CFD-Based Virtual Prototyping For Enhanced Understanding and Optimisation of Commercial Table Grape Export Packaging

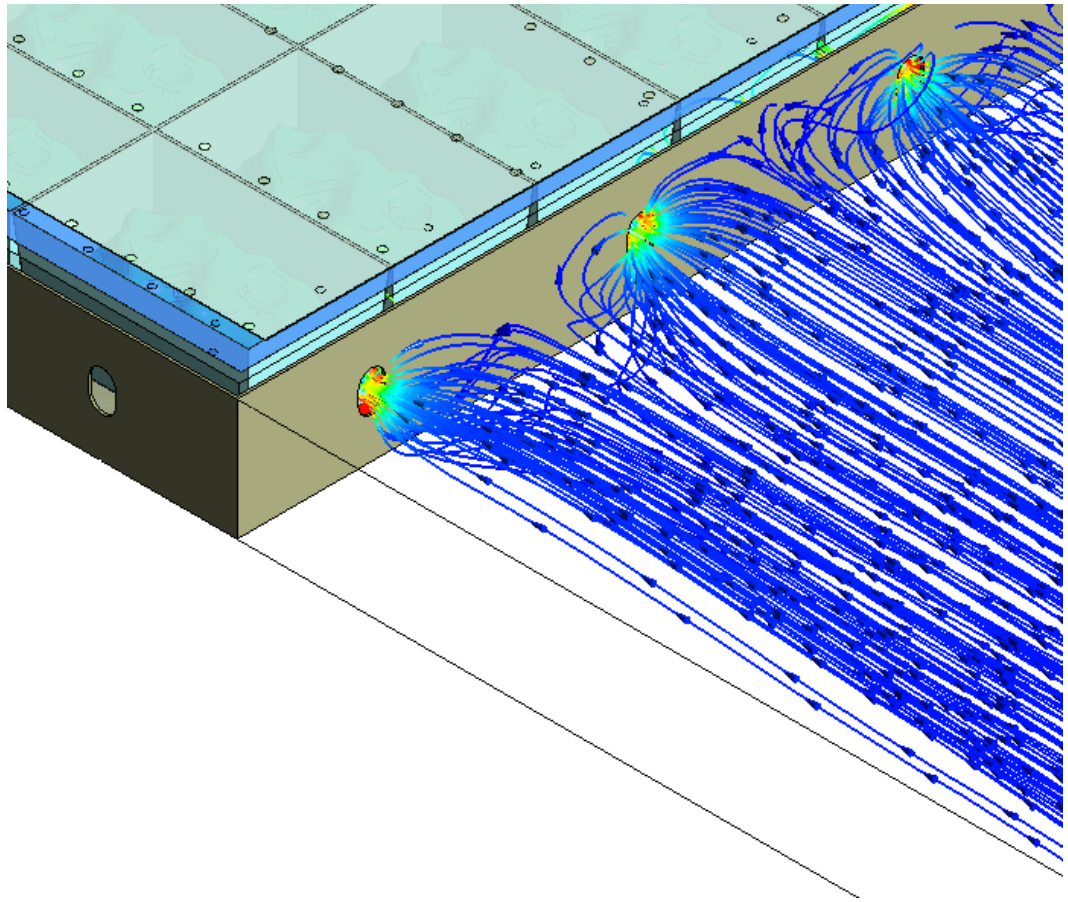
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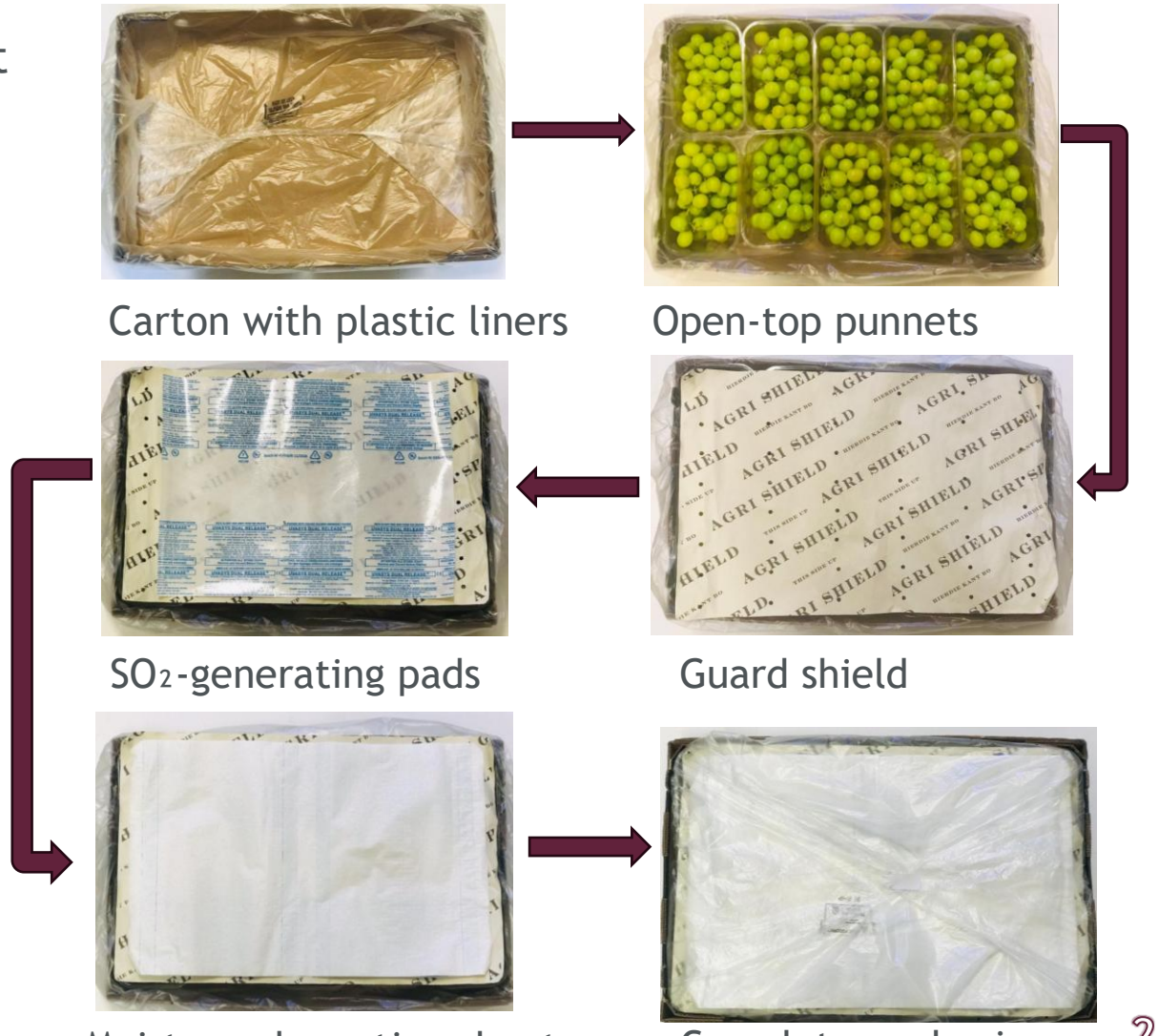
PRESENTATION OUTLINE

- Background
- Objectives
- CFD-Based Virtual Prototyping
- Evaluation of Packaging Design Effects
- Key Take-Home Messages and Practical Implications



BACKGROUND

- The South African table grape industry employs efficient packaging and cold-chain management to preserve fruit quality throughout export
  - Multiple packaging components are used commercially
- Packaging components protect fruit, deliver SO_2 and control moisture
- These components also restrict airflow and ventilation
- Packaging design requires optimisation of competing objectives:
  - Faster cooling (higher ventilation)
  - SO_2 efficacy and moisture retention
- Identifying the optimal balance using physical experiments alone is challenging

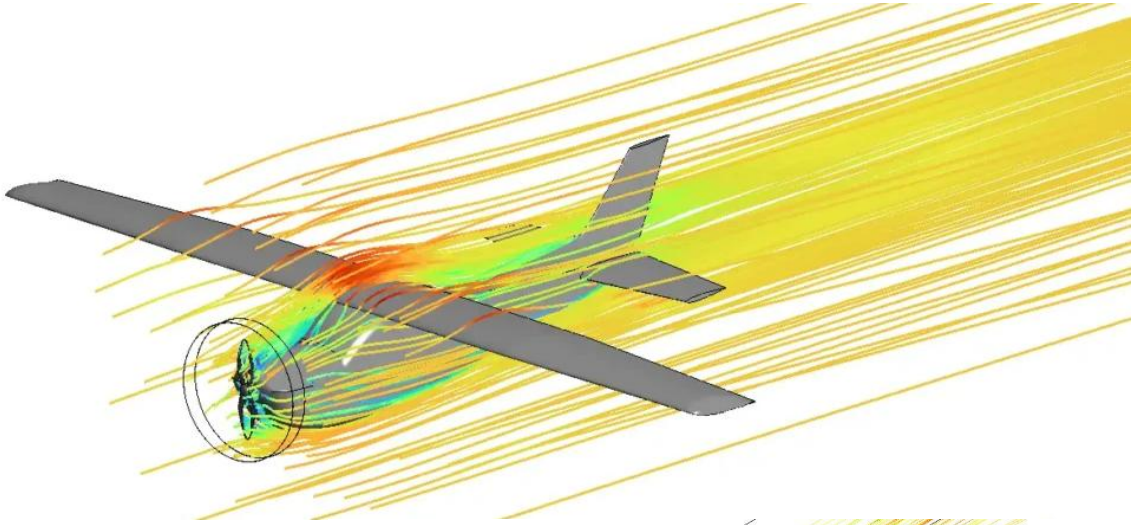


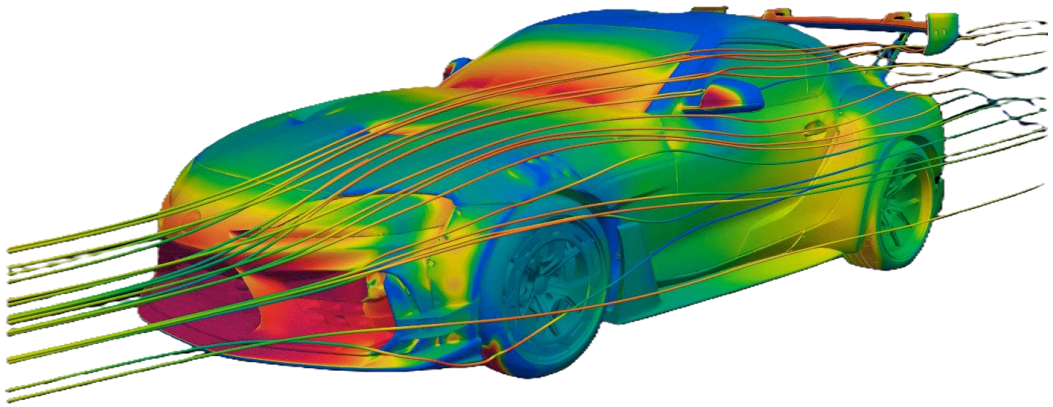
(Ngcobo et al., 2013)

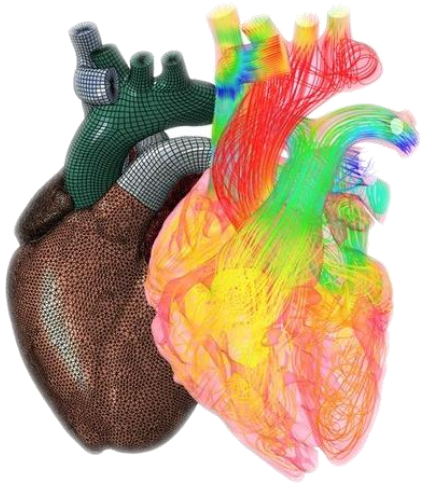
BACKGROUND

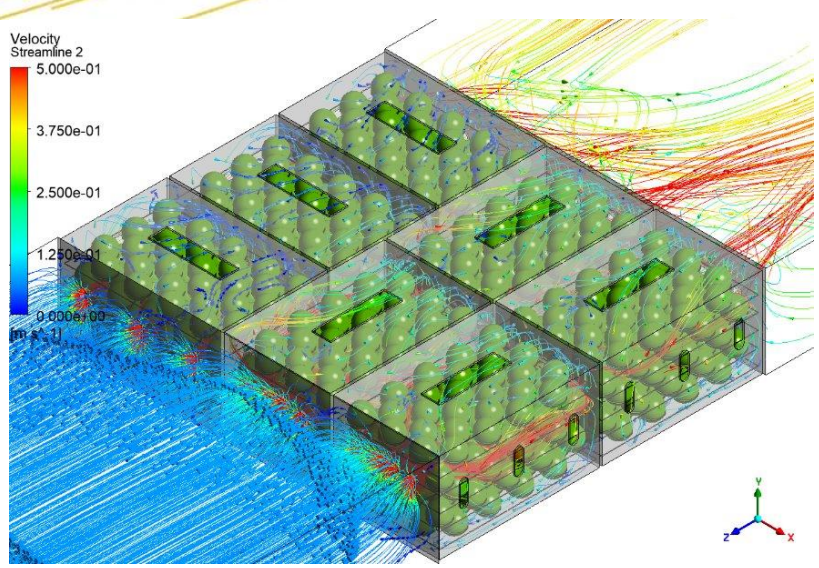
Computational Fluid Dynamics (CFD)

- A well-established computational tool for analysing airflow, heat transfer, and mass transfer
- Predicts airflow, cooling, and gas distribution within packaging systems
- Enables virtual evaluation and optimisation of packaging designs before physical testing









OBJECTIVES

Aim

- To investigate the effects of commercial table grape packaging on airflow, heat, moisture, and SO_2 transport using virtual modelling approach (3D CFD model), and to evaluate packaging performance during cold storage



Objectives

- Quantify airflow resistance of commercial packaging
- Evaluate the effects of carton design, liners and cultivar on cooling performance
- Identify packaging configurations that improve cooling uniformity and energy efficiency



APPROACH

Workflow

Developed a 3-D CFD model of the commercial packaging

Developed a 3D CFD model to evaluate airflow distribution and cooling performance inside commercial export packaging

Experimental characterization

Conducted experimental measurements of airflow resistance, cooling, and warming performance

CFD Model Validation

Compared CFD-predicted cooling and warming behaviour with measured temperature profiles

Evaluation of packaging performance

The validated CFD model enabled detailed analysis of packaging performance

CFD DEVELOPMENT

Box and Punnet construction and selection

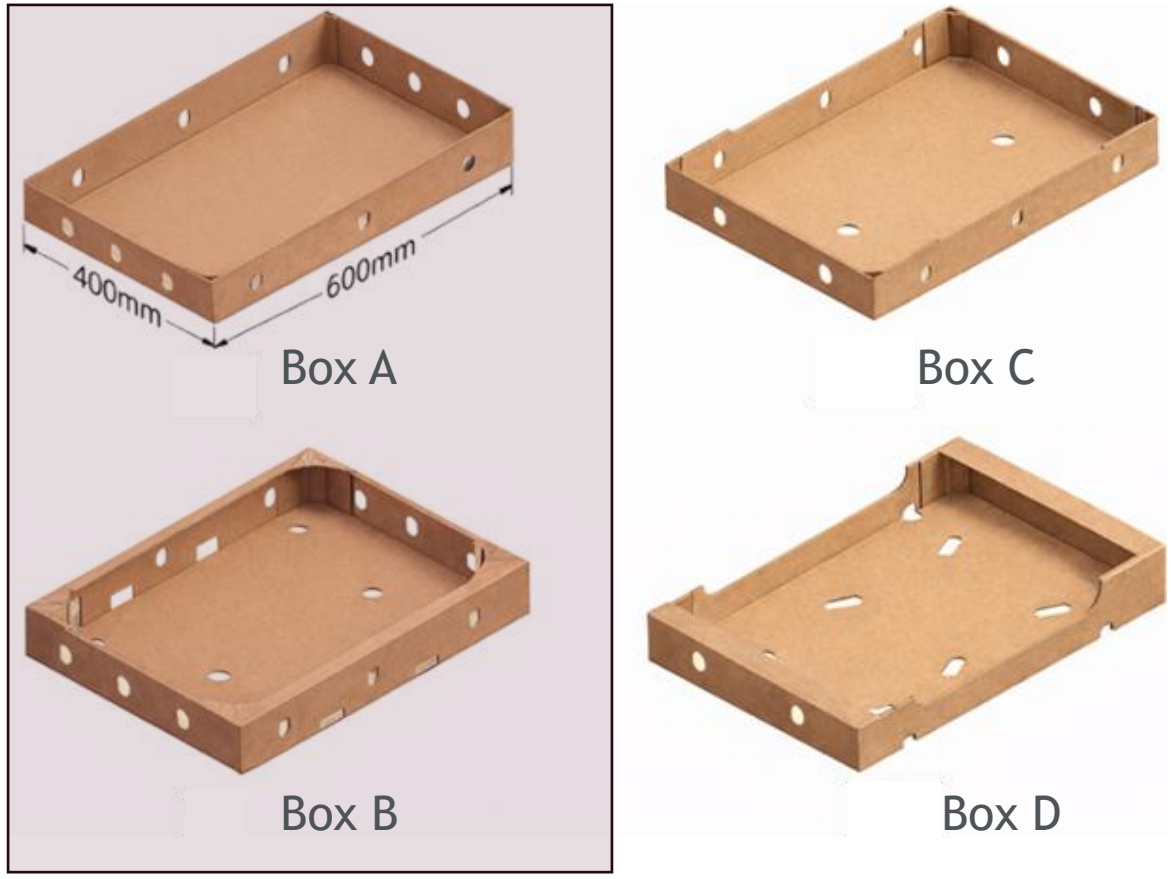


Fig. 1: Commercial table grape export carton used in the South African industry

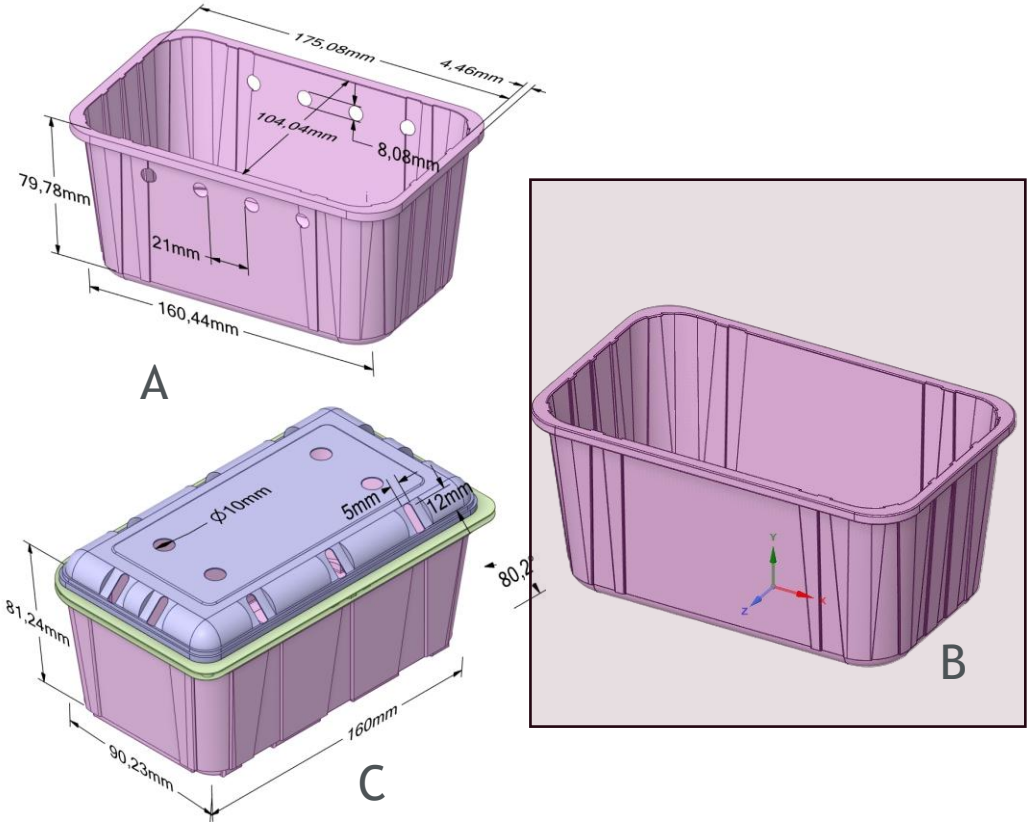
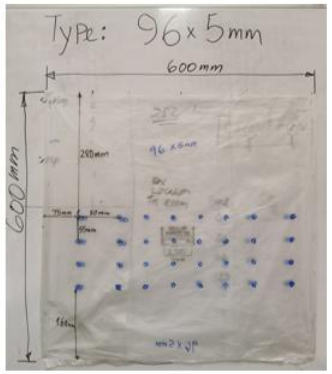
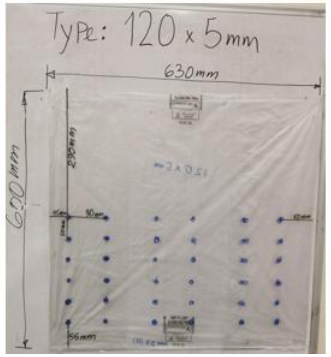


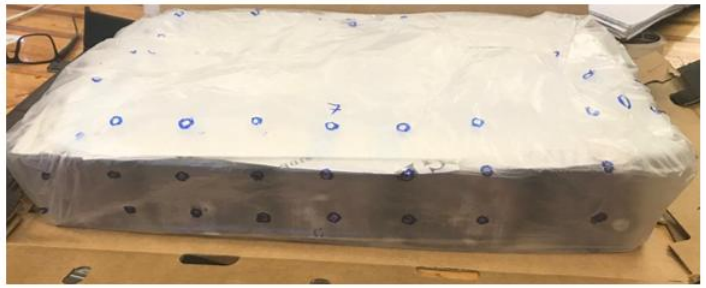
Fig. 2: Commercial table grape punnet used in the South African export industry

CFD DEVELOPMENT

Liner selection











96 × 5 mm



120 × 5 mm

Liner Design	Total Holes	Functional Vents	Blocked Vents	Vent Efficiency
120 × 5 mm	120	53	67	**44.2%**
96 × 5 mm	96	78	18	**81.3%**



CFD DEVELOPMENT

Capturing the fruit geometry

1



2



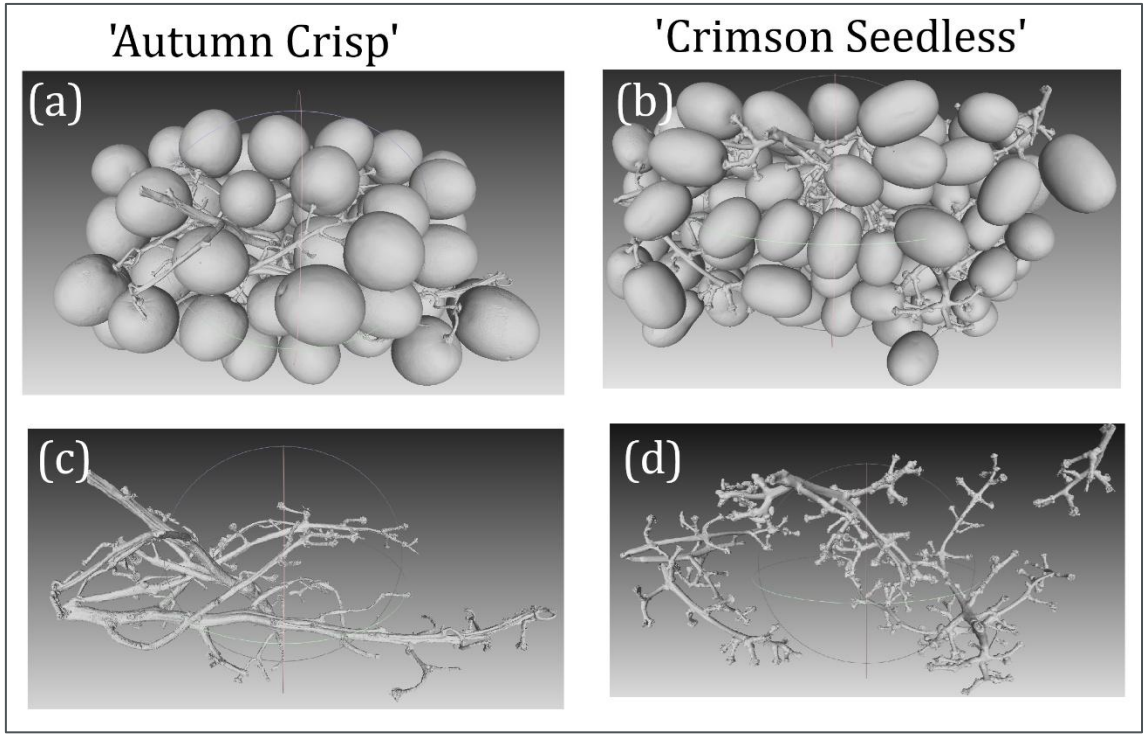


Fig. 3: Berry-cluster geometries generated using X-ray CT for CFD modelling

CFD DEVELOPMENT

One-Layer Pallet Airflow configuration

Box A

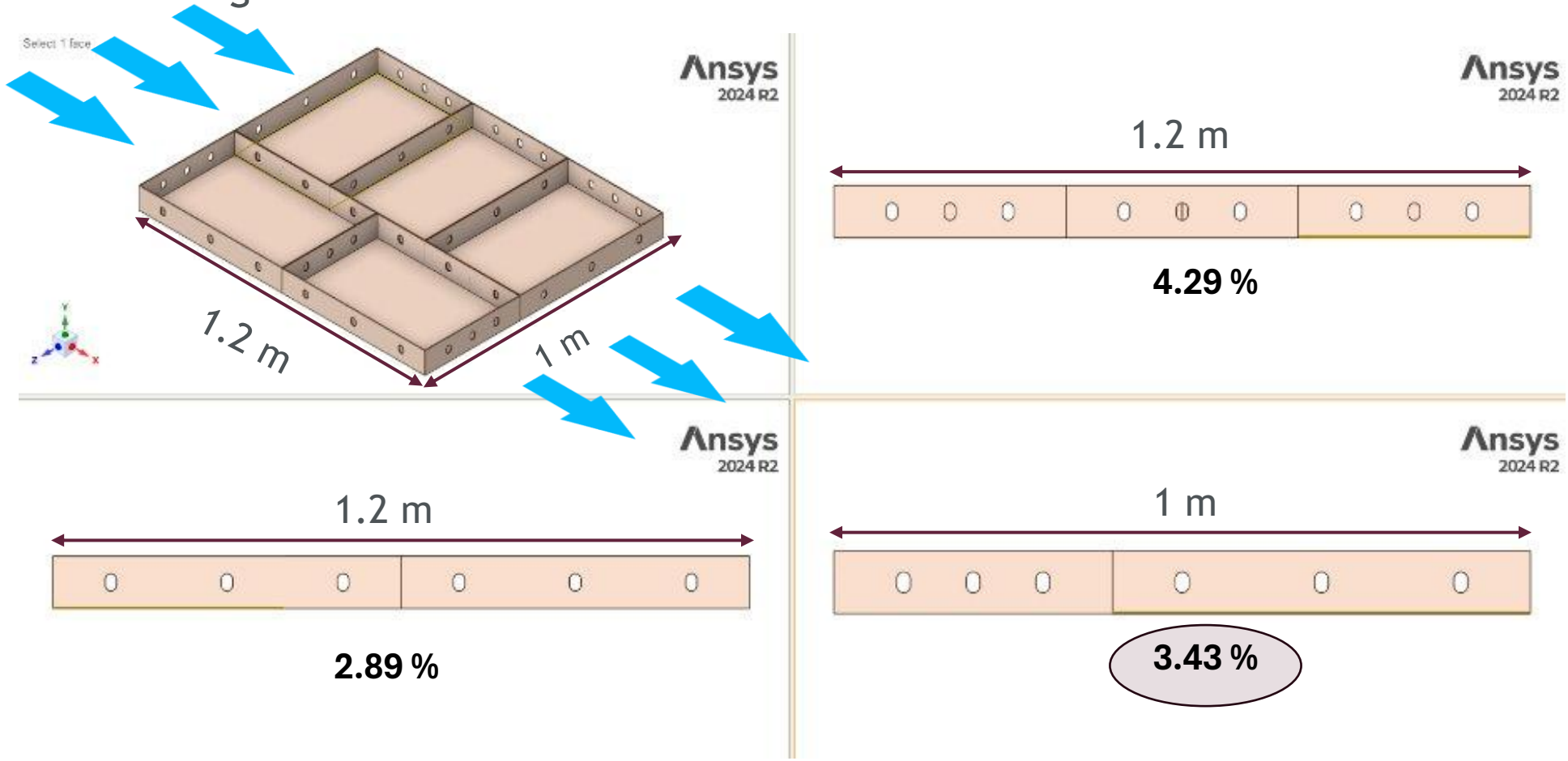


Fig. 4: One-layer pallet geometry and ventilation configurations of Box A used for CFD modelling

CFD DEVELOPMENT

One-Layer Pallet Airflow configuration

Box B

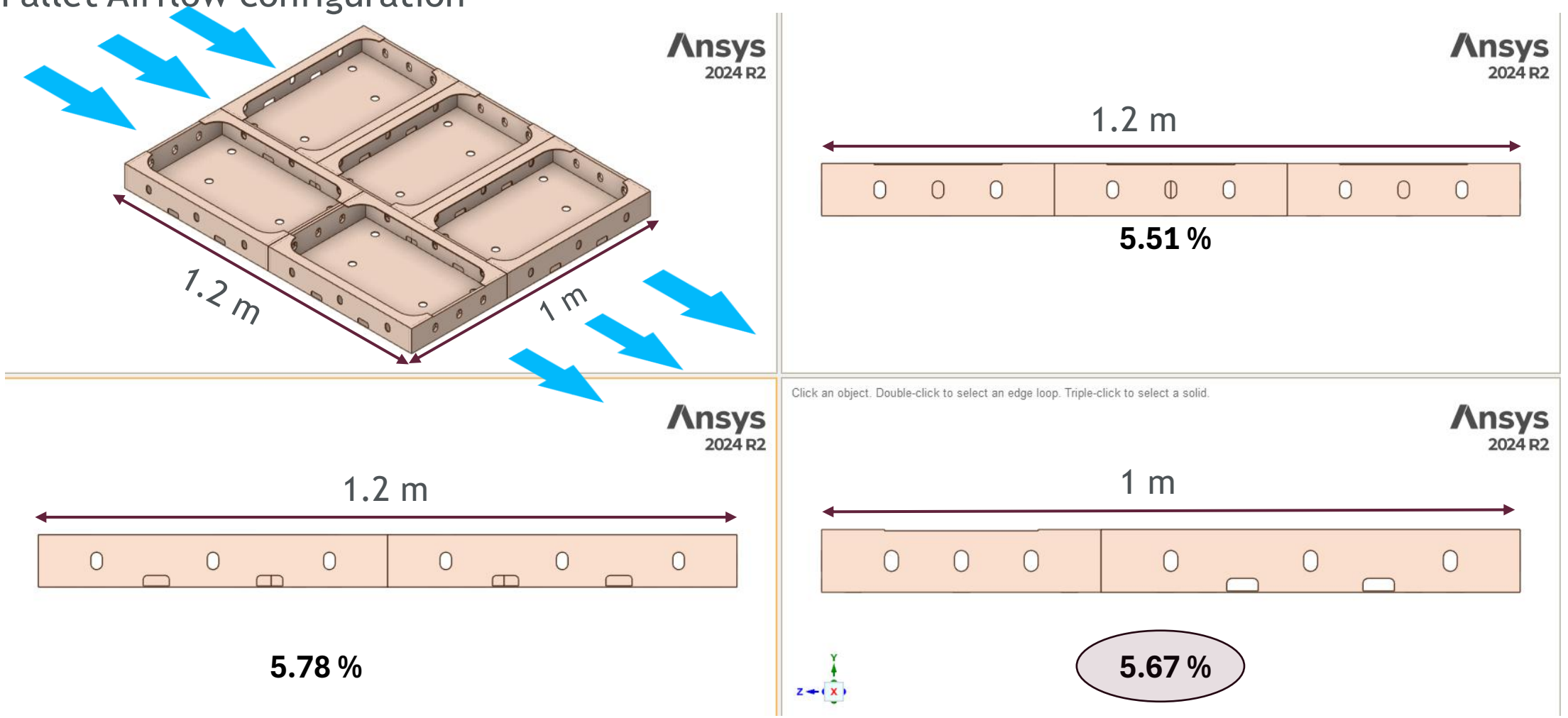


Fig. 5: One-layer pallet geometry and ventilation configurations of Box B used for CFD modelling

CFD DEVELOPMENT (CONT…)

- **ANSYS CFX 2024 R2** was used for the CFD simulations
- Airflow was solved using the **continuity** and **Navier-Stokes** equations

$$\nabla \cdot \mathbf{u} = 0$$

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right) = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{F}$$

- Heat transfer was modelled using the **energy equation**

$$\rho C_p\left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T\right) = \nabla \cdot (k \nabla T) + S_h$$

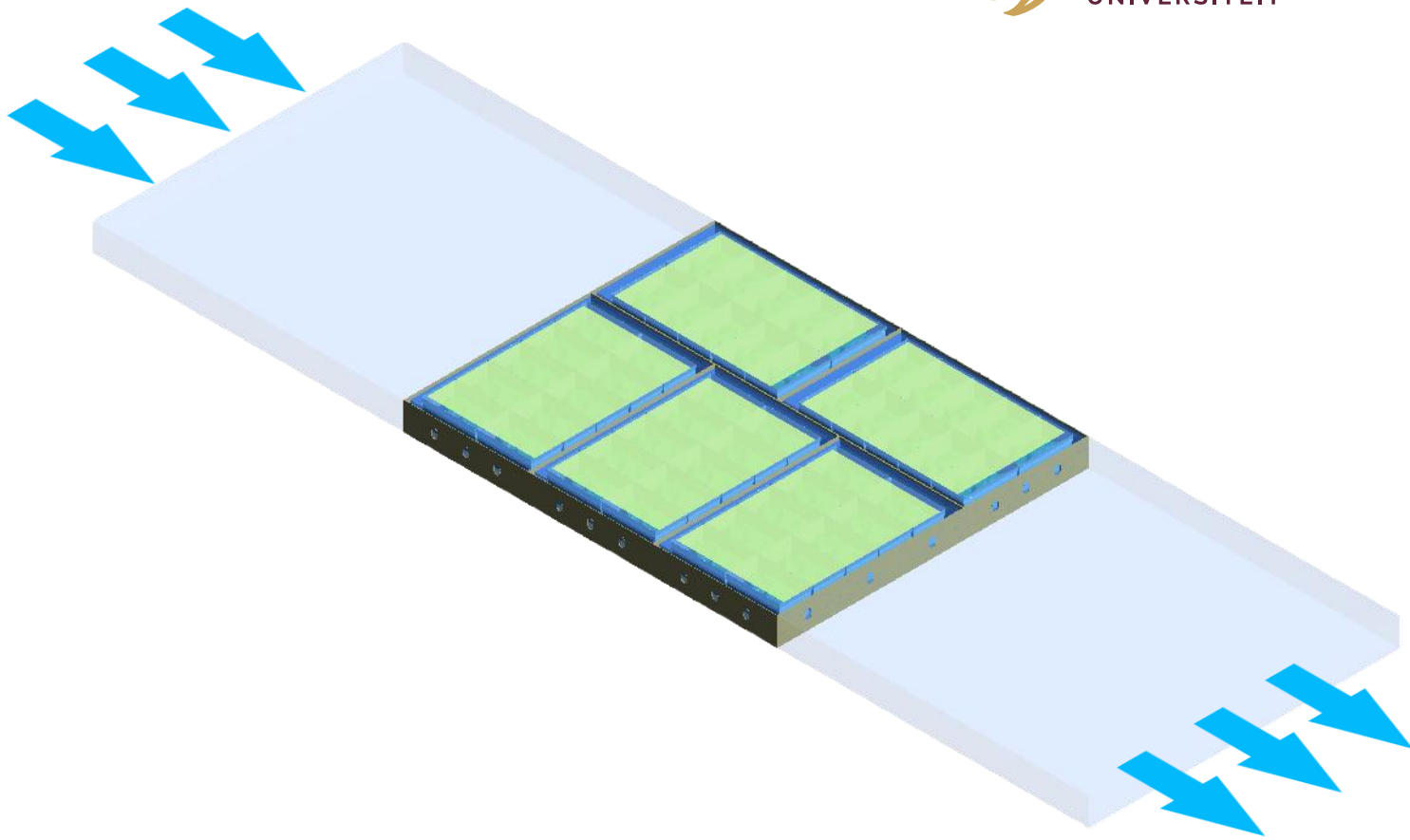


Fig. 6: Geometry used for airflow resistance simulations

EXPERIMENTAL CHARACTERISATION

Airflow resistance

- Measured airflow resistance of commercial table grape packaging
- Tested progressively assembled packaging components:
  - empty boxes,
  - boxes with punnets only,
  - boxes with punnets and liners,
  - and complete packaging units
- **Velocity**: Alnor Velometer AVM440
- **Pressure**: WIKA A2G-25 Air Flow Meter

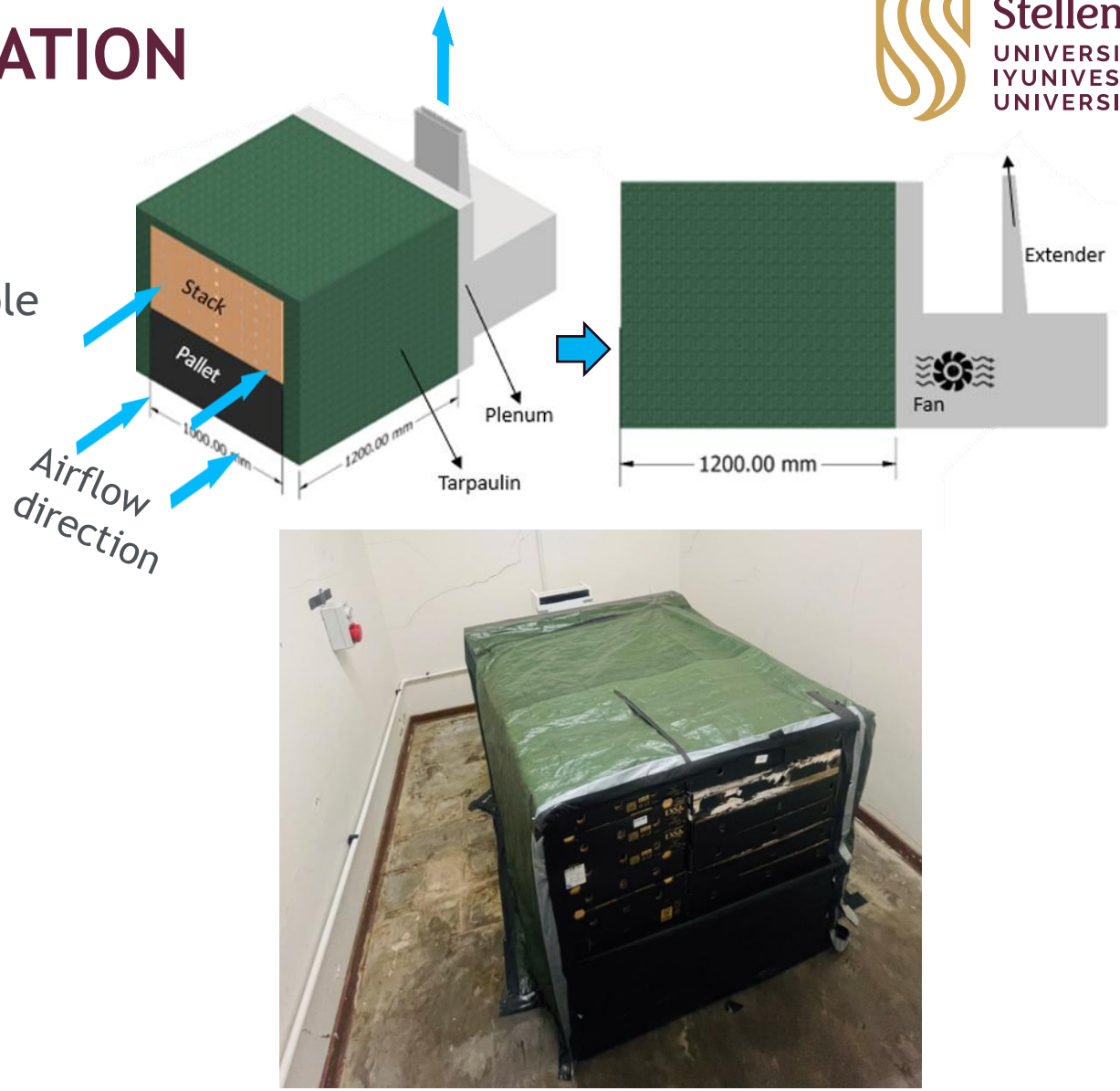


Fig. 7: An experimental setup of a forced-air cooler

EXPERIMENTAL CHARACTERISATION

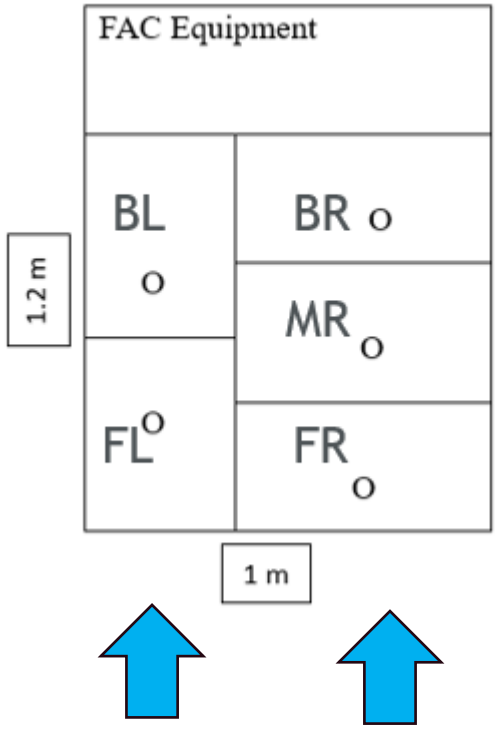
Thermal Performance

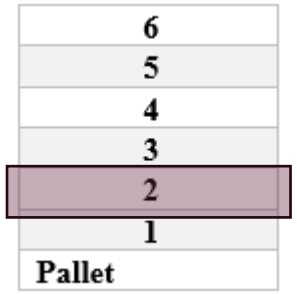
- Forced air cooling (Seven-eighths cooling time (SECT) (0 ± 0.5 ˚C))
- Warming up (Half warming time (HWT) (23 ± 1.4 ˚C))
- **Temperature:** Gemini TGP-4510 Temperature Data Logger





Fig. 8: Experimental setup for cooling down and warming up of fruits

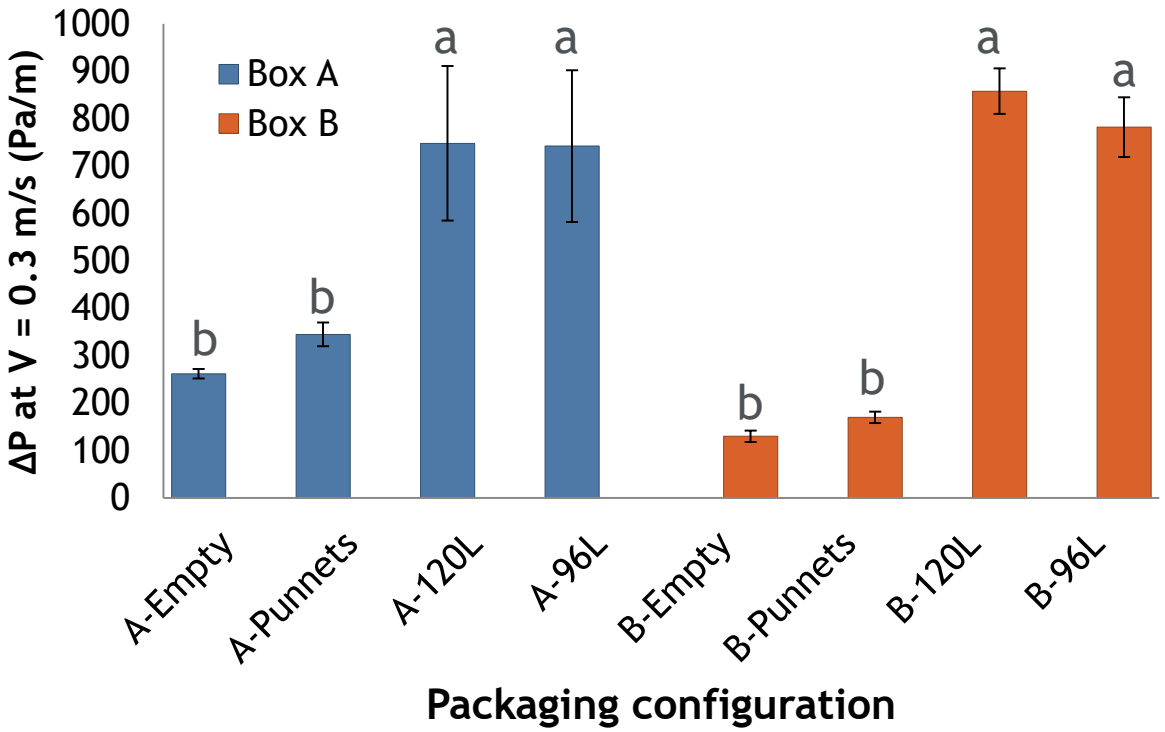


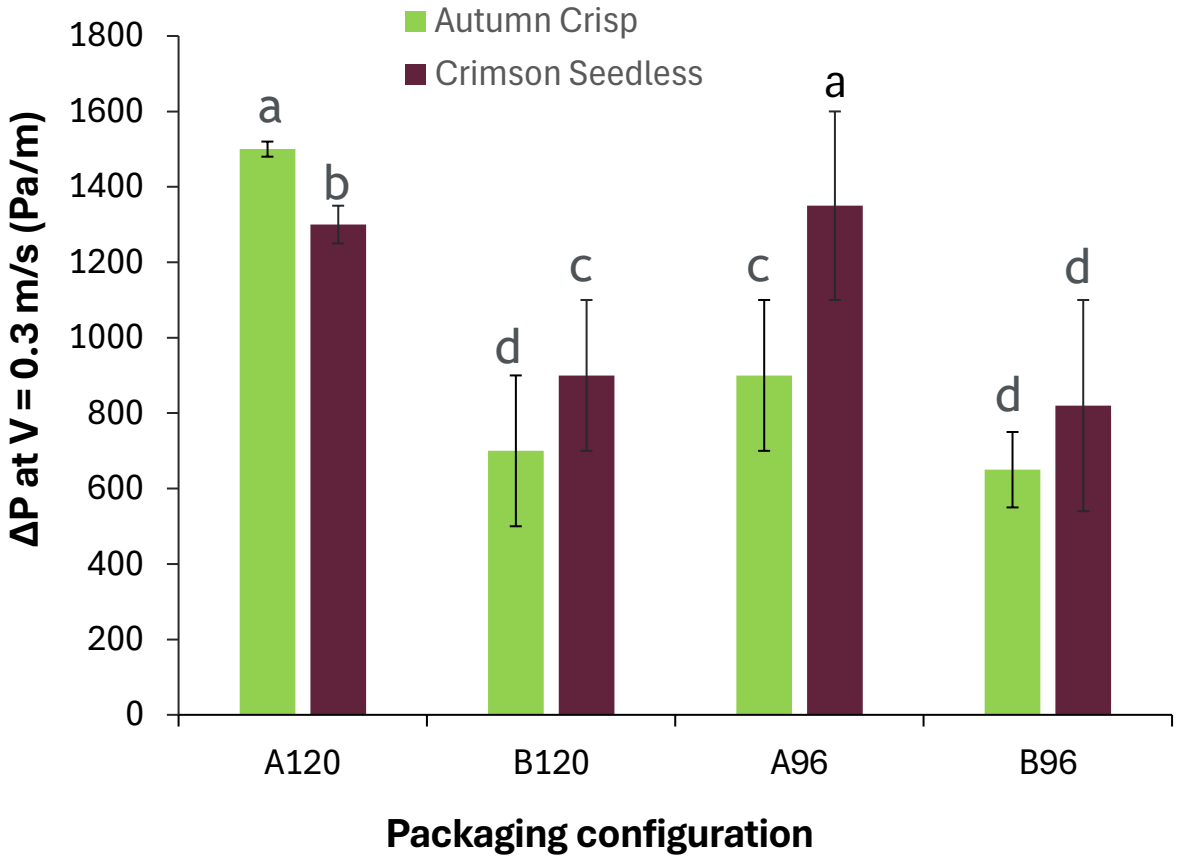


FL – Front Left
FR - Front Right
BL – Back Left
MR – Middle Right
BR – Back Right

AIRFLOW RESISTANCE RESULTS

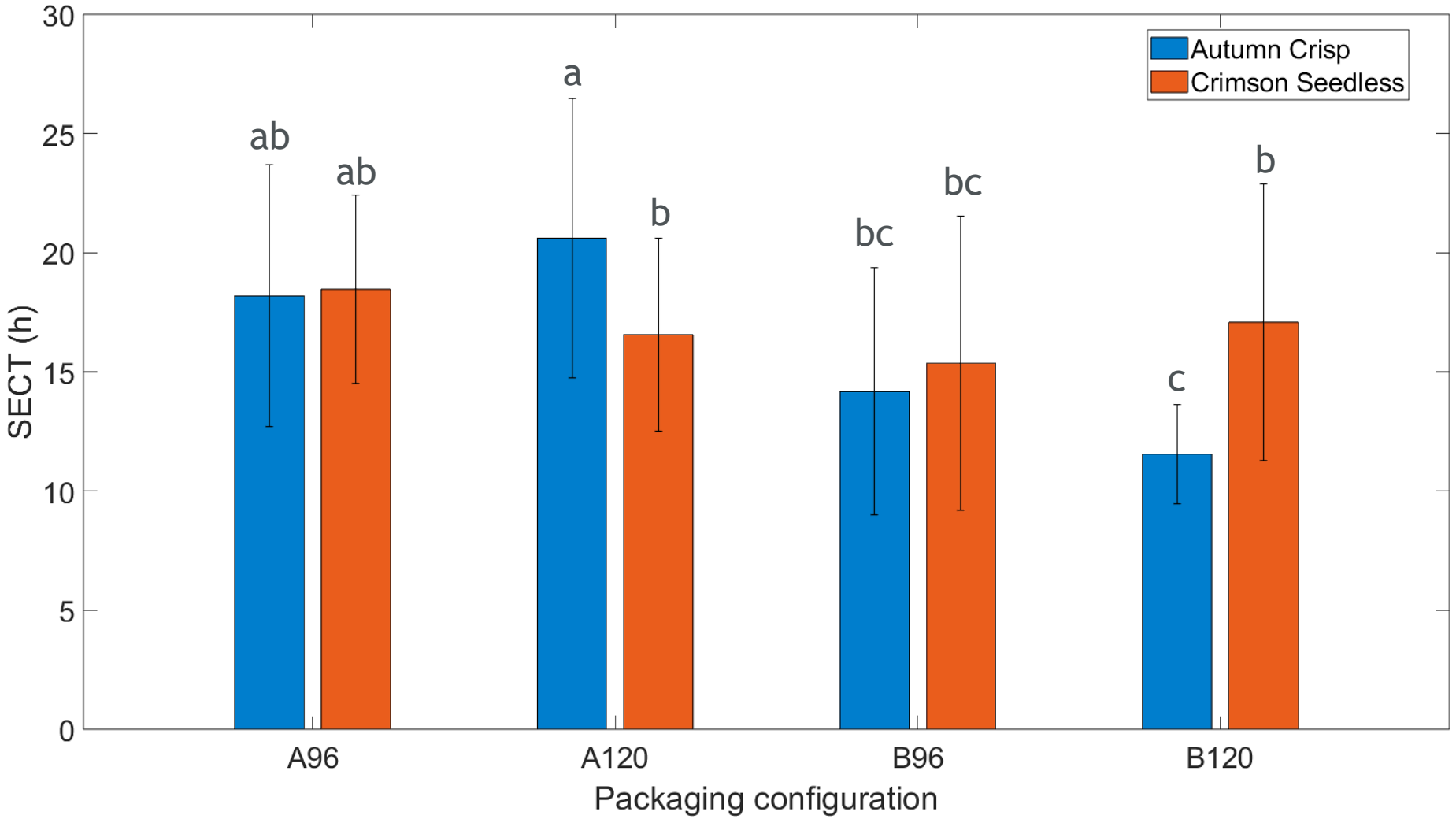
Pressure drop was measured to identify which packaging components contributed most to airflow resistance





- Box B showed lower airflow resistance than Box A
- The effect of liner configuration (120 vs. 96 holes) varied between cultivars

EFFECTS OF PACKAGING DESIGN ON COOLING



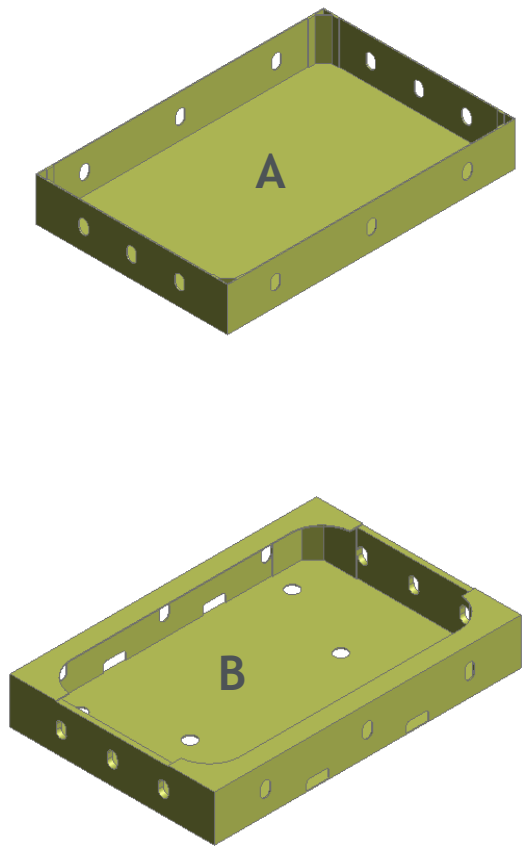
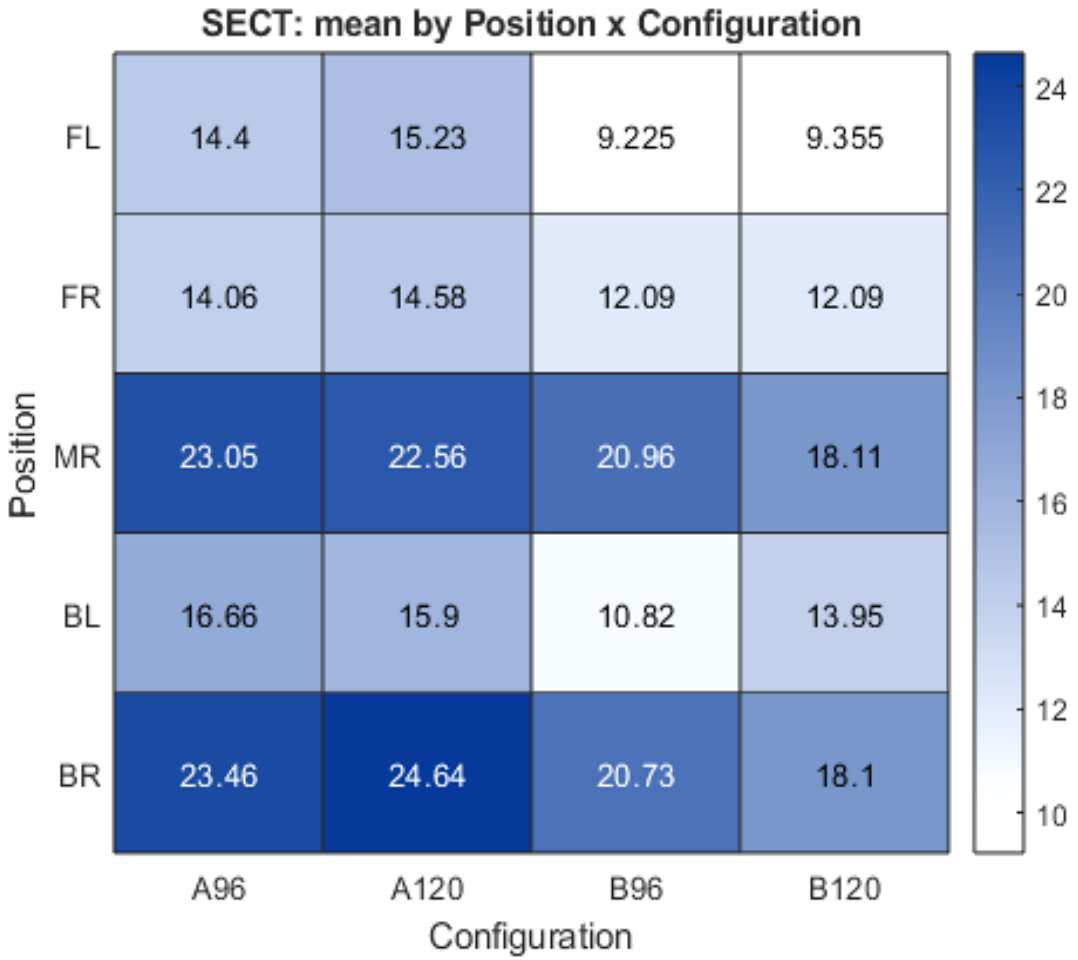
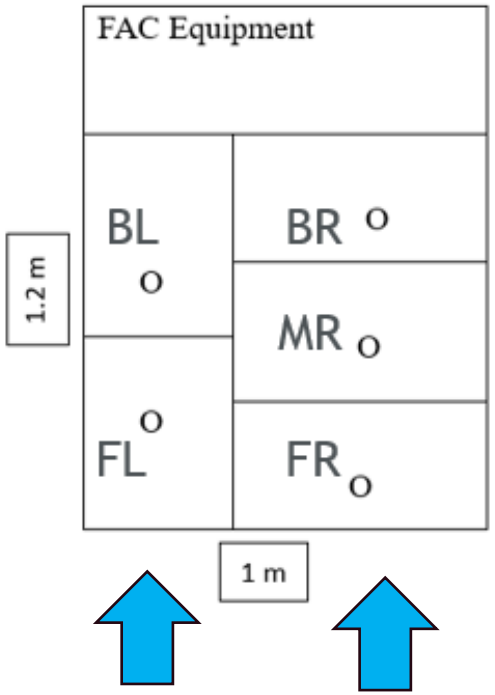


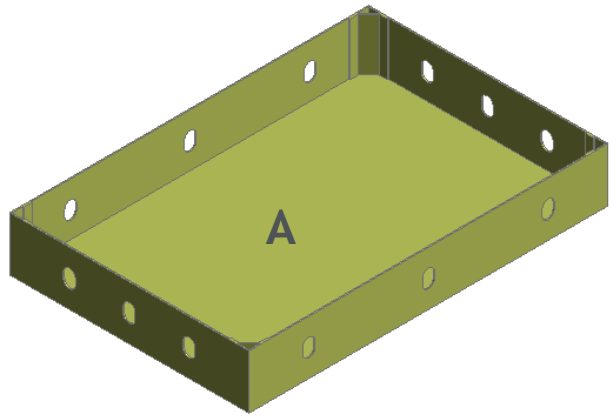
Fig. 9: Effects of packaging configuration and cultivar on seven-eighths cooling time (SECT) during forced-air cooling at 0.2 m/s and 0 ± 0.5°C air temperature

EFFECT OF PACKAGE POSITION ON COOLING UNIFORMITY



- Front positions cooled up to twice as fast as middle and back positions





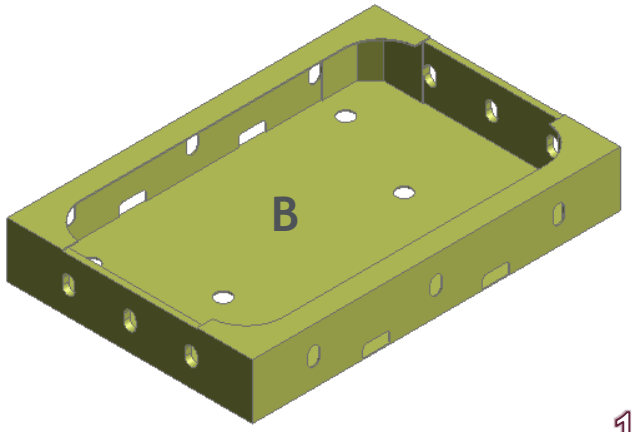
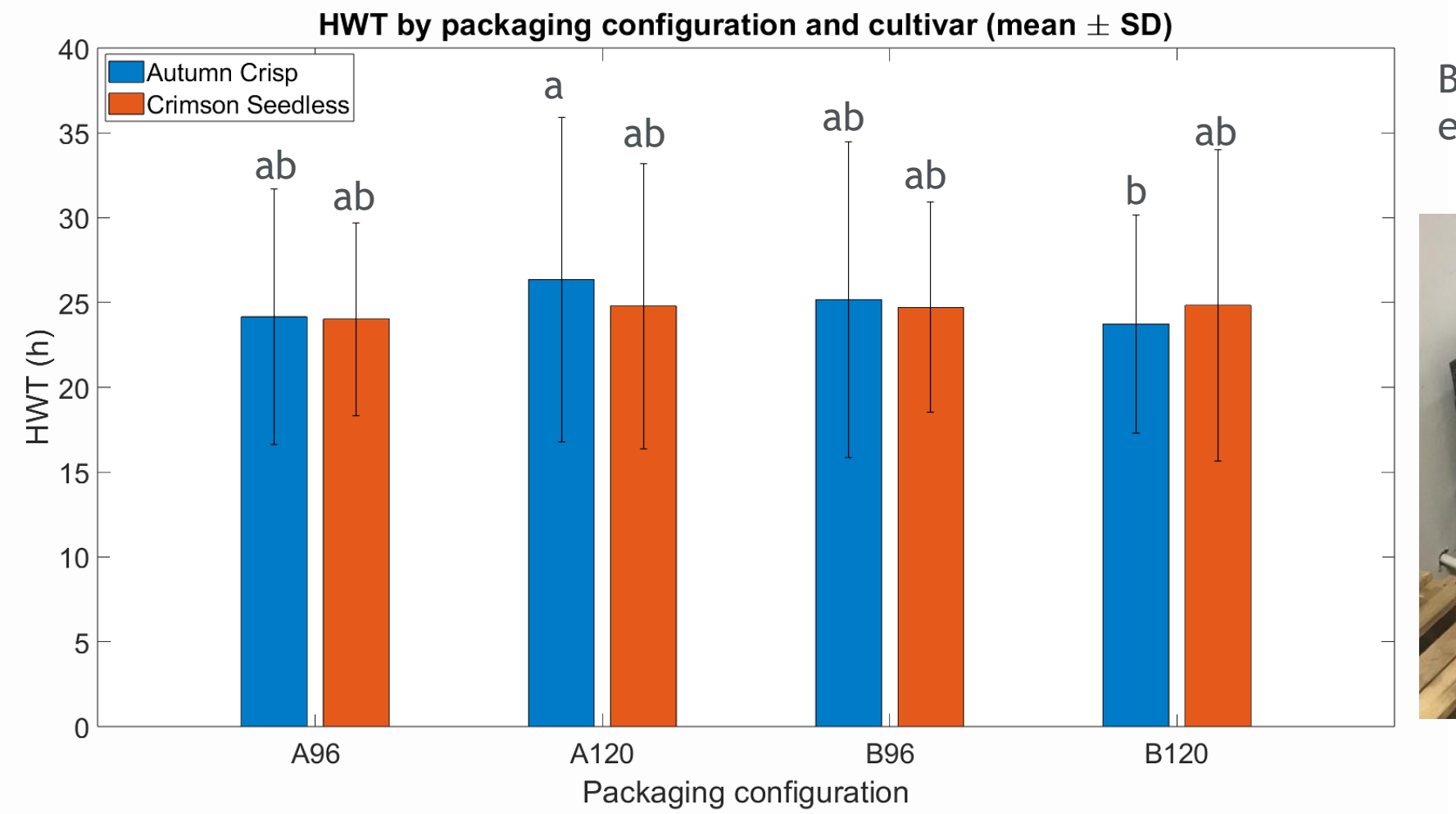


Fig. 10: Effects of packaging configuration and box position on seven-eighths cooling time (SECT) under forced-air cooling at air temperature of 0 ± 0.5 °C and air velocity of 0.2 m s^{-1}

EFFECTS OF PACKAGING DESIGN ON WARMING

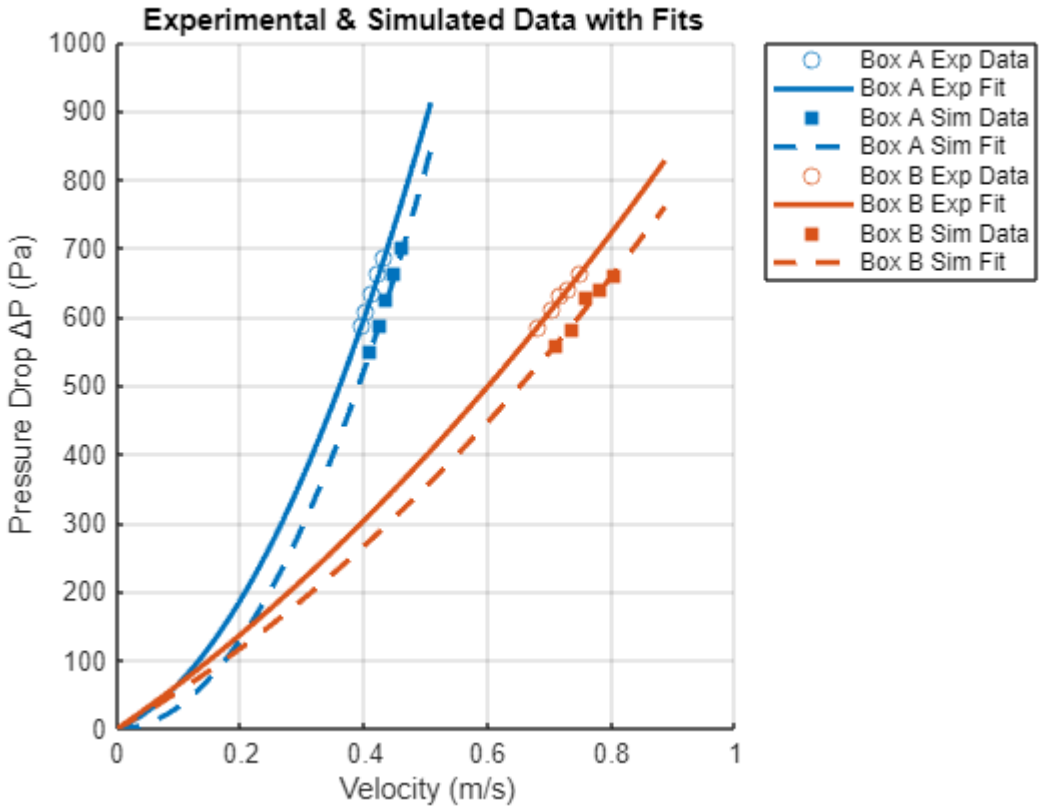


Box design had no significant effect on half warming time



Fig. 11: Effects of packaging configuration and cultivar on half warming time, at air temperature of 23 ± 1.4 °C

CFD MODEL VALIDATION



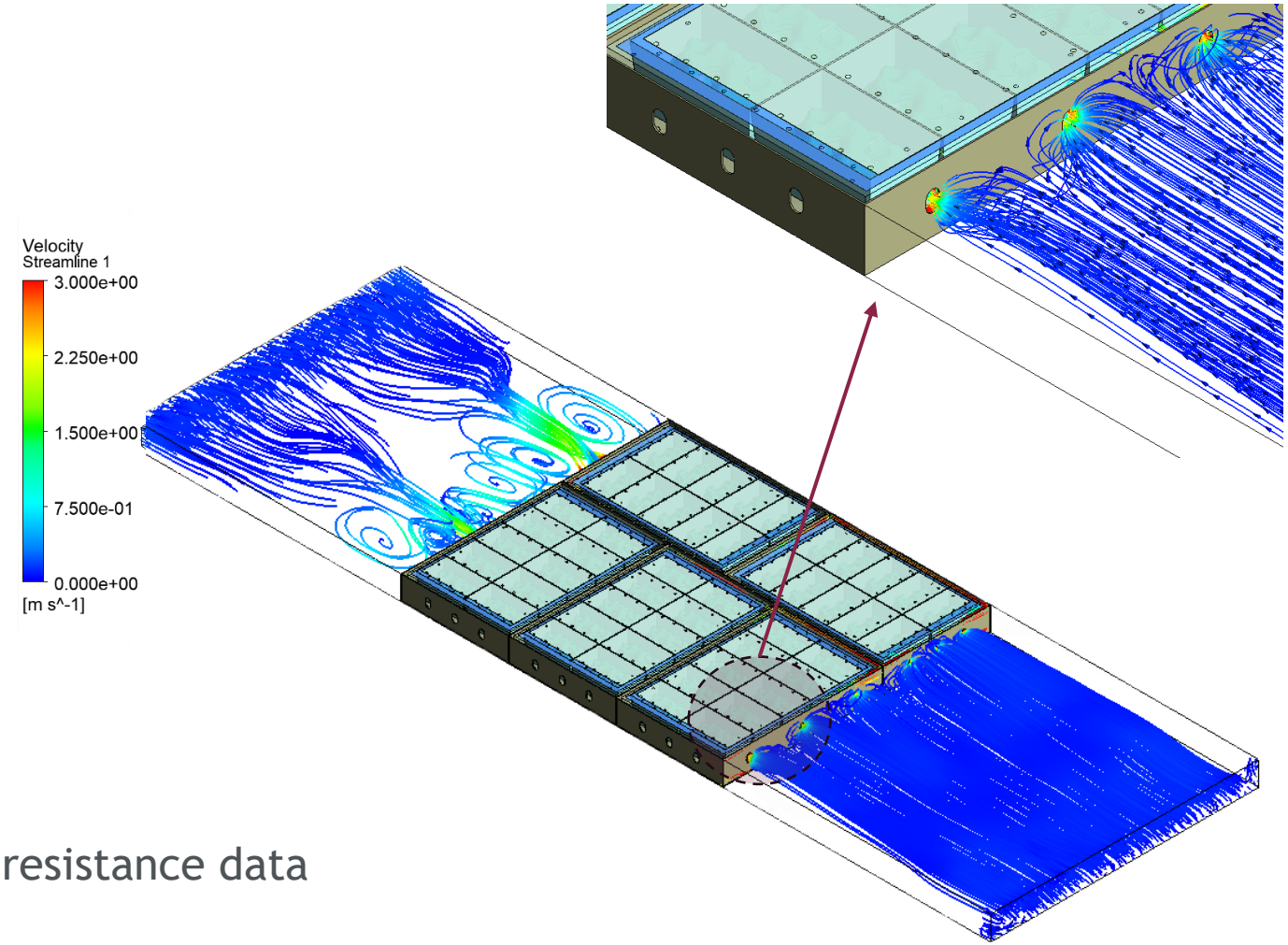


Fig. 12: Simulated and experimental airflow resistance data

KEY TAKE-HOME MESSAGES AND PRACTICAL IMPLICATIONS

- Packaging performance is governed by interactions between carton, liner, cultivar and pallet position
- **B96** had the **lowest airflow resistance**
- **Box B** generally cooled faster than Box A
- **B120** showed the best cooling uniformity
- Consider cultivar-specific packaging to improve cooling performance and product quality
- CFD-based virtual prototyping can support faster and more informed packaging development
- Further validation across cultivars and seasons is required before industry-wide implementation

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REFERENCES

- Ngcobo, M. E. K., Delele, M. A., Opara, U. L., & Meyer, C. J. (2013). Performance of multi-packaging for table grapes based on airflow, cooling rates and fruit quality. Journal of Food Engineering, 116(2), 613–621. https://doi.org/10.1016/j.jfoodeng.2012.12.044


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