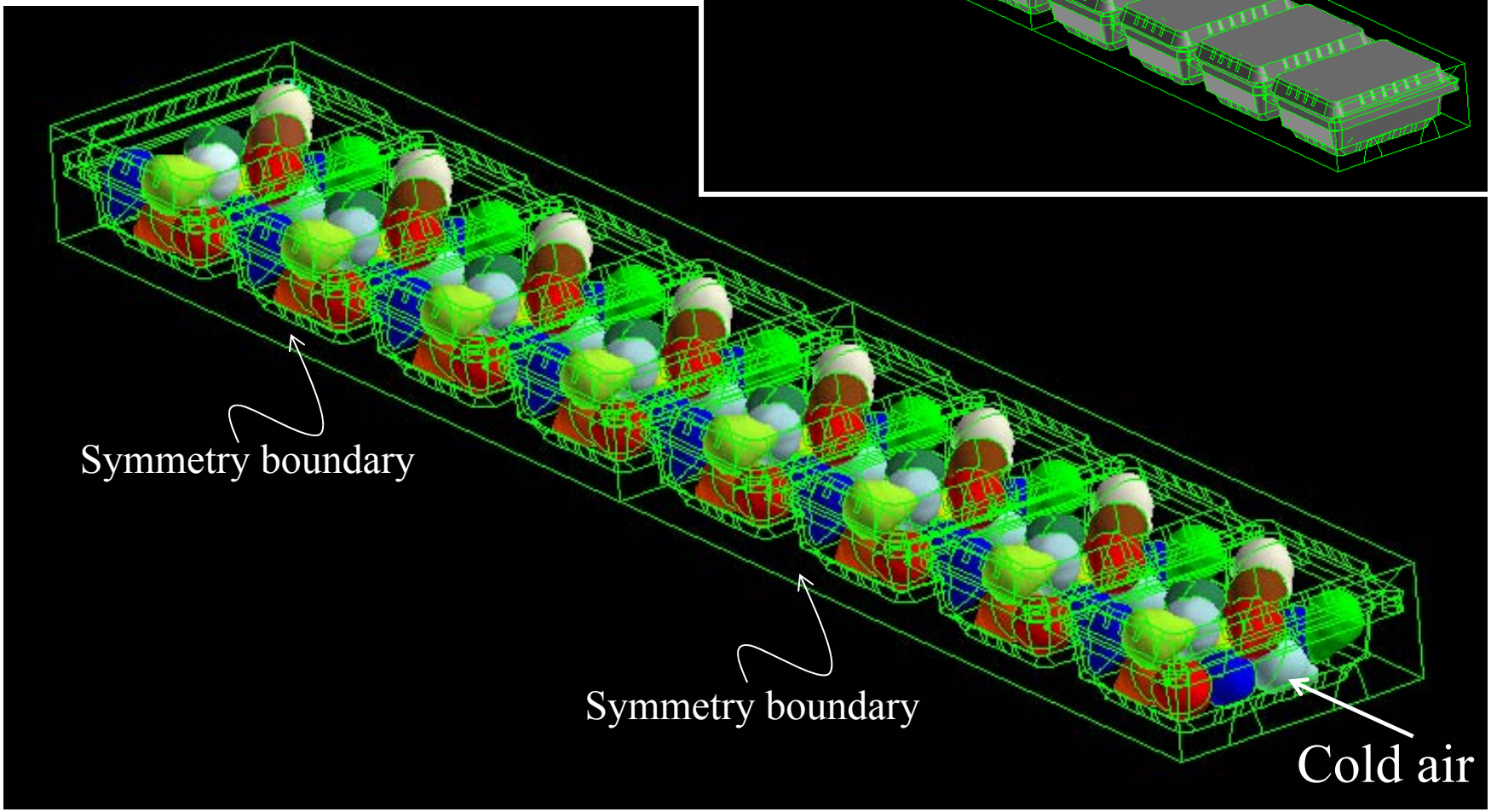




COMPUTATIONAL DOMAIN

- Mesh contained 2,940,000 elements.
  - 66% within the fluid region of the domain.



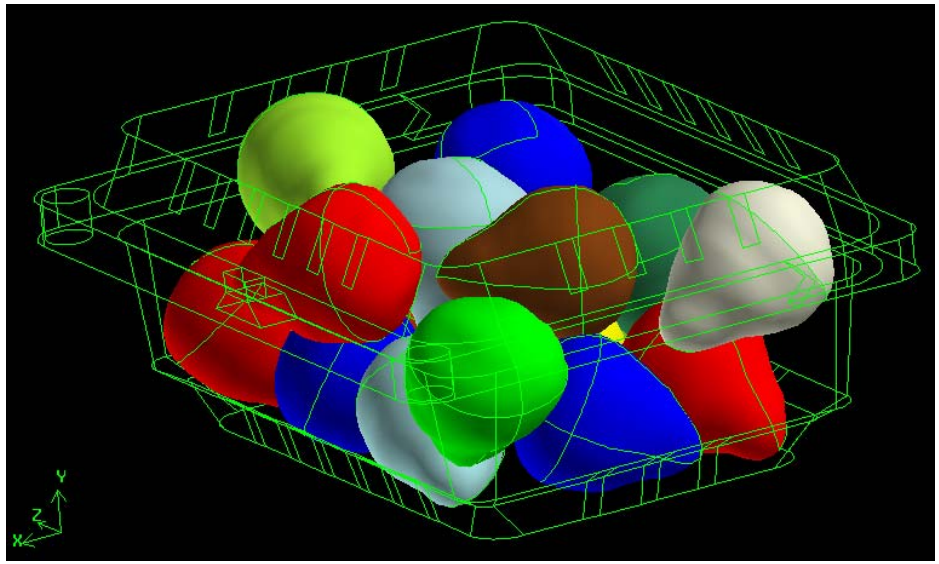


FLOW FIELD MODEL

- The local airflow behavior within packages was modeled using the standard Navier-Stokes equations.

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

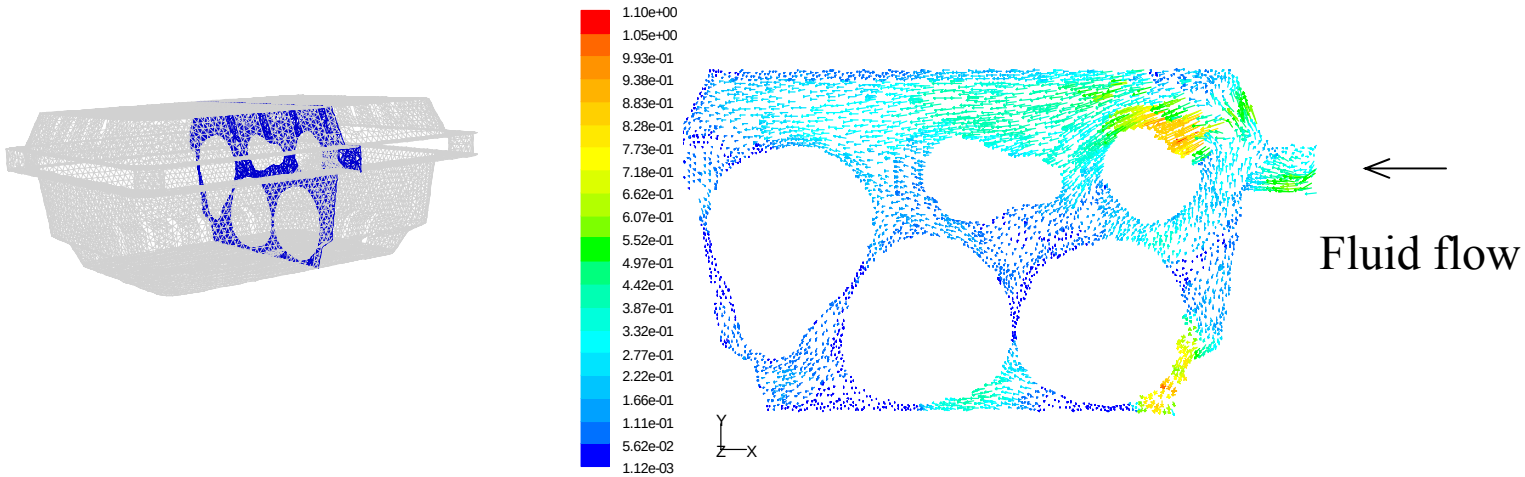
$$U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \mathrm{P}}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j} + g_i$$



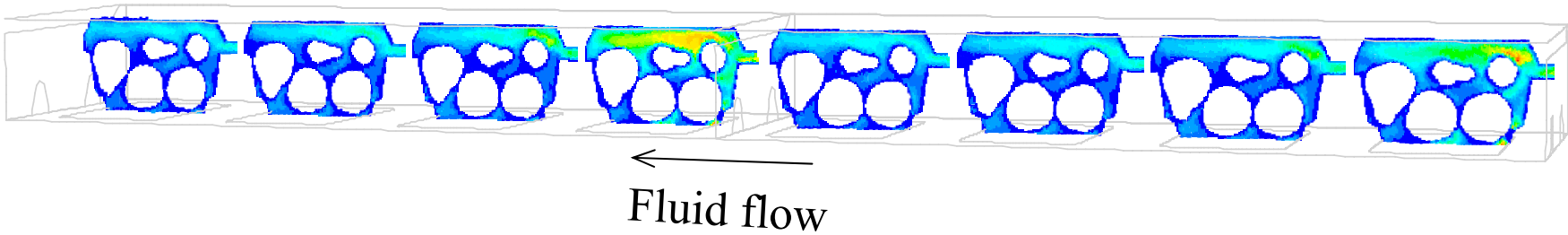
NUMERICAL RESULTS

- CFD analysis provide a detailed flow field description.

1. Velocity field within clamshells (m/s).

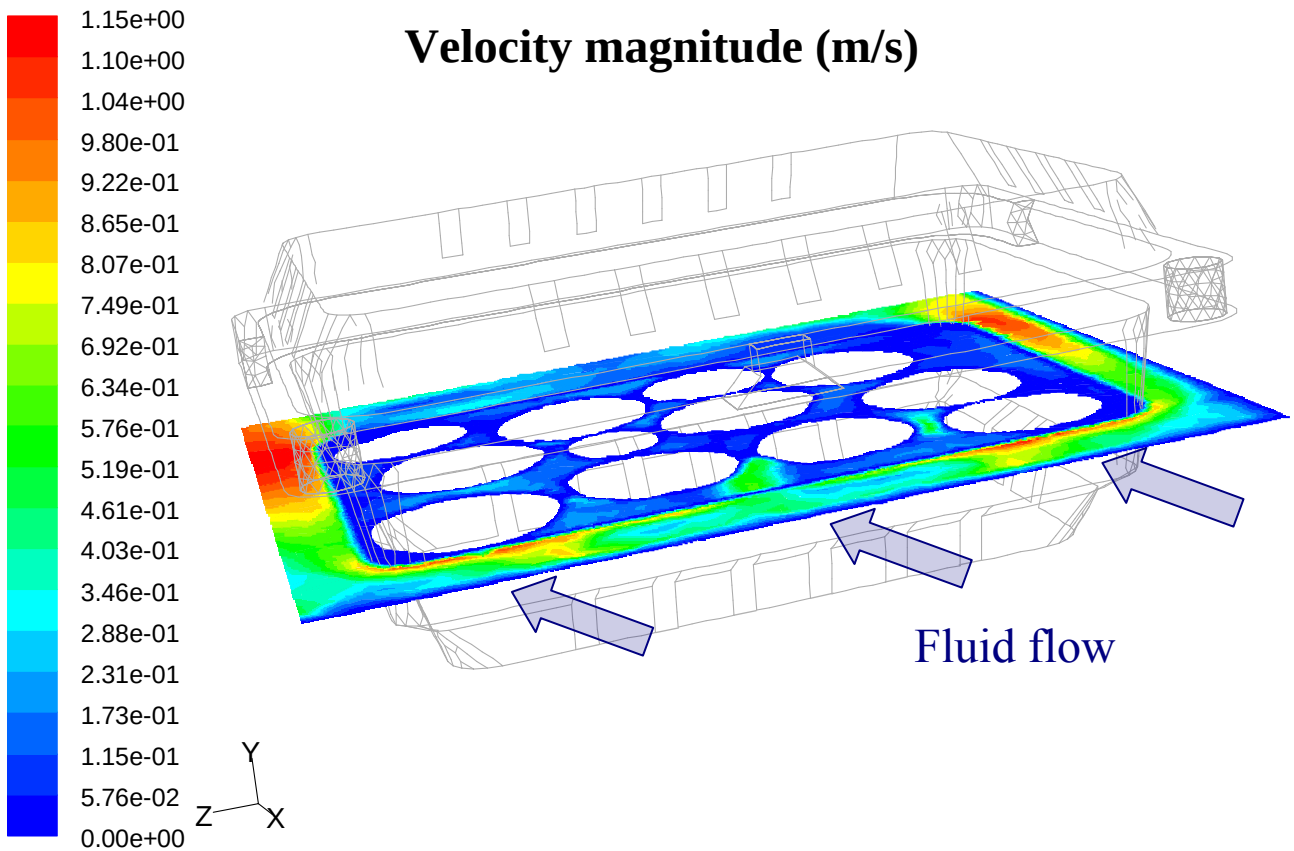


2. Velocity field within different clamshells (m/s).



NUMERICAL RESULTS

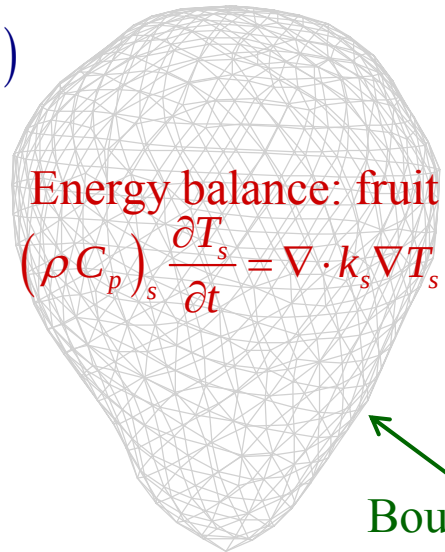
- On average 75% of the total airflow bypass clamshells.
  - 71% bypasses the first clamshell within each tray.
  - 77% bypasses all the other clamshells within each tray.



ENERGY MODEL

Energy balance: fluid

$$\left(\rho C_p\right)_f \left[\frac{\partial T_f}{\partial t} + \nabla \cdot \mathbf{u} T_f\right] = \nabla \cdot \left(k_f \nabla T_f\right)$$



Energy balance: fruit

$$\left(\rho C_p\right)_s \frac{\partial T_s}{\partial t} = \nabla \cdot k_s \nabla T_s$$

Boundary conditions: fruit surface

$$T_f\left(\underline{x},t\right) = T_s\left(\underline{x},t\right)$$

$$\mathbf{n_{fs}} \cdot k_s \nabla T_s\left(\underline{x},t\right) = \mathbf{n_{fs}} \cdot k_f \nabla T_f\left(\underline{x},t\right) + \frac{\dot{m}\left(\underline{x},t\right)}{A_{face}\left(\underline{x},t\right)} \Delta H_{evap}\left(\underline{x},t\right)$$

ENERGY MODEL

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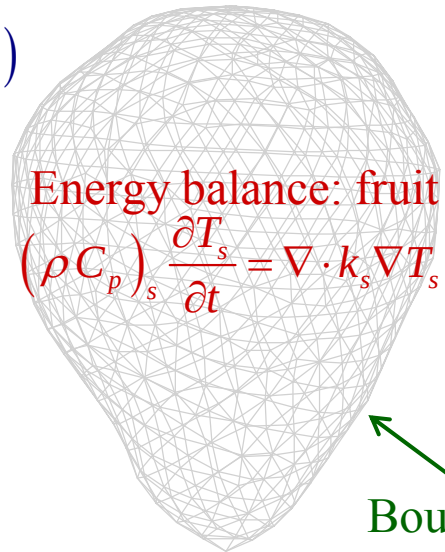

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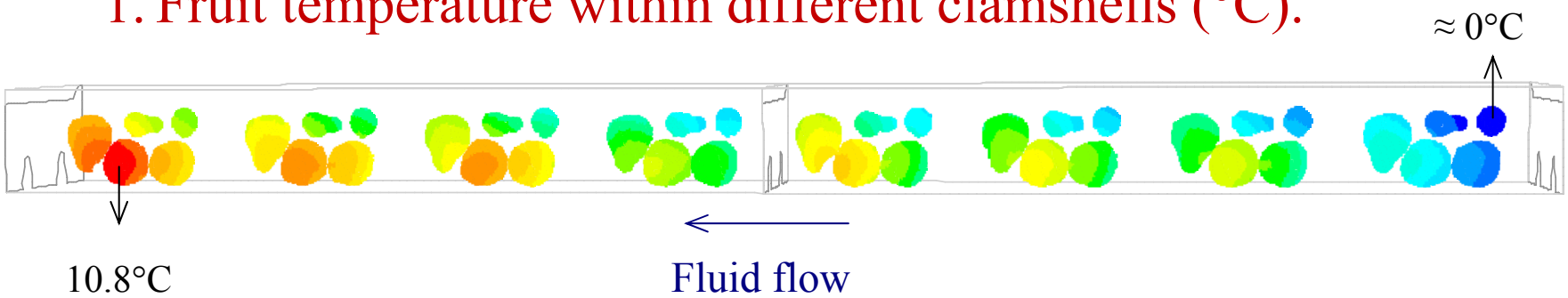
$$\Downarrow$$

$$\frac{\dot{m}\left(\underline{x},t\right)}{A_{face}\left(\underline{x},t\right)} = \frac{P_{w,s}\left(\underline{x},t\right) - P_{w,f}\left(\text{Package},t\right)}{\dfrac{1}{k_{skin}\left(\underline{x},t\right)} + \dfrac{1}{k_{ext}\left(\underline{x},t\right)}}$$

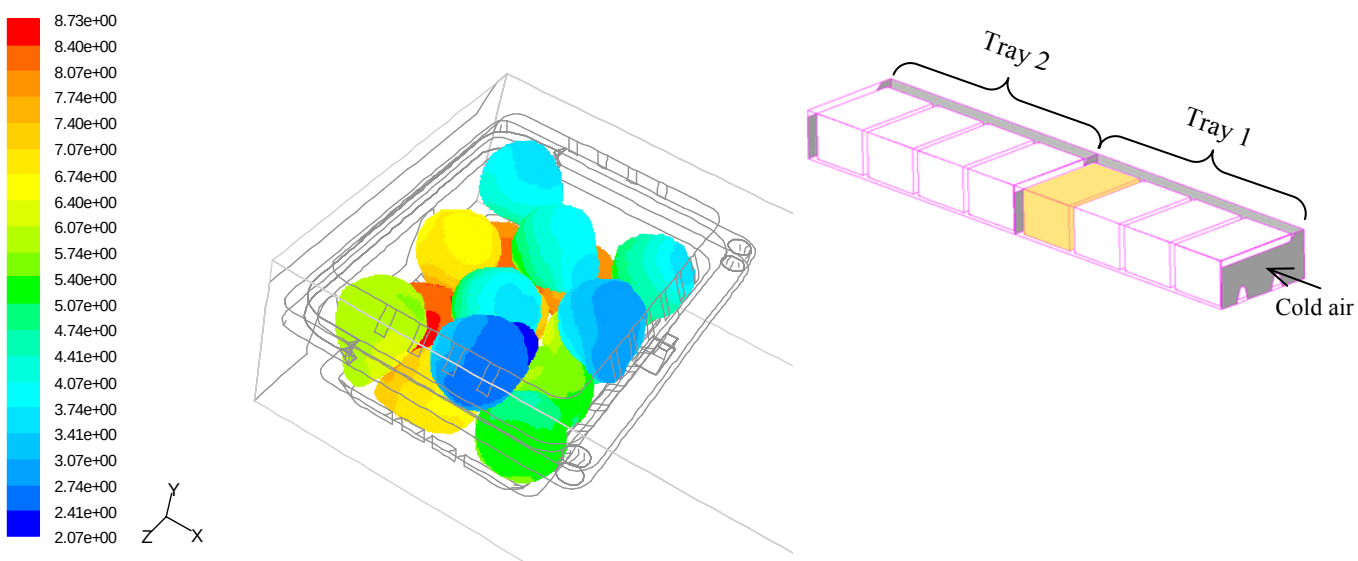
NUMERICAL RESULTS (1 hour)

- Heterogeneity of the heat transfer process.

1. Fruit temperature within different clamshells (°C).



2. Fruit temperature within individual clamshells (°C).

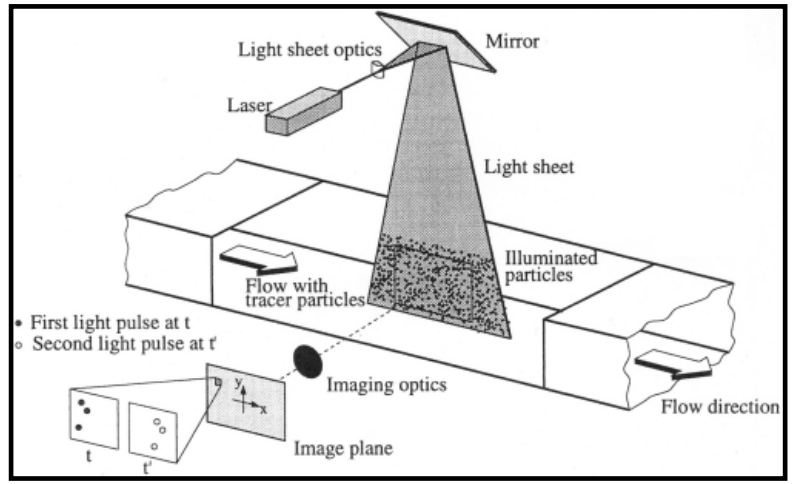


FLOW FIELD VALIDATION

PARTICLE IMAGE VELOCIMETRY (PIV)

PARTICLE IMAGE VELOCIMETRY

- 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.



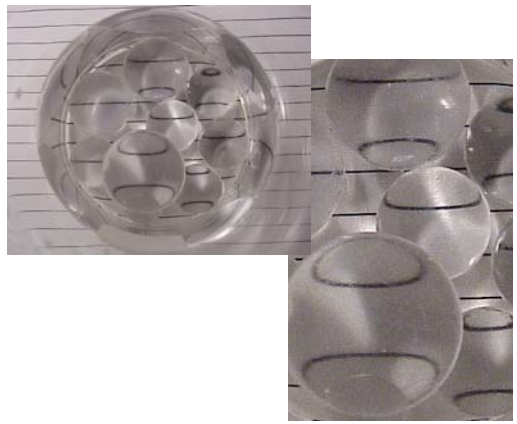
The requirement of <u>optical access to the flow</u> has limited PIV application to simple geometries.

TRANSPARENT SET UP

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

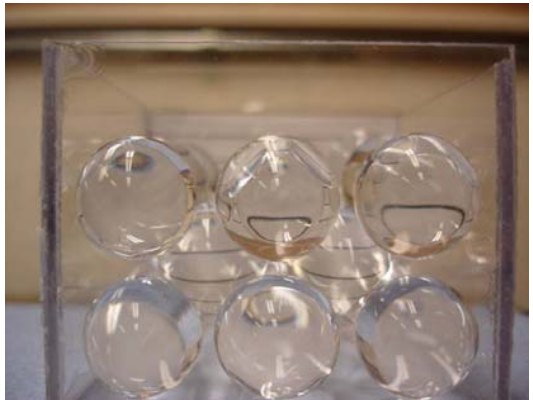
  - Perfect refractive index (η) match between the transparent model setup and the working fluid (to avoid distortions of both the laser sheet and the scattered light as they pass through the system).

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



TRANSPARENT SET UP

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



Fused silica spheres.
Air

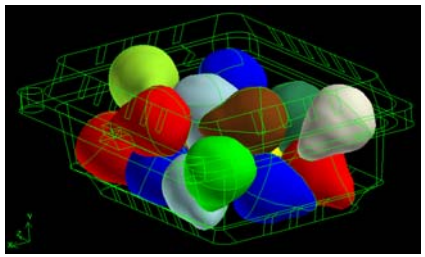
Fused silica spheres.
Johnson & Johnson baby oil-Drakesol 260 oil mixture.

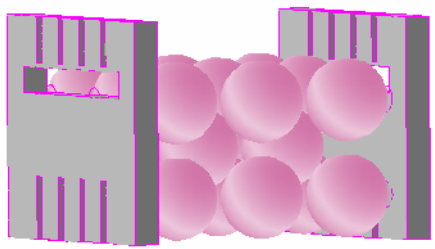
EXPERIMENTAL SYSTEM DEVELOPMENT

PIV SYSTEM

TRANSPARENT SET UP, THAT REPLICATE THE CFD DOMAIN

2D FLOW MEASUREMENT TECHNIQUE





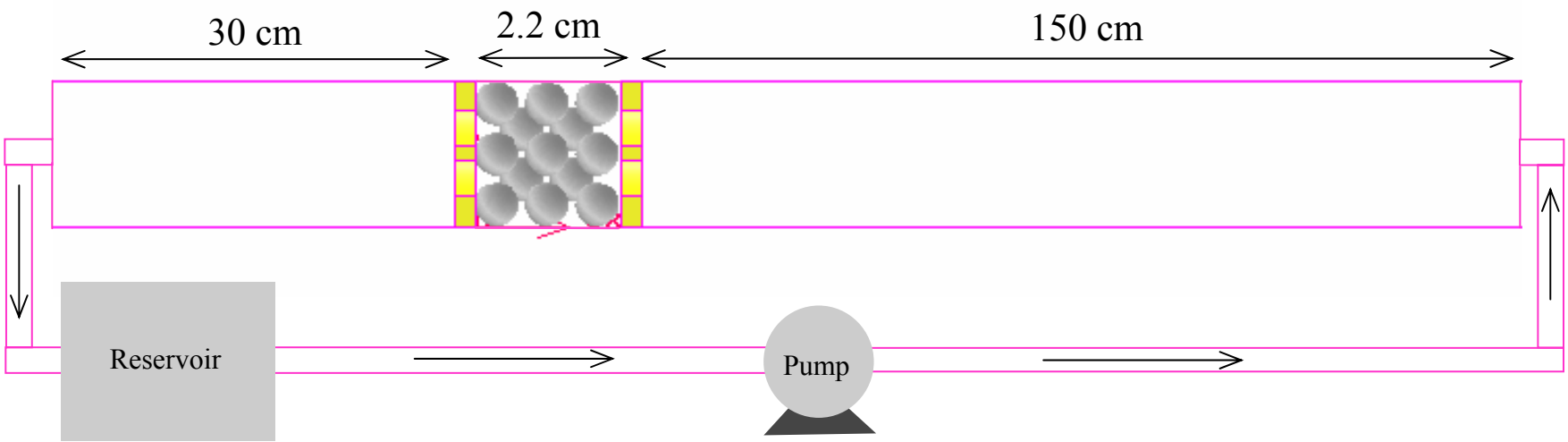
Reproduce geometry and packaging structure

Experimental packed system:

- Relatively simple to be created using fused silica.
- Reproduce the packaging structure within fruit packages.
- The x-, y- and z- velocity components of the 3D flow must have the same order of magnitude.

EXPERIMENTAL SYSTEM

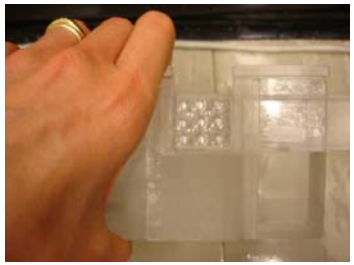
- Symmetrical packed structure of **35 spheres** arranged in a **cubic centered distribution**.
  - Reproduced packaging factor of fruit clamshells (51% vs. 54%).
  - Allowed the use of a 2D PIV to trace planar velocity fields within the 3D flow field developed within the packed structure.



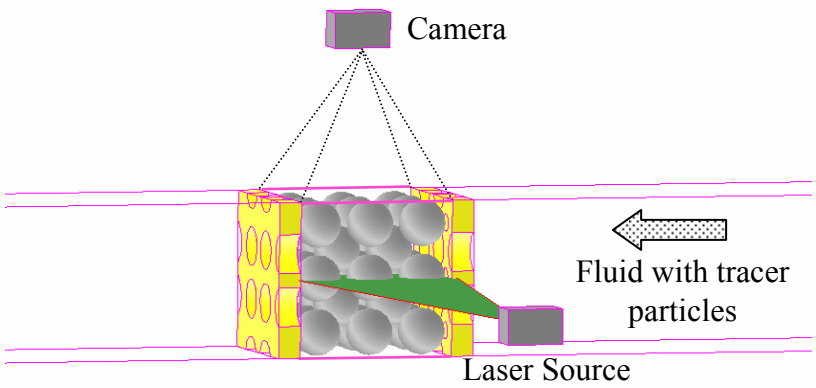
Flow rate of the oil mixture replicated the flow conditions within fruit clamshells (Reynolds number matching, Re_p= 180).

FLOW MODEL VALIDATION

EXPERIMENTAL SYSTEM

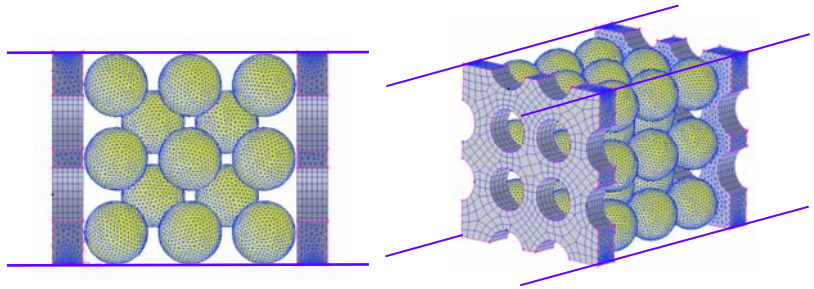


PIV measurements

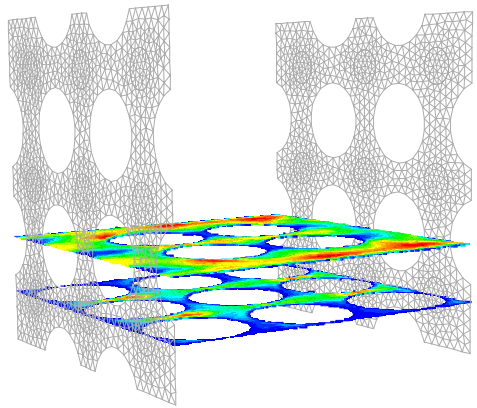


Experimental velocity field within different planes

CFD ANALYSIS



Navier-Stokes model

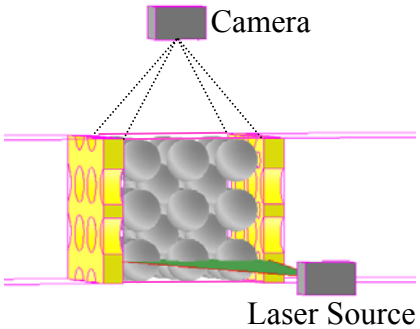


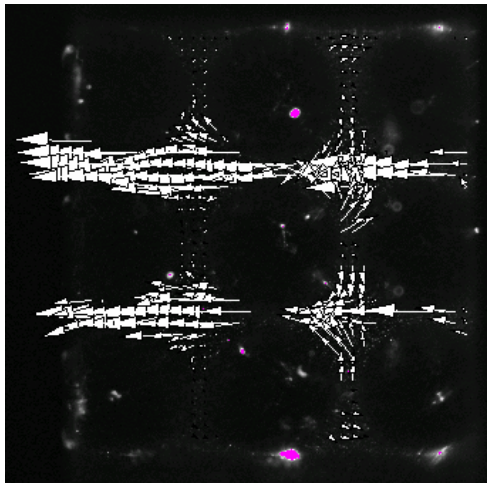
Predicted velocity field within different planes

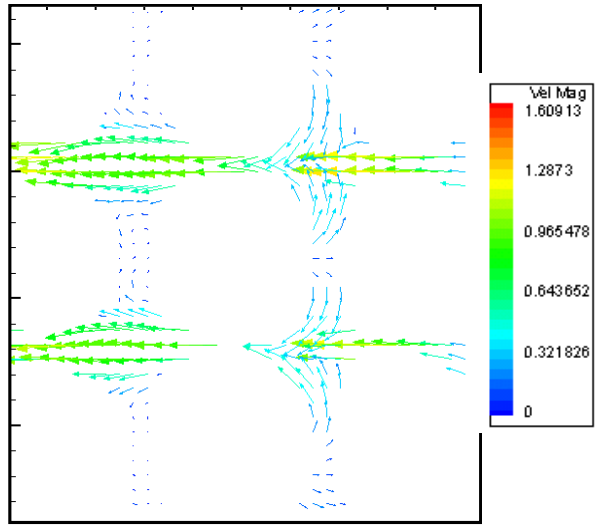
VALIDATION

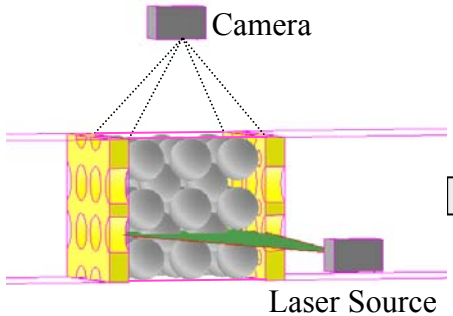
PIV MEASUREMENTS

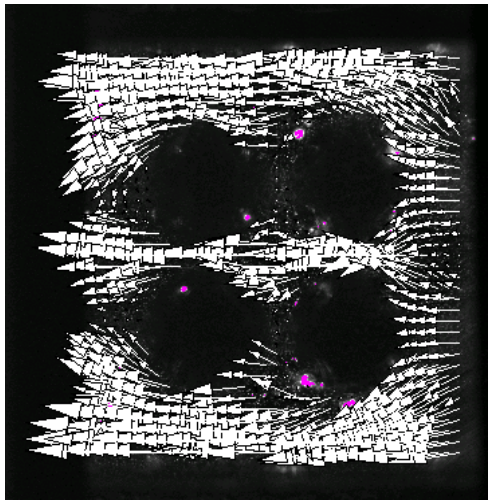
Markers displacement **Velocity field (m/s)**

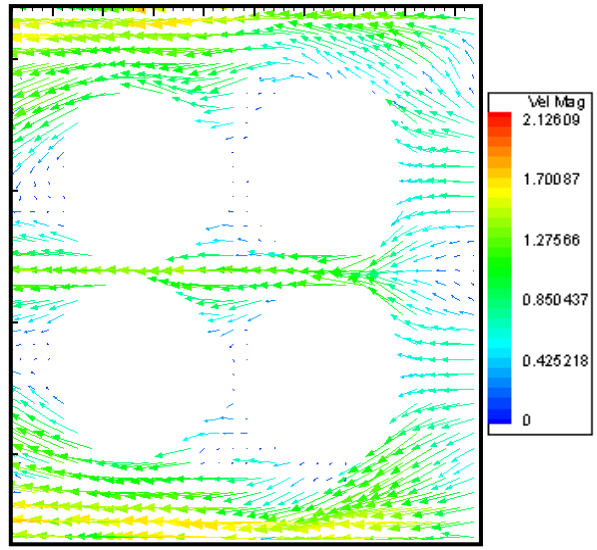






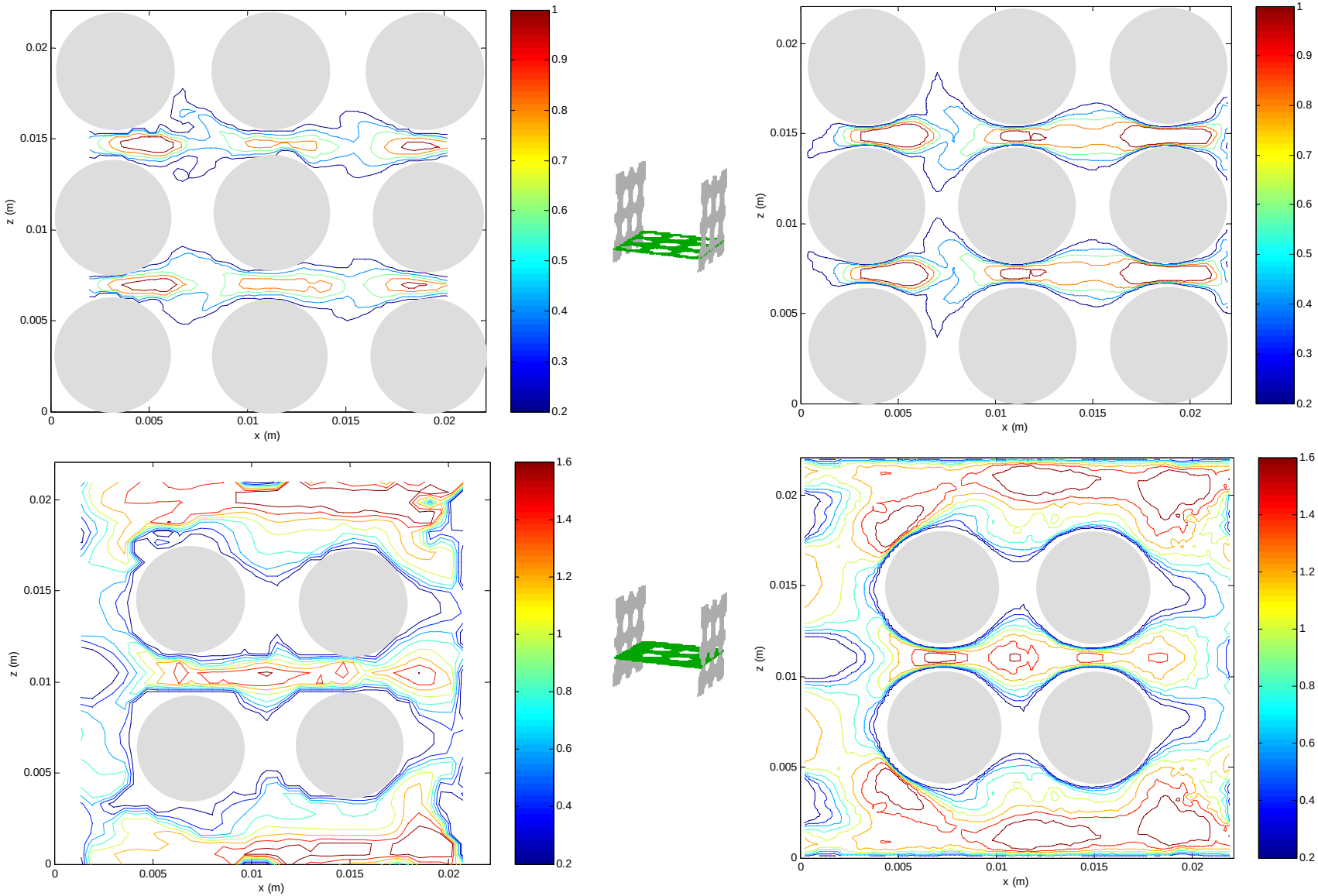






FLOW VALIDATION

Experimental flow field | **Predicted flow field**



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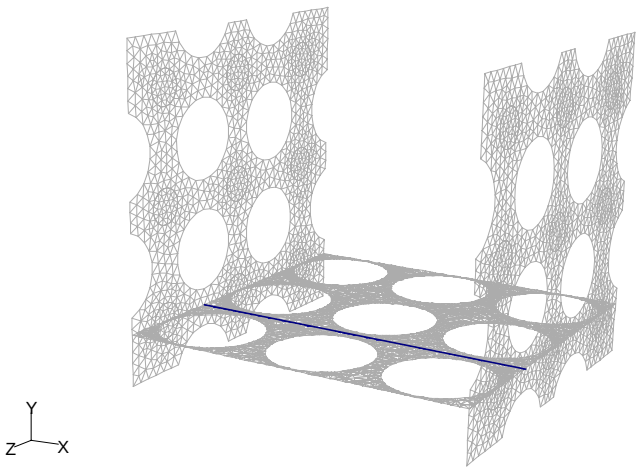

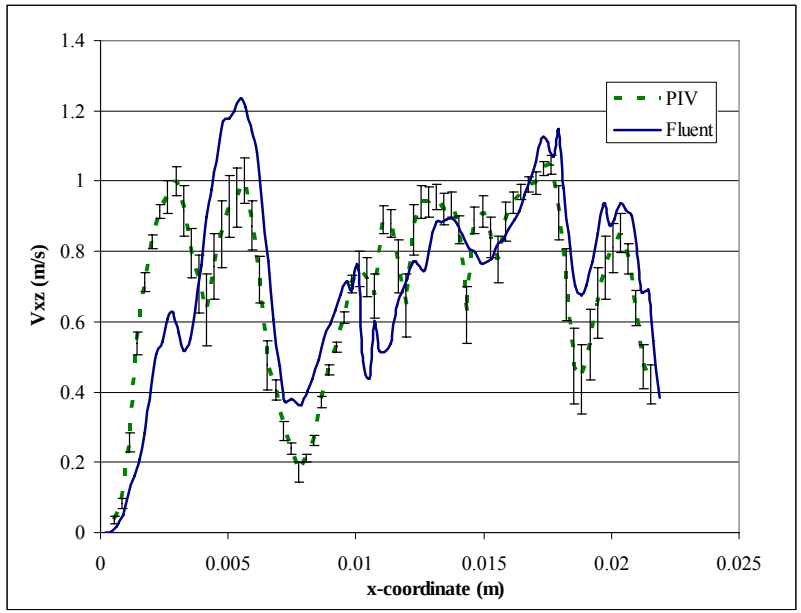

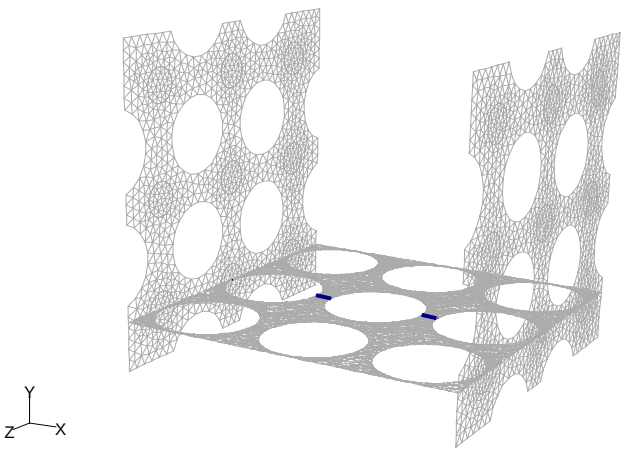

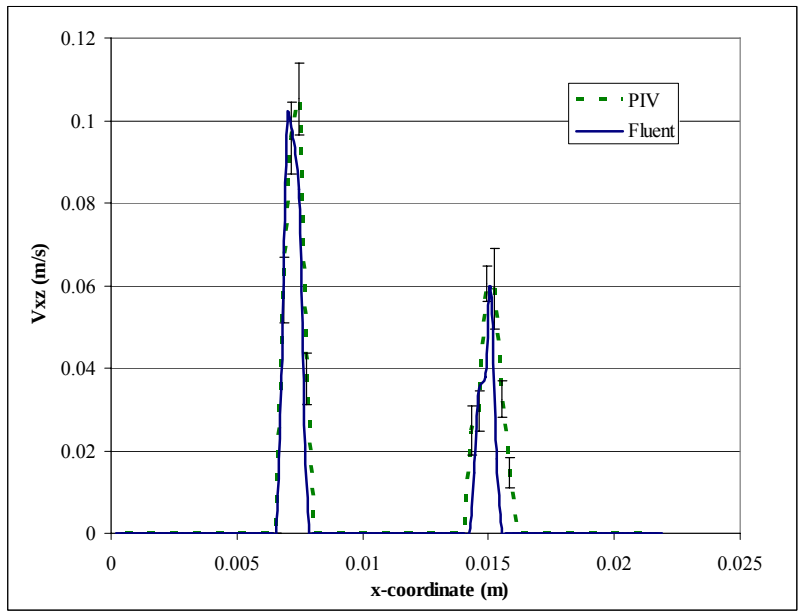

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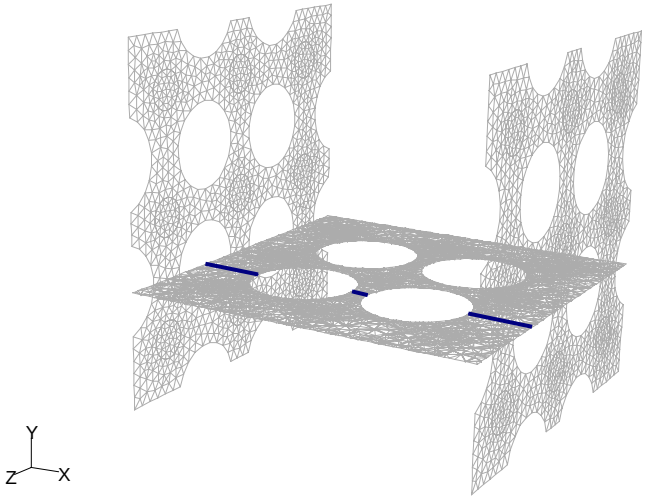
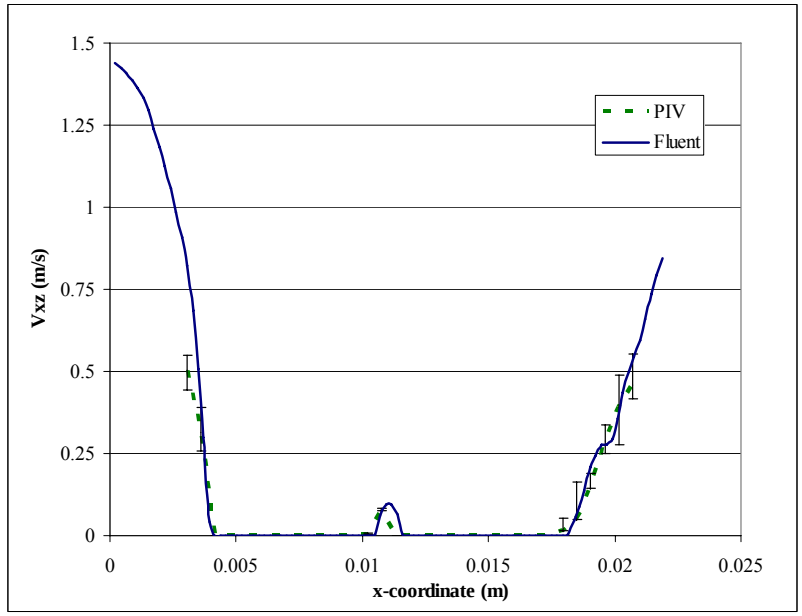
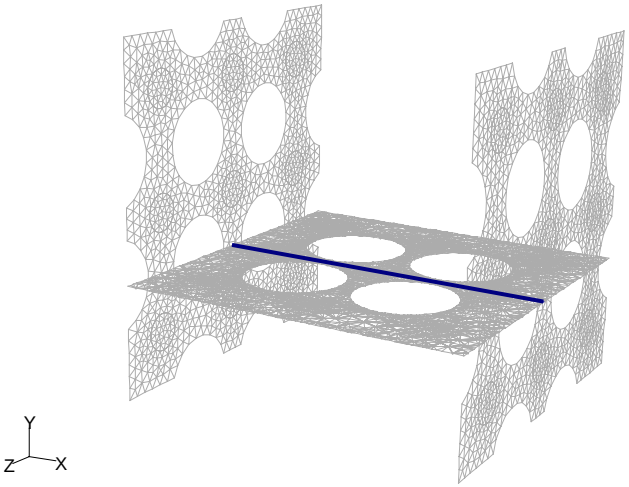
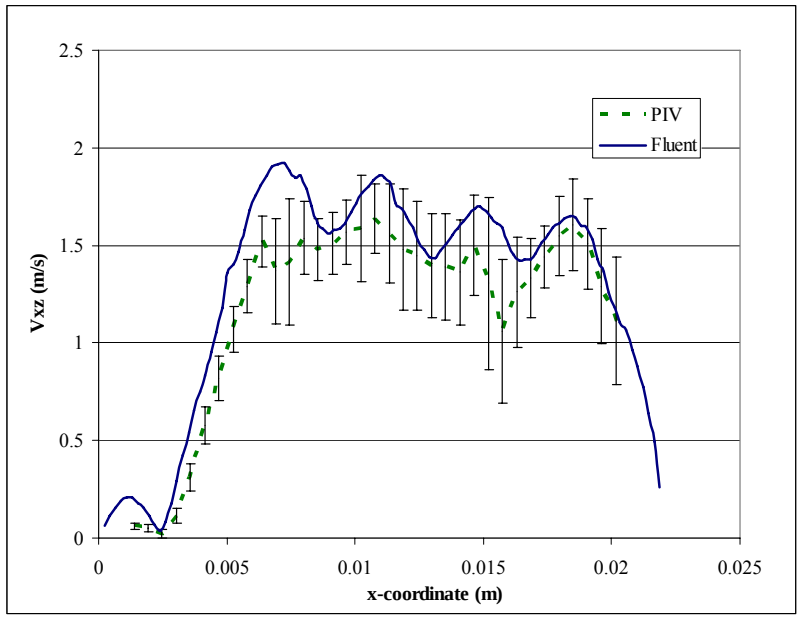








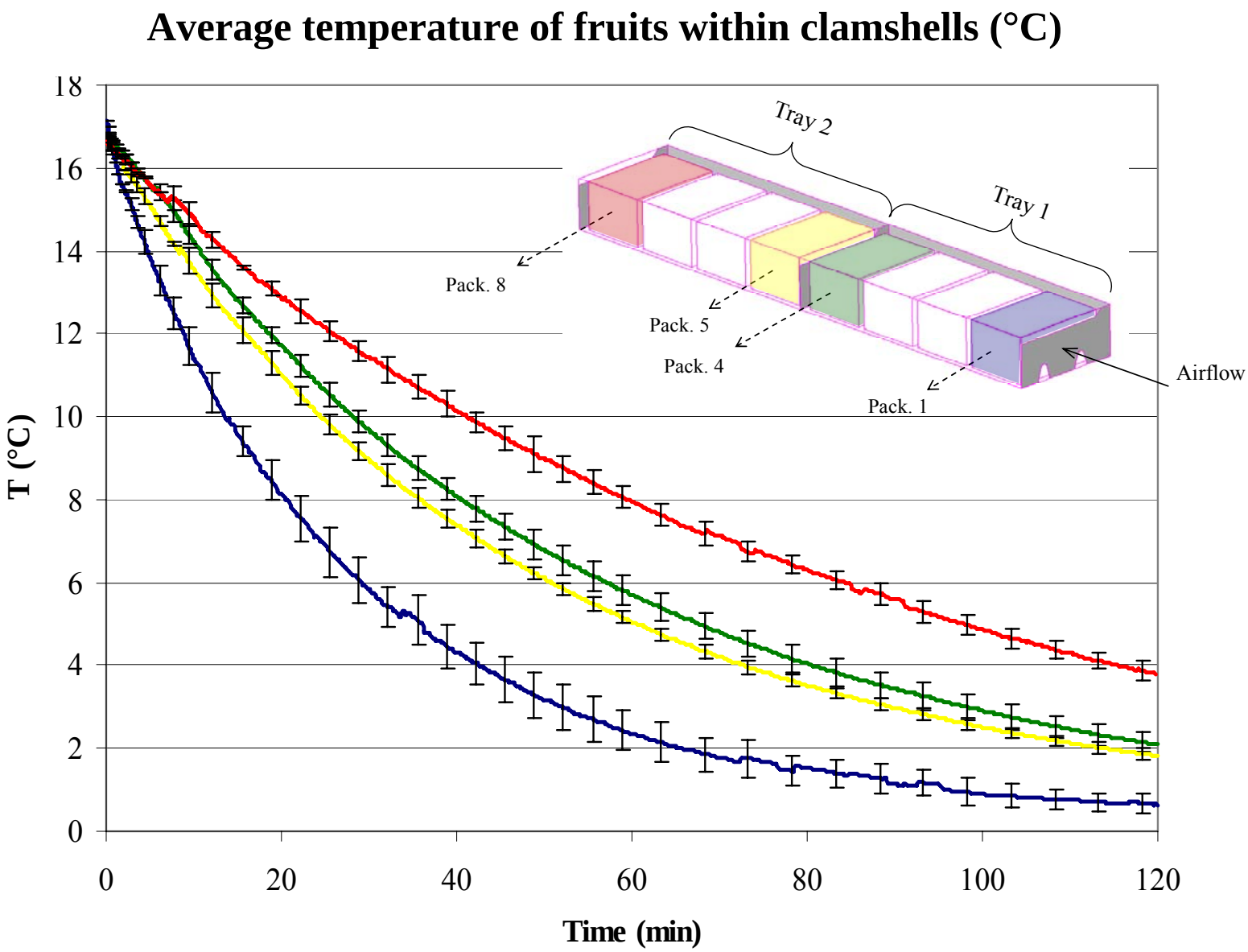
VALIDATION OF HEAT TRANSFER IN CLAMSHELL/TRAY SYSTEM

VALIDATION

- A custom-built system was used to validate the predicted cooling rate of packed strawberries.
  - Reproduced the airflow conditions.
  - Reproduced the packaging design and structure.

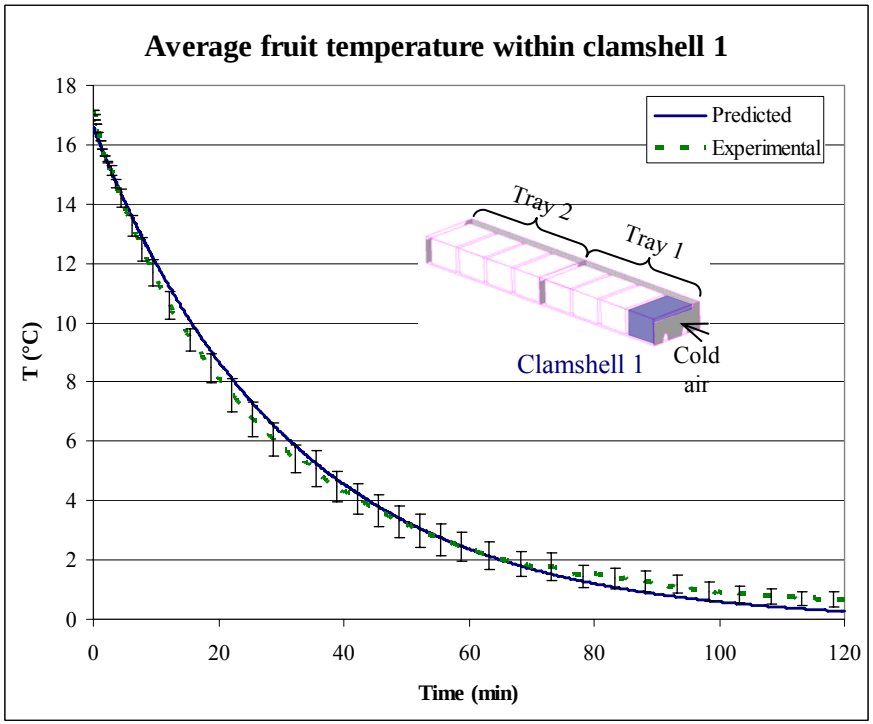
Temperature measurements using 34 thermocouples

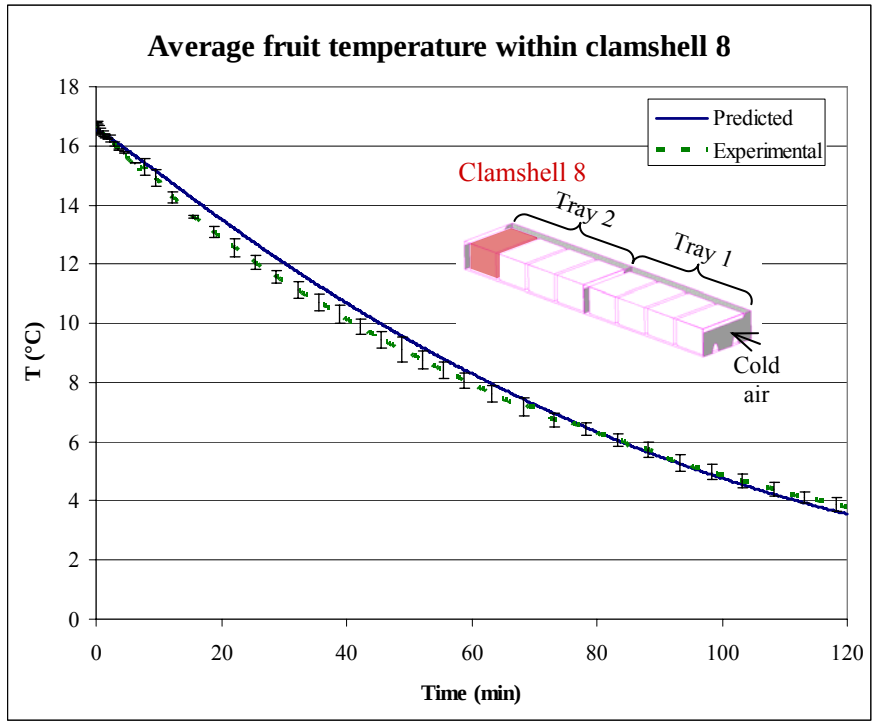
EXPERIMENTAL MEASUREMENTS (TRIPLICATES)



VALIDATION

Time history of the average temperature of fruits per clamshell





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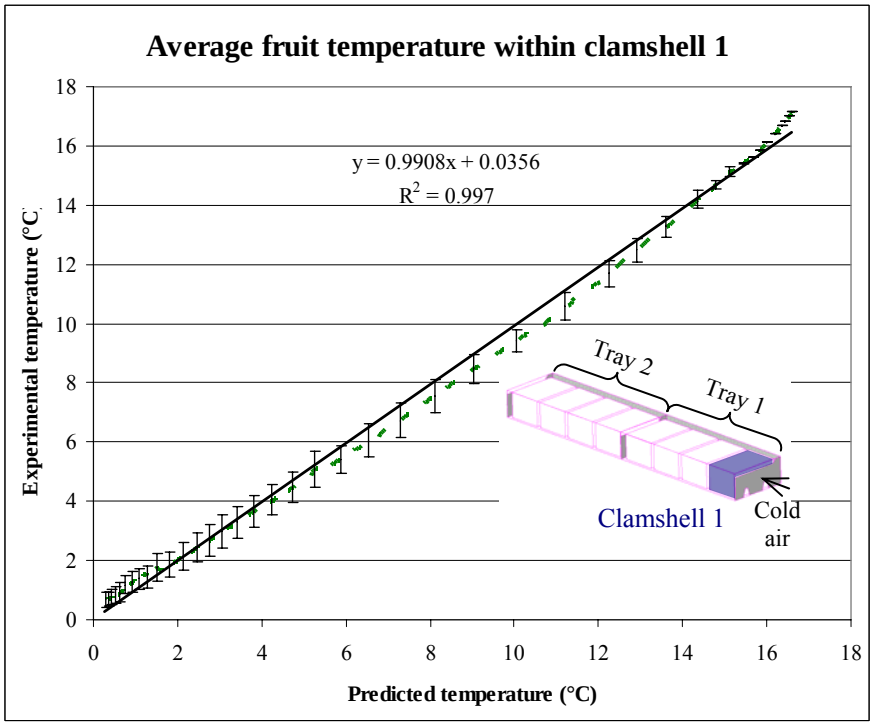
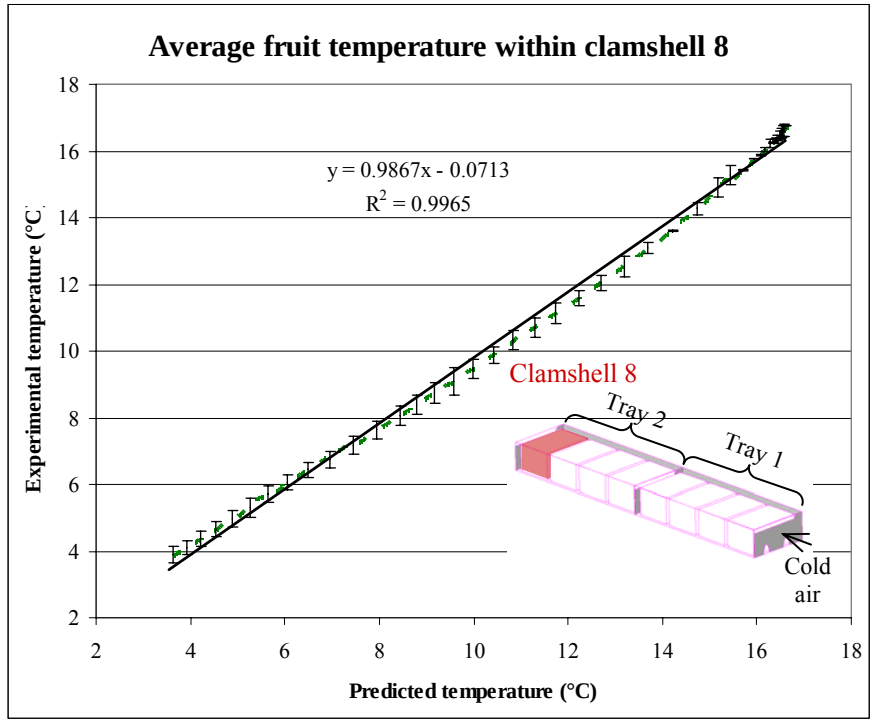
Time history of the average temperature of fruits per clamshell





CONCLUSIONS

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- The agreement found between experimental and predicted data proved the goodness of fit of the proposed model.
- The validated CFD model can be used to predict the flow field behavior and heat transfer process within packages of produce, without the requirement of expensive, time consuming and intrusive experimental trials.

CFD modeling can be used as a powerful tool to improve the design and efficiency of the forced-air cooling process.

ACKNOWLEDGEMENTS

- USDA – NRI Competitive Grant (# 05-35503-15381).