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

1. INTRODUCTION

Traditionally, horticultural crops such as strawberries, blueberries, and raspberries have been packed and sold in open-topped pint baskets. About 10 years ago, the berry industry began packing their product in individual consumer packages, typically in thermoformed clamshell packages. In the last few years these packages have been increasingly used for table grapes, cherries and pears. An indication of this shift in packaging trends can be seen from the market statistics available for strawberries. According to the California Strawberry Commission (2002), in 1999 the one-pound consumer pack accounted to 61% of the packages sold in the spring and 84% of those sold in the summer.

Fruit is placed in the clamshell packages in the field or in packinghouse operations. The packages are placed in corrugated or plastic master containers and the containers are stacked on pallets (Fig. 1). They are then cooled in forced-air cooling systems. The refrigerated product (0-2°C) is then shipped to distribution centers and sold in retail stores.

Unlike the pint basket, which typically has an open top and a very large vent area, the one-pound consumer pack typically has a solid lid and vents that represent less than 10% of the package surface area. This design leads to less bruising and cutting of strawberries than the traditional pint basket (Singh, 1992; Émond and Julien, 1993 a and b). Additionally as compared to bulk packaging and shipping in trays, consumer packages reduce handling in the transportation and retail chain reducing physical damage to the fruit and reducing chances of product contamination.

Anderson et al. (2004) have shown that some designs of individual packages (such as clamshells) and master containers can result in significantly slower cooling than others. Émond and Julien (1993 a and b) reported a problem with product temperature uniformity. Differences of as much as 10ºC in the same pallet of strawberries after 90 min of forced-air-cooling were observed. Poor

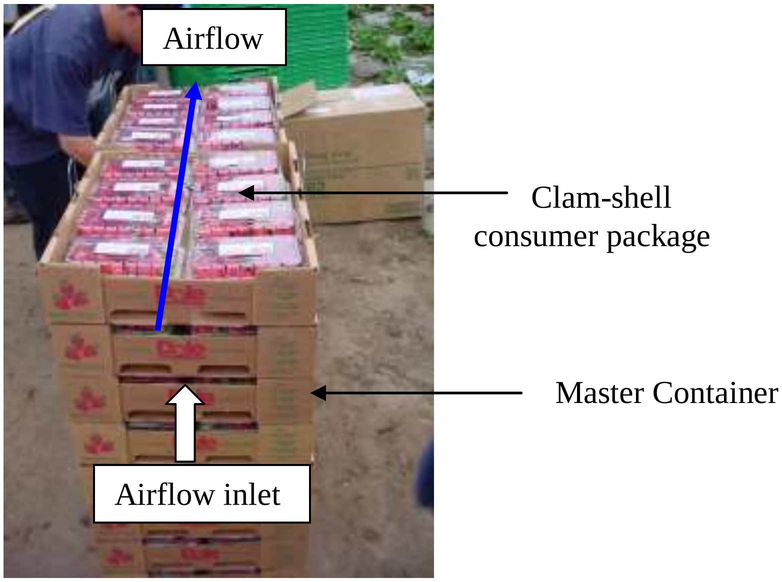


Fig. 1. Strawberries in clamshell consumer packages are placed in a corrugated fiberboard master container. Arrows indicate direction of airflow in forced-air cooling.

designs result in low and uneven airflow rates through the packages and considerable channeling of airflow through gaps between clamshell packages and through the headspace above them. Low and non-uniform airflow through the product results in slow and non-uniform product cooling. Slow cooling decreases pallet throughput capacity at the cooling facility and forces uncooled product to be stored outside until cooling space becomes available. This is particularly a problem on hot days when a great deal of product must be harvested and high ambient temperatures cause measurable quality loss in just a few hours of cooling delay. Non-uniform cooling inside the package results in warm product in parts of the package or requires a long time to completely and uniformly cool the product.

In the case of produce packed in packages-in-a-master container (as shown in Fig. 1), proper design of consumer packages and master containers is necessary to reduce postharvest losses and improve utilization of existing cooling facilities. The design process should include design of the consumer packs, master containers, and the interaction of the two. Experimental attempts at improvement of design of such systems (Anderson et al, 2004; Émond et al, 1996) have indicated that the uniformity and rate of cooling is controlled by a complex interaction of design parameters such as percentage vent area, vent spacing, vent size, arrangement of clamshells in a master container, and arrangement of master container on pallets. There are a huge number of possible designs considering the number of variables and their wide range in magnitude. This makes it difficult to evaluate the design options without a theoretical understanding of the effect of these parameters on airflow patterns inside the packages and the effect of highly non-uniform airflow on product cooling. The goal of this proposal is to develop a theoretical model of cooling of produce packages and use the model to develop design guidelines for consumer packages and master containers that will allow packaged product to be quickly and uniformly cooled.

1.1 Theoretical basis of fluid flow and heat transfer in packed beds

Various researchers have developed theoretical basis for predicting fluid flow and heat transfer in bulks of agricultural commodities. The porous media approach is the most widely accepted technique for analyzing drying of commodities such as cereal grains and other small-size particulates contained in large structures such as bins (Baird and Gaffney, 1976; Bakker-Arkema and Bickert, 1966, Bakker-Arkema et al 1969). This approach is based on the assumptions of pressure driven flows with average uniform velocities in the porous media, and lumped or transient heat transfer within the solid particulates. Applying this theory directly to large-size particulates in relation to a small container (e.g. strawberries in a consumer package) has several limitations.

In case of airflow around large-size particulates packed in a relatively small-size container, there is significant velocity variation inside the porous bed, and the viscous effects become substantial because of the closeness of walls (Vaifai and Tien, 1980). Van der Sman (1999 & 2002) and Xu and Burfoot (1999) have suggested modifications to the original packed-bed theory for its application to situations concerning large-size particulates. They suggest using the Darcy-Forchheimer equation to describe fluid flow in packed beds with the addition of the Brinkman term for estimating the viscous effects (called DFB equation, Eq. 1), along with the continuity equation (Eq. 2).

$$-\nabla p = \frac{\mu}{\kappa}\vec{u} + \beta\rho u\vec{u} - \mu_{eff}\nabla^2\vec{u} \tag{1}$$

$$\nabla \cdot \vec{u} = 0 \tag{2}$$

where, $$\frac{1}{\kappa} = K_1 \frac{(1-\varepsilon)^2}{d_{eff}^2 \varepsilon^3}, \qquad \beta = K_2 \frac{(1-\varepsilon)}{d_{eff} \varepsilon^3}, \tag{3, 4}$$

and p is the pressure, μ is the viscosity of air, κ is the permeability of the porous medium, u is the air velocity, β is the Forchheimer constant, ρ is the density of air and μ_{eff} is the effective viscosity. In Eqs. 3 and 4, K_1 and K_2 are the Ergun constants; d_{eff} is the effective diameter and ε is the porosity of the medium. The Darcy-Forchheimer equation describes the airflow at high flow rates, Re>1, and the Brinkman term (third term on the right hand side of Eq.1) is the correction factor for the solid porous interface at the wall of a container and other viscous effects (detailed description in Whitaker, 1999). The Ergun constants, the effective diameter and the porosity are shape and product dependent. Typically, Ergun constants are obtained from experiments conducted in a one-dimensional flow in a bin of granular material with minimal wall effects. The constants are calculated from regression analysis of the pressure drop per unit length of the bin and the superficial air velocity (Ergun, 1952; Macdonald et al, 1979; Chau et al, 1983; Comiti and Renaud, 1989; Irvine et al, 1993).

The determination of the effective viscosity, μ_{eff}, is somewhat more difficult and has been arbitrarily assumed as a constant by most authors (Van der Sman, 1999 & 2002; and Xu and Burfoot, 1999). Such arbitrary assumptions may cause considerable errors in cases where the air flows through complex packaging systems such as packages-in-a-master container. For such cases, the wall effects may be more significant relative to the bulk. With the knowledge of the Ergun coefficients, effective viscosity, and appropriate boundary conditions, Eqs. (1) and (2) may be solved numerically in two or three dimensions using computational fluid dynamics (CFD) to determine velocity profiles.

The heat transfer in porous packed beds may be obtained in various ways. Using an energy balance, the thermal energy equation for the air phase inside a porous media may be written as:

$$\rho_a c_a \left\{ \frac{\partial T_a}{\partial t} + \nabla\left(\vec{u} T_a\right) \right\} = -hA\left(T_a - T_p\right) \tag{5}$$

Where, c is the specific heat, T is the temperature, t is time, h is the heat transfer coefficient between solid and air, and A is specific surface area of the air product interface. The subscripts a and p represents air and product, respectively. The temperature of the product, T_p, is determined from the energy equation for the solid phase (product) which can be assumed to be lumped for cases where Biot number for the flow is smaller than 0.1 (Eq. 6).

$$\rho_p c_p \frac{\partial T_p}{\partial t} = hA\left(T_a - T_p\right) + \dot{m} A H \tag{6}$$

The rate of convective mass loss per unit area ($\dot{m}$) may be determined using the similarity between convective heat and mass transfer, also known as the Lewis analogy (Incropriera and deWitt, 1990). H is the enthalpy of vaporization of water for the average film temperature. In cases where Biot number is large (larger than 0.1), the lumped approach (Eq. 6) is not valid and T_p varies within the product. In such cases, the energy equation inside the product must be solved as a transient problem with a convective boundary to determine T_p at the surface of the product (Eqs. 7 and 8).

$$\frac{1}{r^2} \frac{1}{\partial r} \left(k r^2 \frac{\partial T_p}{\partial r} \right) = \rho c_p \frac{\partial T_p}{\partial t} \tag{7}$$

$$h\left(T_a - T_p^{surface}\right) + \dot{m}H = -k\frac{\partial T_p}{\partial r} \qquad (8)$$

Where, *r* is the radius and *k* the thermal conductivity. The existing theoretical models have limitations when applied to a complex packaging system such as packages in a master container.

1.2 Limitations of existing theoretical models of air flow through packages containing large-size particulates

Jaccobsson et al. (2004) studied the applicability of DFB-based numerical methods for packed beds of relatively large-size commodities such as potatoes or broccoli in a box. They found that a major limitation of the DFB-based approach in packed beds (section 1.1) is due to the effects of turbulence. Though turbulence is widely accepted to decay in fluid flow in packed beds of granular material, such may not be the case for porous media with larger size particulates.

To understand the limitation of the porous media approach, consider each individual term in Eq. 1. The magnitude of the third term on the right hand side of the equation (the viscous term) is influenced by the magnitude of the effective viscosity (μ_{eff}) which is a sum of kinematic viscosity, turbulent viscosity, and viscosity due to wall shear. Many researchers have assumed that turbulence decays in a porous medium and hence μ_{eff} decays in the porous media along the length of the fluid flow (except near the walls). This assumption is valid for beds of grains or small-size particulates in large bins. Similar decay in turbulence may even be true for beds of large particulates as long as the ratio between the package effective dimension ($D_{package}$) and the effective dimension of the product ($D_{product}$) is relatively large, as was the case in research done by van der Sman (2002). However, a limiting value for this ratio is still an unknown that the proposed research will address.

Recent experimental work done by Alvarez & Flick (1999) on air velocities and turbulence patterns in beds with relatively large-size particulates as compared to the flow path shows that the porous media approach may have certain limitations when the diameter ratio is not satisfied. They measured velocity and turbulence intensity profiles at various downstream locations in a bin with two layers of spherical products ($D_{product}$ = 0.075 m) in a tray with effective flow dimension ($D_{package}$) of 0.275 m. Their results indicated considerable heterogeneity of velocity maps at various locations along the length of the flow. Turbulence intensity is high in the bin (up to 50%) and may be generated either by the inlet vents into the bin or by vortex dissipation of the products.

Another limitation of applying the porous media approach to packages-in-a-master container arises from the discontinuous nature of the problem. In these packing systems, the discontinuity between individual packages creates considerable wall effects. Such discontinuities also result in channeling of airflow through the gaps between the packages.

The preceding discussion highlights the need for improving the existing DFB theory by including the effect of turbulence and wall effects. Such improvements require extensive flow field measurements inside packed beds of large-size particulates. For this purpose, the use of anemometer for point measurement of velocity, as done traditionally, is not sufficient. Anemometric measurement techniques do not provide detailed information of the entire flow-field, moreover they are intrusive techniques, and the presence of the anemometer sensor in a

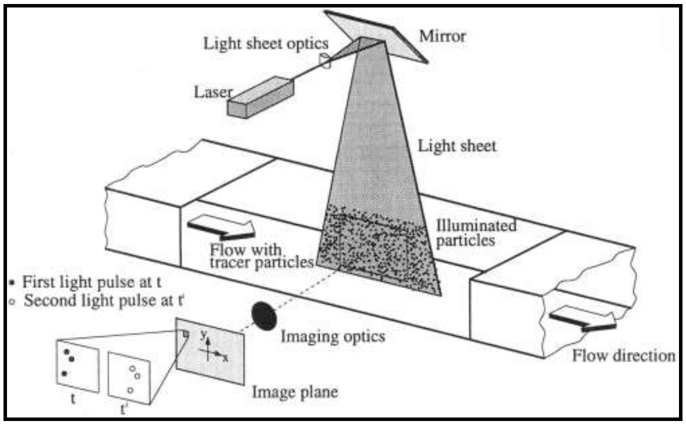


Fig 2a. PIV optical system

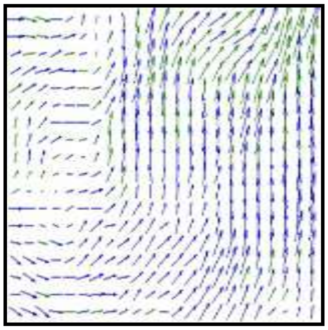


Fig 2b. Velocity field

constricted space may cause significant uncertainties in flow measurements. Hence in the proposed research, a newer non-intrusive optical technique, particle imaging velocimetry (PIV), will be used to study flow fields in packed beds.

1.3 Use of PIV to study airflow in packed beds

PIV is a non-intrusive, image-based, technique developed in the past ten years to determine fluid velocities in laboratory experiments (Adrian, 1991). PIV determines the flow fields over global domains by measuring the motion of small markers that are seeded in the flow. The location of the markers at various instants of time is recorded optically: the markers are illuminated by a pulsed sheet of laser light and the light is scattered by the particles into a photographic lens (Fig. 2a). The local velocities are determined based on the statistical correlation of the image subregions, and the vector field is obtained by repeating this process on a grid of such subregions (Fig. 2b). To perform a flow field study of a porous media using PIV, one must have an optical access to the flow (i.e. a transparent model of the solid object), and the refractive indices of the solid object and the working fluid must match perfectly to eliminate the refraction of the laser sheet as it passes through the system or any distortion of light scattered from the seeded particles (Hopking et al, 2000; Kelly et al, 2000).

While PIV technique is being extensively used in aerodynamics and biomechanics studies (Lim et al., 2001; Lieber et al. 2002), only one study was found in the literature where a particle imaging technique was applied to study the flow patterns in a food system (Zitoun, et al. 2001). The requirement of optical access to the flow has limited the application of PIV to complex flow paths, such as those commonly found in food systems. However, the recent availability of rapid prototyping techniques using transparent materials that are capable of withstanding the energy of the laser light overcomes this difficulty. Rapid prototyping techniques allow quick generation of replicate prototypes from computer files (Sun & Lal, 2002; Mironov et al. 2003). There are various rapid prototyping machines that use different materials to produce replicate parts. In particular, stereo-lithographic techniques can produce three-dimensional models in water-clear urethanes compatible with PIV analysis. Hopking et al (2000) and Kelly et al (2000) have used models devised using rapid prototyping for fluid flow studies in complex geometries such as to determine airflow in human nasal passages.

2. PRELIMINARY STUDIES:

During the last year, we have conducted a series of preliminary experiments to develop the proposed research protocol. Specific studies conducted for this purpose include the following.

2.1 **Cooling rates of packaged strawberries**: The overall problem of cooling of strawberries packaged in consumer packages in a master container were studied at three packing houses located in California. Temperature measurements of strawberries in consumer packages showed considerable non-uniformity (Anderson, 2004). The results indicated that differences in vent designs, arrangement of packages in master containers, and arrangement of master containers in pallets resulted in 20-40 % difference in 7/8th cooling time (Thompson et al, 1998). For example, top venting of packages resulted in 80 min cooling time as compared to 58 min for side vents. This study demonstrated that differences in cooling times occurred due to a complex interaction of various design factors. The location of vents, and vent area in master containers and consumer packages, were identified as major factors affecting the cooling rates and uniformity of cooling.

2.2 **Use of CFD to Predict Temperatures in Packaged Strawberries during Cooling**: To examine the applicability of computational fluid dynamics (CFD) to airflow in packages-in-a-master-container, we investigated two alternative packing arrangements (Fig 3a). Because of the limitations in the existing theory, airflow was simulated, using original Navier-Stokes equations, only through the air channels between the consumer packages in the master container. The results showed that in case of the traditional arrangement (Fig 3b), there is considerable heterogeneous airflow downstream (Plane B in Fig 3b). This non-uniform airflow may lead to uneven cooling of the product. A slightly modified arrangement of placing packages in the master container (Fig 3a) led to an improved and more homogenous downstream airflow distribution (Plane B in Fig 3c).

Traditional arrangement of clamshell packages in a master container

Modified arrangement of clamshells in a master container

Fig 3a Two arrangements of individual strawberry packages in a master container

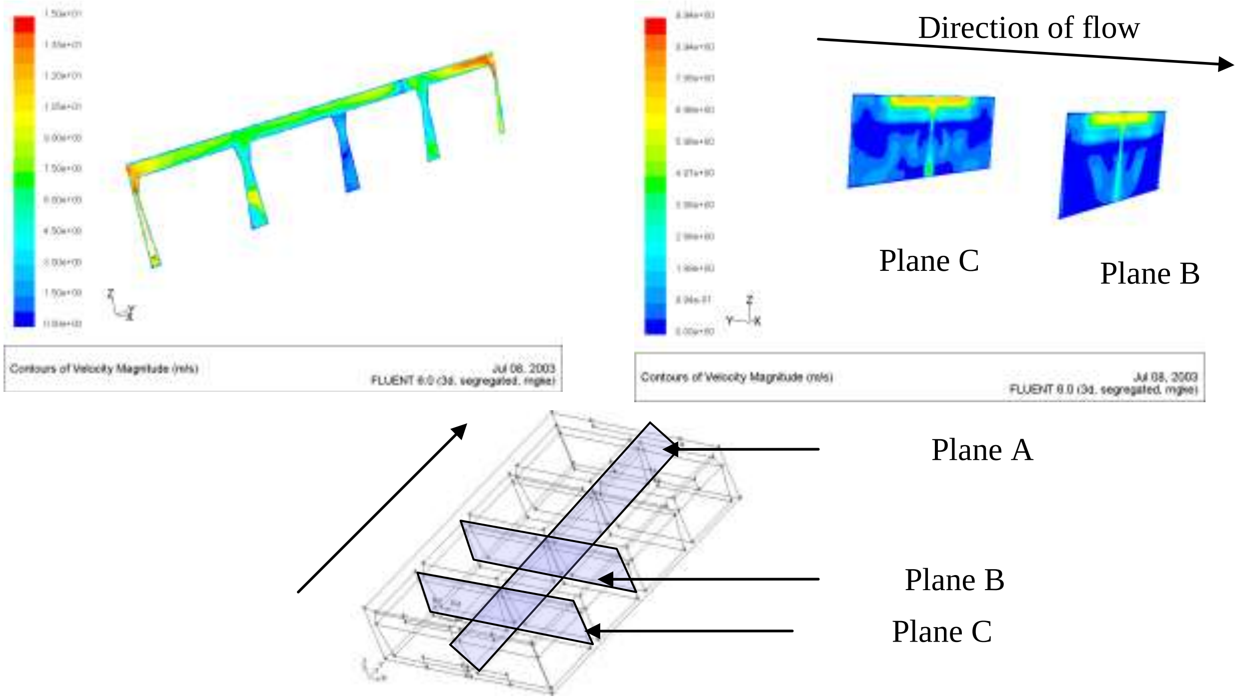


Fig 3b Airflow in traditional arrangement

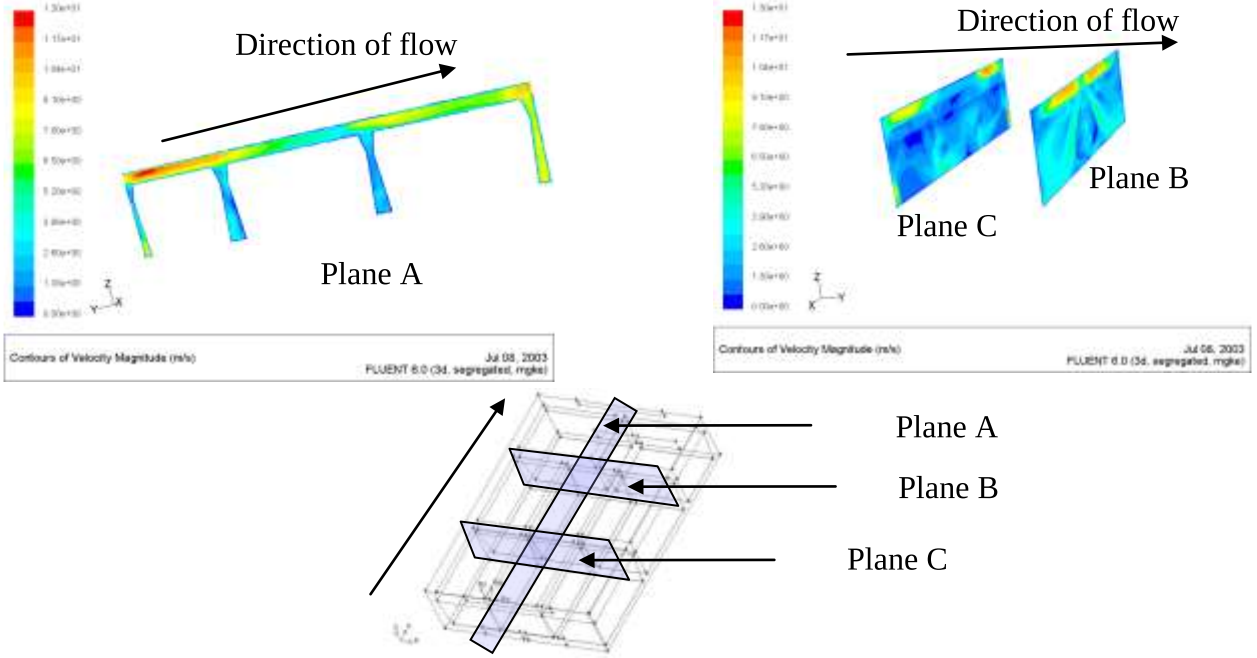
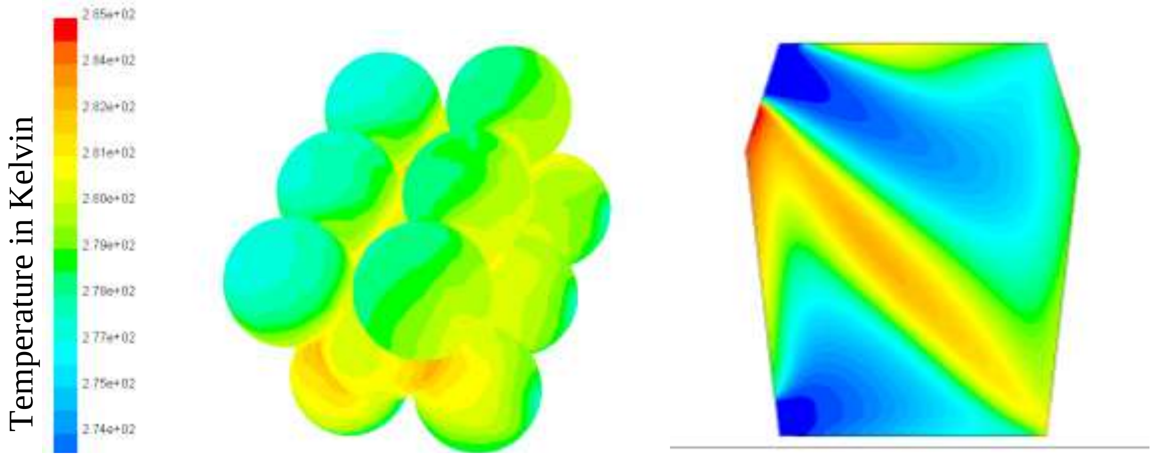


Fig 3c Airflow in modified arrangement

2.3 **Prediction of Temperature in strawberries in individual Clam-shell packages**: Simulations were conducted using CFD solver to examine the application of the current theory to predict temperatures within the consumer packages. Figure 4a shows temperature contours in a packed bed of strawberries (assumed as perfect spheres for simplicity) obtained by a complete solution of the original Navier-Stokes equations after



(a) **(b)**

Fig 4. Temperature contours in clamshell package of strawberries after 30 min of cooling, a) complete CFD analysis b) porous media approach with lumped heat transfer

30 min of cooling in an air stream at 0°C (273 K) from an initial temperature of 20°C. These contours are considered to be accurate representation since there are no assumptions used to simplify the original flow equations. But, these simulations require very long computation times (several days on a Pentium 4, 2.1GHz computer) and they become impractical when applied to packages-in-a-master-container. Figure 4b shows temperature profiles in a cross section of an individual package of strawberries obtained by using the existing DFB theory. The results on temperature distribution show considerable deviation from each other (Figs 4a and 4b). This discrepancy in results further demonstrates the need to modify and improve the existing DFB theory. These examples show the usefulness of numerical simulations to improve package designs. However, modifications of the theoretical basis must be carried out to develop an accurate numerical approach to predict temperature of packaged produce.

2.4 **Use of PIV to study flow field**: A preliminary trial was conducted with PIV equipment to study airflow around four spheres of different sizes (Fig. 5a) connected to each other in a series (similar to berry fruit in a package, but only for a single layer of fruits instead of multiple layers). As seen in Fig 5, PIV is a useful technique to determine velocity, turbulence intensity and vortex structures formed at various locations of the flow-field. The results show that along the direction of flow, turbulence increases at certain downstream locations while at others it decays in magnitude (Fig 5c). The results also indicate that the low turbulence at certain downstream location correspond to high rate of vortex dissipation (Fig. 5d). These types of complete flow field maps obtained using PIV are useful to study flow features to improve package parameters (such as vents), quantify viscous dissipation rates (μ_{eff}) which is directly related to turbulence intensity (Fig. 5c), and also to validate any simulated flow-field .

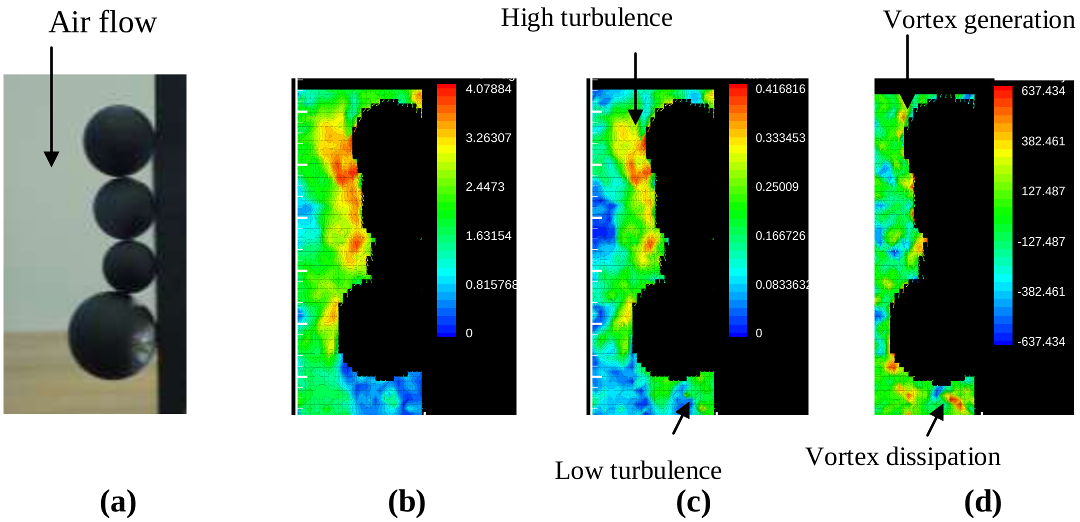


Fig 5 PIV measurements of flow-filed around an array of spherical geometries a) arrangement of spheres, b) velocity field, c) turbulence intensity field, d) vorticity field

2.5 **Transparent models for PIV applications**: To use PIV to study fluid flow in a packed bed, the physical set up must allow optical access to the flow field, and the index of refraction of the packed material must match perfectly with the refractive index of the fluid. Difference in refractive indices cause deviation in the path of light resulting in errors in measurement. Since gases have different orders of magnitude inrefractive index than solid, air cannot be used as the working fluid. Hence appropriate liquid-solid combinations must be selected that can replicate the interaction of the actual air/food system in the package. Birch and Dickinson (2003), and Kelly et al (2000), have shown that the flow field of an air/solid system may be simulated with a liquid/solid system, using similitude analysis, and appropriate matching of Reynolds number for the flow conditions. To achieve this objective, we have investigated which liquid/solid combination will be appropriate for our purpose. Various combinations of transparent solids and oils were examined as listed in Table 1. In addition to matching refractive indices, other important factors are viscosity and density of the liquid so that it can be easily pumped.

Table 1: Refractive index of solid-liquid system for PIV applications

Solid (refractive index @ 20°C)	Liquid (refractive index @ 20°C)	Pros and Cons
Silicone (1.430)	Glycerol / water ~ 60% (1.430)	Non-homogenous refractive properties of solid. High viscous liquid (10.7 cP), difficult to pump
Quartz glass (1.458)	Mineral oil (1.459)	Expensive material. High viscous liquid (11.0 cP), difficult to pump
Plexiglass (1.485)	Aniseed oil / Mineral oil 33.3 % (1.484)	Low cost material. Desired shapes are easily available in the market. Lower viscosity (6.8 cP).

2.6 **Void Space and Packing Structure**: Determination of effective diameter of the solid particulates packed in a bed, and the Reynolds number, requires a good understanding of

(a) (b) (c)

Fig 6 (a) and (b) A strawberry package filled with resin to determine the packaging structure. (c) Example of one-cm thick slice obtained from the solidified resin.

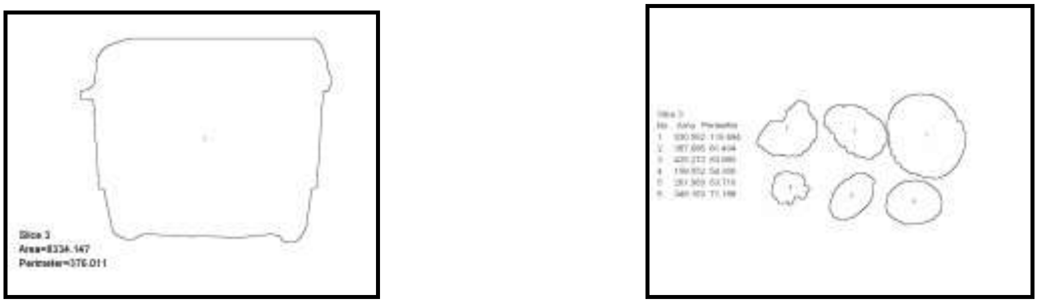


Fig 7 Area and perimeter obtained by image processing of slice shown in Fig 6c

the packing structure (void space and the wetted perimeter (Propster and Szekely, 1977). To characterize the void space inside a real package with strawberries, a resin was poured around strawberries inside a clam-shell package and allowed to solidify (Fig. 6 a and b). The solid matrix was then sectioned into one centimeter-thick slabs (Fig. 6 c). Upon removing the berry debris, the area of the open space and the wetted perimeter for each slab section was obtained using image analysis (Fig. 7). A ratio of the void space and wetted perimeter gave the effective diameter for each slice, and values from all slices were averaged to determine overall effective diameter (d_{eff}). Similarly, the porosity was obtained from the void space.

3. OBJECTIVES

To meet the overall goal of developing design guidelines for consumer packages in a master container that promote rapid and uniform cooling, the following objectives will be addressed.

1. Determine the growth and/or decay of turbulence and viscous dissipation factors for airflow in a packaging system using Particle Imaging Velocimetry (PIV).
2. Modify the Darcy-Forcheimer-Brinkman (DFB) equations with experimentally determined viscous dissipation factors to describe airflow in a packaging system.
3. Use the modified DFB equations to predict temperature of produce in consumer packages in a master container during forced air cooling.
4. Validate the mathematically predicted air velocity and product temperature using experimental trials with PIV equipment and temperature measurements.
5. Use the mathematical model (the modified DFB equations) to develop guidelines for designing packaging systems for rapid and uniform cooling, and create an Internet-assisted database of design guidelines for industrial practitioners.
6. Determine the economic effects of cooling packaging systems that meet the design criteria of rapid and uniform cooling.

4. RATIONALE AND SIGNIFICANCE

Preliminary studies conducted by the authors of this proposal demonstrate that cooling of berry fruit packed in consumer packages in a master container is highly dependent upon several design factors. They include the arrangement of packages in the master container, size and location of the vents in the consumer packages and the master container. Modifications are necessary in the existing DFB-type theoretical formulation to accurately simulate airflow through such packaging systems. Due to the complexity of the flow field, a non-intrusive flow measurement method such as Particle Imaging Velocimetry (PIV) should provide valuable information to improve the theoretical basis of fluid flow in packed beds. The modified theoretical formulation can be then numerically solved using CFD solvers and used to predict cooling of produce packed in consumer packages in a master container. More importantly, the proposed approach will provide scientifically-based predictive methods to design new generation of packaging systems that allow complete and rapid cooling. From a broader perspective, the proposed research will demonstrate the applicability of theoretical fluid mechanics and heat transfer in combination with the latest flow-field measurement techniques to problems that are atypical to food processing.

The commercial significance of this research is in the development of the design criteria for proper vent design in consumer packages and master containers. Buyers of packaging systems will no longer need to depend on expensive empirical testing of multitude of designs to determine which commercially available packaging system cools most effectively. The impact of the proposed study on the fresh produce industry is expected to be substantial considering that the U.S. strawberry sales alone amount to $1 billion annually.

The economic analysis will allow operators of cooling facilities to predict the real cost of cooling produce with various designs of packaging system. A user-friendly Internet-assisted database of design guidelines will be available to industrial practitioners who seek energy efficient packaging systems for cooling packaged produce.

5. APPROACH

The complexity of the fluid flow in packaging systems such as consumer packages in a master container requires that a systematic study be conducted to obtain data useful in modifying the existing theory of flow in porous media. For this purpose, Figure 8 shows a flow diagram of how the proposed objectives will be met using information obtained from experiments.

5.1. Flow field studies

Flow field studies in packages-in-a-master container system will be conducted using Particle Imaging Velocimetry (PIV) as follows.

5.1a Fabrication of transparent models of a berry-package system: For the initial set of trials with PIV, the berry fruit will be modeled using spheres. Spherical shape is chosen for two reasons, first, many berry fruits are of spherical shape, such as blueberries, cranberries, and some varieties of grapes; second, irregular shapes, such as strawberries, can be expressed in terms of equivalent spheres using an effective dimension. For a transparent model, our preliminary studies have indicated that plexiglass, as a solid material, and a mixture of aniseed and mineral oil is an ideal combination for PIV applications (Table 1). For solid objects, spheres of plexiglass will be obtained of different diameters (5 to 20 mm) to represent various sizes of berries.

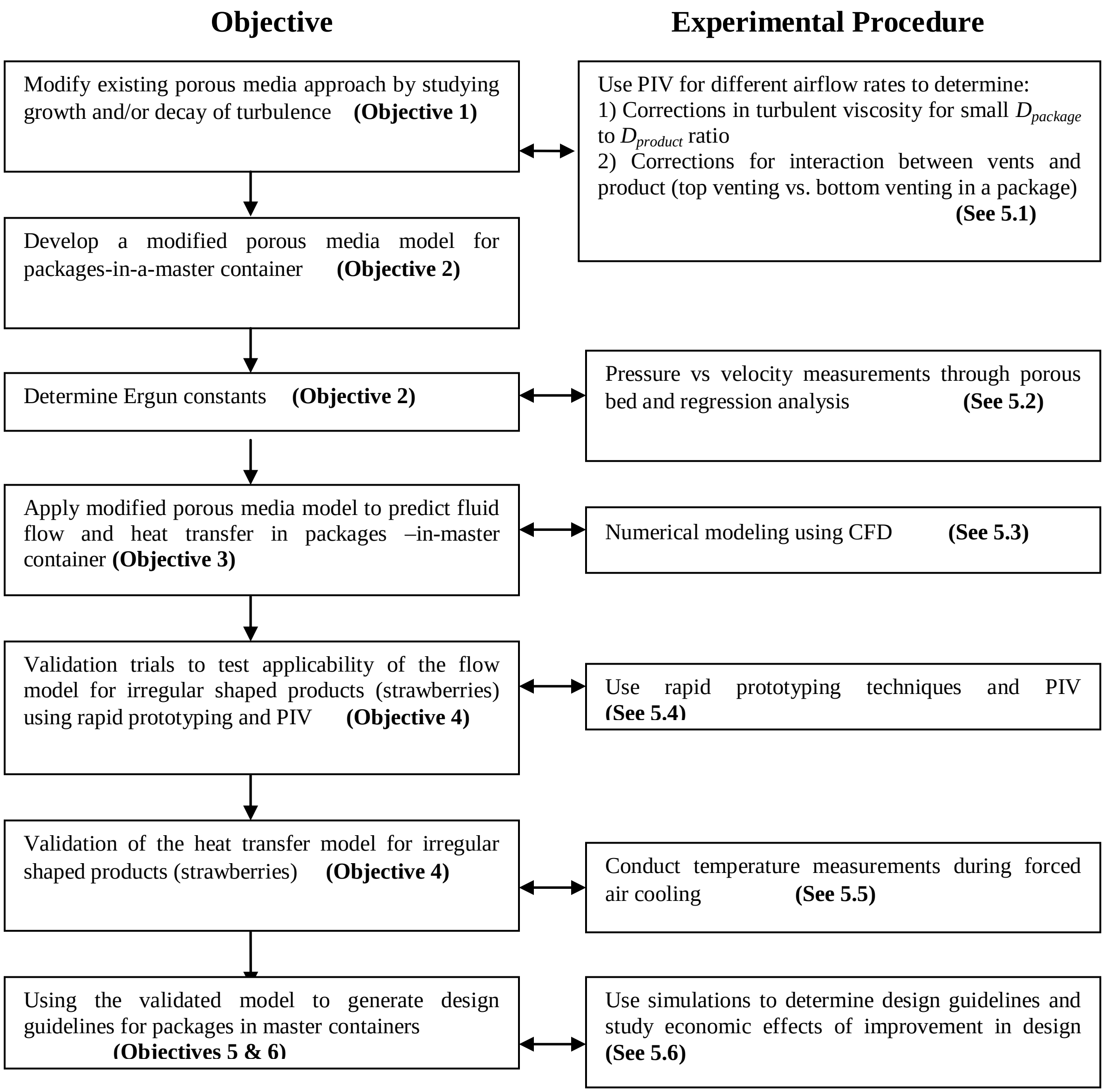


Fig. 8. A flow diagram of the experimental plan

5.1b Experimental setup for flow field studies: The experimental setup involving the transparent test model will include a pump, flow channel, pipe and fittings (Fig. 9). The test section viewed by the PIV will correspond to the dimension of a typical clam-shell package. This section will be a small part of a rectangular duct made of plexiglass (9 cm width x 9 cm high x 14 cm length) through which the working liquid (such as a mixture of aniseed and mineral oil) will be pumped. At the upstream of the duct, a honeycomb section will be used as a flow straightener. The upstream wall of the test section will have vent openings with selected area and location for each trial. A PIV measurement setup will be used to study the flow field in the test section.

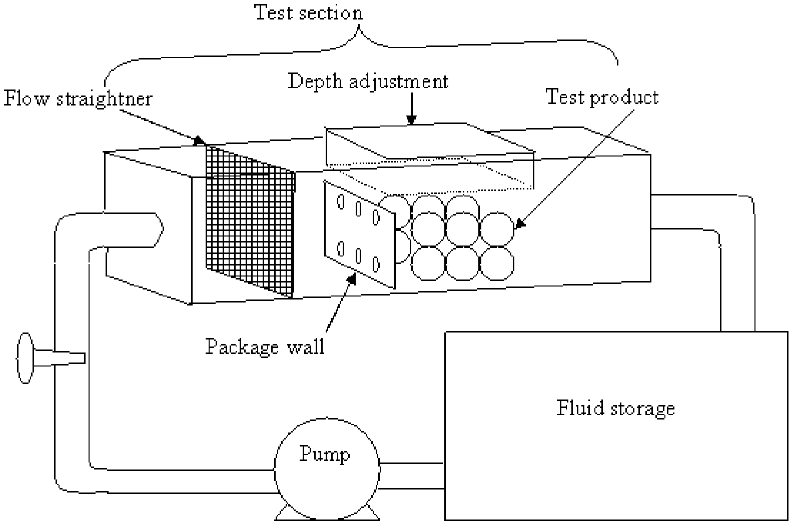


Fig. 9. Experimental setup for testing flow through packed material and package (not drawn to scale)

5.1c Experimental Trials: The influence on the effective viscosity of airflow rate, the $D_{package}/D_{product}$ ratio, and the percentage and distribution of vents in individual packages will be studied. Since typical airflow rates used for horticultural commodities are in the range from 0.0005-0.0020 $m^3s^{-1}kg^{-1}$ of product (0.5-2 ft^3/min-lb of product), the experiments will be designed for airflow rates of 0.0005, 0.001, 0.0015 and 0.0020 $m^3s^{-1}kg^{-1}$ of product, to determine flow characteristics. Corresponding flow rates of the working fluid will be determined, using similitude analysis, for same Reynolds' number.

The existing theoretical models for fluid flow and heat transfer simulations in packed beds are insufficient for applications of large-size agricultural commodities packaged in relative small-size containers ($D_{package} / D_{product} < 10$). Preliminary tests indicated that $D_{package} / D_{product}$ ratio for individual packages of strawberries and blueberries ranged from 2 to 3 and 4 to 6 respectively. New information about the turbulence and wall effects in packed beds with $D_{package} / D_{product} < 10$ is required. Although these effects have been considered in the previous DFB models by incorporating the value of the effective viscosity (μ_{eff}), until now this parameter has been assumed arbitrarily constant and there is a lack of experimental information regarding it. Our experiments will fill these gaps in the existing theory by determining the value of the effective viscosity as a function of position inside the packed bed for different air flow rates. This study will be done with packages containing large-size spheres (5 to 20 mm diameter). The experimental value of $\mu_{eff}(x,y,z)$ will be used as a parameter in the DFB equation (Eq. 1) and solved numerically to simulate airflow in consumer packages in a master container. The validity of this modified theoretical model, developed for spherical products, will be extended to non-spherical product such as strawberries by using equivalent dimensions.

The next step is to study the effect of vents in a packaging system on the flow through the porous media. Typical vent area of 10 % is common in commercial package designs. Very low venting area results in the obstruction of the flow while high venting area results in loss in structural integrity of the package and increased bruising of the product. Also important in the design of packages is the location of vents. High venting at the top of the package may result in

Table 2. Experimental plan to study effects of venting area and location

Trials	Total venting area (%)	Distribution of vent area	Location of vents and vent area (%)		
			Top third of package wall	Middle third of package wall	Bottom third of package wall
1	5	Higher top venting	3.33	0.83	0.83
2	5	Equal venting	1.67	1.67	1.67
3	5	Higher bottom venting	0.83	0.83	3.33
4	7.5	Higher top venting	5	1.25	1.25
5	7.5	Equal venting	2.5	2.5	2.5
6	7.5	Higher bottom venting	1.25	1.25	5
7	10	Higher top venting	6.67	1.67	1.67
8	10	Equal venting	3.33	3.33	3.33
9	10	Higher bottom venting	1.67	1.67	6.67
10	12.5	Higher top venting	8.33	2.08	2.08
11	12.5	Equal venting	4.17	4.17	4.17
12	12.5	Higher bottom venting	2.08	2.08	8.33

excessive air channelling through the package headspace while low venting at top and high venting at the bottom may be obstructed by the product resulting in low airflow through the package. Such design considerations can be ideally studied using numerical simulations with CFD as shown in the preliminary results (section 2.2). For these simulations to be accurate, there is a need to study the viscous effects in the entry region in an individual package with product in contact with the package wall. Therefore, a detailed study will be conducted to determine $\mu_{eff}(x,y,z)$ by studying the velocity patterns in packages for venting conditions using PIV as summarized in Table 2.

5.2 Determination of Ergun constants, effective diameter, and porosity

The next set of information required for simulating the flow field are the Ergun constants and other characteristics of the porous media. Ergun constants for various agricultural and non-agricultural commodities have been experimentally determined by several researchers (Ergun, 1952; Chau et al, 1983; Comiti and Renaud, 1989; Irvine et al, 1993). Ergun constants will be determined for one dimensional flow with no wall effects, entrance effects or other significant viscous effects. For a one-dimensional case, Eq. 1 reduces to

$$-\frac{dp}{dx} = \frac{\mu}{\kappa} u + \beta \rho u^2 \tag{9}$$

with Ergun constants earlier defined by Eqns (3) and (4)

K_1 and K_2 (in Eqs. 3 and 4) are the unknown Ergun constants; d_{eff} is the effective diameter and ε is the porosity of the medium. Thus, if in the experimental domain, the pressure gradient and superficial velocities are known, then the Ergun coefficients can be determined using a linear regression approach. To accomplish this, a custom built cooling tunnel will be used. The tunnel has a 45 cm x 45 cm cross-section and 100 cm length for flow. Airflow rate can be adjusted as described by Anderson et al (2004). Flow rate will be measured to determine the superficial velocity. Pressure will be measured using a manometer along the length of the flow at 40, 50, and 60 cm from the flow inlet at the geometric center of the cross section. This will prevent errors due to viscous effects at the entrance, exit and the walls. Calculation of Ergun constants also requires estimation of effective diameter (d_{eff}) and the porosity (ε) of the packed bed. As shown in the preliminary experiments (section 2.6), a resin will be used for this purpose. This approach will be used to determine porosity in packages containing strawberries and blueberries.

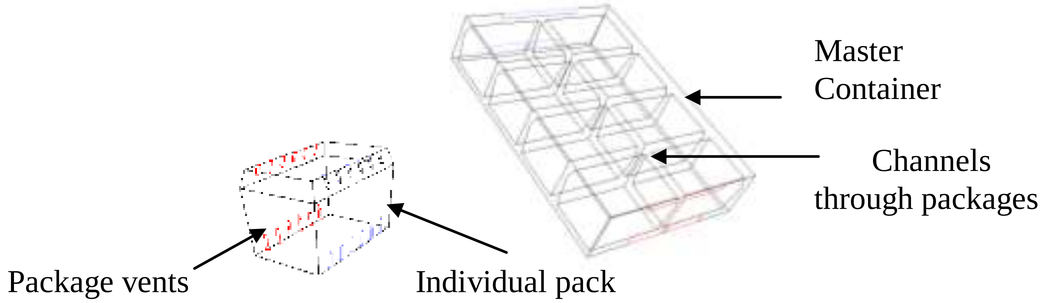


Fig. 10. Simulation geometry of consumer package of strawberries in a master container

5.3 Numerical modeling of flow and heat transfer using flow field results

The numerical modeling of the airflow, using CFD, will be based on the effective viscosity (μ_{eff}) determined for equivalent spheres. Validation trials will be conducted for both spherical shaped berries (blueberries) and irregular shaped berries (strawberries). The results of the experimental procedure will be used to simulate the test case of strawberries in consumer packages. Figure 10 shows a sample arrangement of packages-in-a-master-container. The airflow through the channels between the packages will be obtained using the solution of Navier Stokes equations with appropriate boundary conditions as was demonstrated in the preliminary trials (section 2.3). But, unlike the trials conducted in preliminary research, the proposed simulation will include studying airflow inside each individual package (Fig. 10). This will be accomplished using the DFB equation with modifications. The modifications will include incorporating μ_{eff} as a function of position inside the domain of the individual package and experimentally obtained Ergun constants. A steady-state solution of flow equation will be obtained. Thus, we will obtain the velocity profiles in the flow field. Using the velocity profiles, energy formulation of a porous medium will be solved. The solution of the energy equation will yield temperature profiles.

5.4 Validation of Numerical Results

5.4a. Flow Field Validation

For flow validation using PIV, the first step is to determine equivalent Reynolds numbers that may be used for liquid/solid combination. The effective diameter of a package of strawberries will be used to determine the Reynolds numbers for flow field calculations. From the equivalent Reynolds number, we will obtain the flow rate of a liquid transparent to the laser.

The second step is the fabrication of a transparent model to obtain geometrically accurate representation of the package containing strawberries. This will be done using rapid-prototyping (Kelly et al, 2000; Clinkenbeard et al 2002; Sun and Lal, 2002). For this purpose, we will use computed tomography (CT) to obtain two dimensional images at 2 mm thickness of the real package. The two dimensional model will be converted to a three-dimensional computer model using software compatible with the CT imager (Voxel Q). Once the three-dimensional computer model of the strawberry package is made, then a three-dimensional analogue is obtained using three dimensional printing technique (called rapid prototyping).

Appropriately chosen liquid (section 2.5) will be pumped with tracer particles through the transparent models of the strawberry packages at flow rates equivalent to 0.0005, 0.001, 0.0015 and 0.0020 m^3/s/kg of product. The flow field will be studied using PIV analysis of velocity fields inside the transparent model and compared to the simulated profiles generated by numerical simulations.

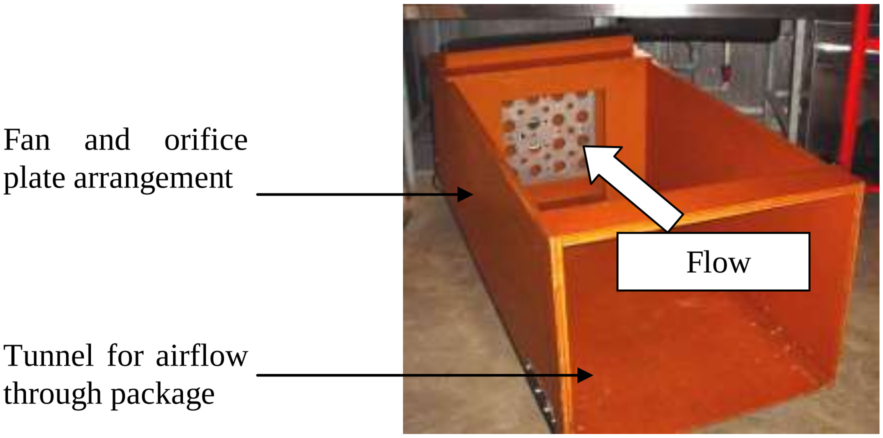


Fig. 11. Experimental arrangement for cooling experiments

5.4b. Heat transfer validation

After the flow field is validated, the predicted temperature of products in consumer packages will be validated using temperature measurements. The procedure for the heat transfer validation experiments will be similar to that followed by Anderson et al (2003). The experimental setup consists of a tunnel with a fan attachment at the end (Fig. 11). The flow rates are adjusted by using an orifice plate device. Packages containing produce, arranged in a master container, are placed in the tunnel for air flow through them. The initial product temperature will be at 20^{o}C and the product will be cooled in a controlled-temperature room with an air temperature of 0^{o}C. Temperatures inside the strawberries will be monitored using 16 T-type thermocouples placed inside strawberries at various locations in the package arrangement. Mass loss from the product during the experiment will be measured using load cells placed at the bottom of the packages during the experiment. Data will be acquired using a 32-bit data acquisition board and appropriate software. The experiments will be done at air flow rates of 0.0005, 0.001, 0.0015 and 0.0020 $m^3s^{-1}kg^{-1}$ of product, which correspond to flow rates used for flow-field validation experiments. The temperature profiles simulated by the CFD models will be compared to the experimentally determined temperature profiles. A potential pitfall of the proposed study may reside in the use of experimentally determined μ_{eff}. It may introduce oscillations in the numerical solution due to non-linearity. In that case, piecewise linearization of μ_{eff} will be used. The model, in that case, may not have universal application, but it will address specific products considered in this study (such as strawberries).

5.5. Application of the experimental results and validated numerical model

A validated numerical model of fluid flow and heat transfer will be used to conduct simulation of various combinations of packaging variables such as vent locations and vent areas. Temperature profiles in produce during cooling will be predicted. These results will be used to determine guidelines that will provide rapid and uniform cooling of packaged produce. The guidelines will include detailed information regarding cooling time, cooling variability, pressure required to facilitate desired flow, and velocities at the required pressure, for various levels of the following potential design variables:

- Percentage vent area in clamshells

- Vent area distribution in clamshells
- Percentage vent area in master container
- Vent area distribution for master container
- Various $D_{package}$ to $D_{product}$ ratios (corresponding to different products)
- Different tray arrangements in a master container
- Different master container arrangements in a pallet

A database of results on temperature profiles will be created for a comprehensive set of preceding design variables. The database will be set up on the Internet. Responses from selected industrial users will be solicited to improve its user friendliness.

5.6. Economic analysis

Capital (i.e., ownership) and operating costs will be determined for a representative range of existing forced-air cooling facilities. The range will include several new cooler designs and several older coolers that are being used in the strawberry industry. Capital cost data will be based on data from commercial cooperators and we will use several examples of typical seasonal fruit throughput to estimate maximum daily and seasonal cooling capacity. Energy use data will be based on several unpublished studies the PIs have done and engineering estimates of energy cost with differing cooling times. Analysis will be done for the range of electricity costs in California. Other cost data that will be evaluated include differences across cooling facilities, such as labor usage and wage rates, plus change-over costs necessary when a firm converts from an existing cooling facility and/or packaging type to one of those in the experimental design. The final results will show the economic value of cooling using well- versus poorly-designed packaging systems in the typical range of coolers and electricity costs found in California.

6. TIMELINE

September 1, 2004 –March 31, 2005: Use PIV to determine turbulence and viscous dissipation in consumer packages in master containers.

April 1, 2005 – August 31, 2005: Modify DFB equations with experimentally determined viscous dissipation factors appropriate for the complex packaging systems.

September 1, 2005 – March 31, 2006 Using CFD, develop numerical simulation to predict temperature in produce in packaging systems.

April 1, 2006 – August 31, 2006: Conduct validation trials of predicted heat transfer and fluid flow using PIV measurement. Conduct economic studies of cooling using improved design of packaging systems.

September 1, 2006 – March 31, 2007: Use numerical model (with modified DFB equations to develop guidelines for designing packaging systems. Continue economic studies of cooling using improved design of packaging systems

April 1, 2007 – August 31, 2007: Develop an Internet based database of design guidelines. Obtain input from industry practitioners and improve the user-friendliness of the database. Write final reports.

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FACILITIES AND EQUIPMENT

The following equipment and facilities for use in the project are available in the Principal Investigator's laboratory:

- Workshop for fabrication of simple models.
- Laser: LaserPulse™ Solo Mini Dual Nd:YAG laser, 50mJ/pulse, 15 Hz pulse rate, unified power supply. Camera: PowerView™ 2M Cross/Auto Correlation Digital CCD camera, 1660 x 1200 pixel resolution, 10 bit output, 30 frames/sec, laser protected CCD array, and high-performance digital camera interface (PCI bus). Software (for image capture and analysis): NSIGHT™ 5 Parallel Processing and integrated TecPlot data visualization software. The PIV system is set up in a protected area certified by the University of California Environmental Health and Safety, and all personnel using the equipment are required to attend safety classes.
- Thermo Haake Rheometer (RS 1) for fluid viscosity measurements.
- Fan device and controlled temperature rooms