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CONTEMPORARY CORRELATIONS FOR HEAT AND MOMENTUM TRANSFER IN IRRIGATED PACKED BEDS APPLIED TO THE DESIGN OF COOLING EQUIPMENT FOR HORTICULTURAL PRODUCE

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ABSTRACT

If it is to remain fresh, horticultural produce such as fruits and vegetables must be cooled as soon after harvest as possible. An effective way of achieving this is to spray chilled water through beds of the produce, after which the water is treated and re-cycled around the system. Designers need guidelines on the effects of design parameters such as the flow rate and temperature of the chilled water, the depth of the beds of produce and the size of the produce on the operation of cooling systems. This three-phase system remains somewhat mathematically intractable on the length scales of the inter-produce pores. Hence, contemporary correlations of heat and momentum transfer in the pores of packed beds have been used in conjunction with a model of conduction heat transfer within the individual pieces of produce. This gives rise to a 'semi-continuum' model. Parameters used in the analysis include the fraction of water within the bed of produce, the degree of wetting of the produce, the produce/water heat transfer coefficient, and an expression has been invoked for the thermal dispersion within the bed. The governing equations for each phase are formulated and a scaling analysis is used to simplify them. Results from the analysis suggest that the conventionally used flow rate of water, namely 10 kg/(m^2.s), appears to be technologically sound. At this flow rate the fraction of produce that is wetted exceeds 0.95, and the water/produce heat transfer coefficient is sufficiently high to not be the rate limiting step in cooling the produce. It is shown that the power consumption of hydrocoolers can be several hundred kilowatts, and that the chilled water must be recycled and treated to maintain its potability. These requirements provide opportunities for engineers to make contributions in an area usually dominated by biologists and chemists.

Key words
Hydrocooler, heat transfer, mass transfer, packed bed, porous.

NOMENCLATURE

a_i	[..]	Empirical constants in equation 7a
A	[1/m]	Surface area of produce per unit volume of bed.
b_i	[..]	Empirical constants in equation 7a
c	[J/(kg.˚C)]	Specific heat,
d_p	[m]	Diameter of individual item of produce.
dr_i	[m]	Incremental radius.
D	[W/(m.˚C)]	Thermal diffusivity
E_1,	[..]	Ergun coefficient
E_2	[..]	Ergun coefficient
f	[..]	Wetting efficiency
Ga_w	[..]	Liquid Galileo group, $Ga_w = gd_p^3\varepsilon^3\rho_w^2 \big/ \left((1-\varepsilon)^3 \mu_w^2\right)$
h	[W/(m^2.˚C)]	Heat transfer coefficient.
H	[..]	Hidden layer variables
k	[W/(m. ˚C)]	Thermal conductivity.
L	[m]	Characteristic length of bed.
Nu	[..]	Nusselt group, $Nu = h_w d_p / k$
r	[m]	Radial distance
R	[m]	Radius of produce, m
Re_w	[..]	Reynolds number, $Re_w = \rho_w u_w d_p \big/ \left((1-\varepsilon)\mu_w\right)$

S	[..]	Normalised output
$S(T_s)$	[W/kg]	Respiration source term.
t	[s]	Time
T	[˚C]	Temperature.
u	[m/s]	Darcian velocity.
$\langle u_w \rangle^w$	[m/s]	Intrinsic phase average velocity.
U	[..]	Normalised input group
x	[m]	Distance along the bed of produce.

Greek symbols

α	[m^2/s]	Thermal diffusivity
β_i	[..]	Functions in equation 11
δ	[m]	Thickness of film.
ε	[..]	Volume fraction
μ	[Pa.s]	Viscosity
ρ	[kg/m^3]	Density'
σ	[N/m]	Surface tension.
ϕ		Sphericity
ω_i		Connectivity weights
$\omega_{i,j}$		Connectivity weights

Subscripts

a	Refers to interstitial air
in	Entering the bed
initial	Initial temperature of the produce
s	Refers to the produce
w	Refers to water

INTRODUCTION

International and domestic markets for horticultural produce increasingly demand produce that is fresh and clean. Horticulturalists have to deal with the problem that fruits and vegetables continue to respire after they have been harvested and this leads to a loss of flavour and texture. As a general rule, the rate of respiration doubles for every 10ºC increase in temperature. The rate of respiration of broccoli is particularly sensitive to temperature and its shelf life at a temperature of 20°C is only 3 days, at 10ºC the shelf life is extended to 11 days whilst at 5ºC the shelf life is about 25 days. It is clear that if the quality of horticultural produce is to be preserved it must be cooled as soon after harvest as possible, particularly in warm climates. An effective method of achieving this is to spray the produce with chilled water, typically with a flow rate 30 litres per second per tonne of produce. The devices used to cool fruit and vegetables are known as hydrocoolers.

The consumption of fresh fruits and vegetables is good for people's health. As a result, health professionals and governments are exhorting the populace to consume more fresh produce. Abelson *et al.* [1] report that contaminated food causes about 5.4 million outbreaks per year of gastroenteritis in Australia, at a cost to the nation of about $1.25 billion per year. Abelson *et al*. [1] do not report the number of outbreaks of food poisoning attributed to fresh horticultural produce, but data [2] compiled by the New South Wales government indicate that about 10% of outbreaks of food poisoning arise from the consumption of fresh fruits and vegetables. Health authorities therefore insist that water used for cooling fruit and vegetables destined for consumption as fresh produce must be potable. It takes typically 15 minutes to cool horticultural produce, depending on the type of produce, the water consumption would be about 30,000 litres per tonne. In this era of increasingly scarce water it is important to minimise the use of water hence it is common practice to recirculate cooling water around hydrocoolers. The recycled water must be physically and chemically treated to ensure that it is potable when it is again sprayed onto the produce.

Postharvest technologists need tools that enable them to predict the effects of design and operating variables on the rate at which produce is cooled such as the height of the beds of produce, the effects of the flow rate and temperature of the cooling water and so on. The temperature of the produce at the bottom of a bed of produce is generally the last to be cooled, and it may be therefore under cooled. The problem of designing systems that use cool, humid air to cool produce is relatively simple because it involves only two phases, namely a gas and a solid. Modern computers allow one to resolve the physical phenomena that occur in such system on the length scales of the interstitial air between the individual pieces of produce, and within the produce itself. This is exemplified by the work of Verboven *et al*. [3] who have computed the velocity field of air flowing through randomly arranged spherical pieces of fruit.

Hydrocooling is somewhat more complicated because it involves three phases, namely a liquid, a solid and a gas. Water flows through the interstices between the individual pieces of produce, the solid phase, and air is likely also be entrapped in the interstices. It is possible, in principle, to use a volume of fluid approach to track the flow of water through the bed of produce and simultaneously calculate the rate of heat transfer between the produce and the cooling water. A fully three-dimensional system would have to be considered, and the range of length scales would be considerable because the film of cooling water would be small compared with the macroscopic system. A significant, and almost certainly prohibitive, amount of computing resources would be required for this method.

This paper reports how modern correlations of phenomena that occur in irrigated packed beds are used to estimate the behaviour of beds of produce being cooled. A model will be formulated that has been dubbed a semi-continuum model because the discrete nature of individual items of produce is retained, and the transient temperature distributions within them are calculated. However, it is assumed that the average temperature of a bed of produce varies continuously and that the discrete nature of the produce does not affect the average temperature profile on the length scale of the pieces of produce. To avoid the need to calculate the temperature distributions in three dimensions the surface temperature of each piece of produce is assumed to be uniform. Thorpe *et al*. [4] and Thorpe and Whitaker [5] indicate that these conditions must be satisfied if a bed of porous medium can be treated as a continuum. Spatial variations of quantities such as velocity and temperature that occur on the length scale of the thickness of the boundary layer are also averaged, and these averaged values are deemed to vary continuously along the length of the bed of produce. To close this semi-continuum model we require the usual rate coefficients such as the heat transfer coefficient between the cooling water and the surface of the produce. A thermal dispersion term also arises in the proposed model and methods of calculating the somewhat elusive values of this hydrodynamic property must be used.

Thorpe [6] has presented the equations that govern the performance of hydrocoolers. He shows that they comprise three partial differential energy conservation equations in the three phases – water, air and solid. A novelty of the present work is a length scale analysis invoked to reduce the model to two simultaneous equations. The equations are solved numerically and in this work convergence criteria are explored.

THE SYSTEM INVESTIGATED

The principal features of the hydrocooling system to be modelled are shown in Figure 1. Water with a temperature T_{in} ºC is sprayed onto the produce to be cooled at an area-specific flow rate of f_w kg/(s.m^2), and at the start of the cooling process the produce has a uniform temperature of $T_{s,initial}$. At a given distance, x, from the upper surface of the bed of produce the average temperatures of the surface of the produce, water and interstitial air are T_{sw}, T_w and T_a respectively, indicated in Figure 1. The heat transfer processes that must be considered are:

> Heat transfer by convection from the cooling water to the surface of the produce.
>
> Thermal conduction within the individual items of produce. Convective heat transfer between the cooling water and the interstitial air.

In addition to these heat transfer phenomena thermal energy is also dispersed as a result hydrodynamic dispersion. Water is contact with the produce has a velocity of zero, whilst water in the region of the free surfaces adjacent to the interstitial air has a finite velocity and heat is advected with this rapidly moving water. The net result is a smearing, or dispersion of heat, and it is governed by a typical dispersion term in the governing equations. A commercial hydrocooler in which refrigerated water is sprayed onto beds of horticultural produce is shown in Figure 2.

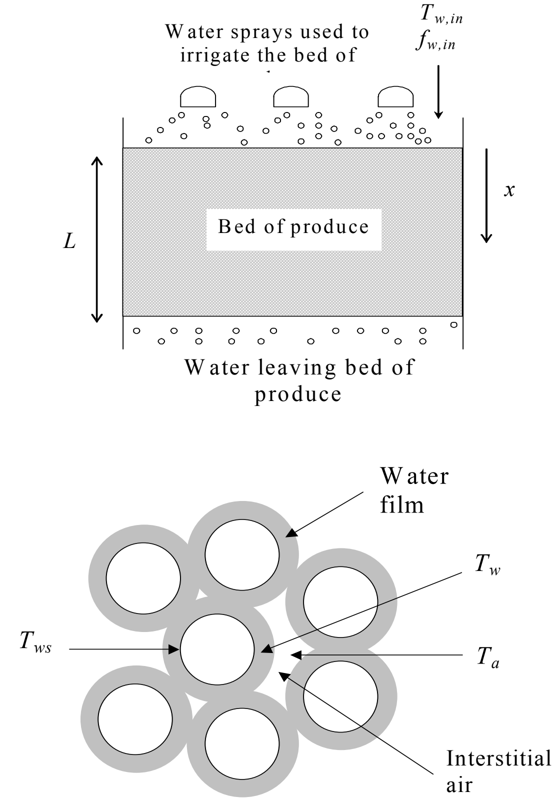

Figure 1. Water is sprayed onto beds of horticultural produce, and water films develop on the surface of the solids.

THE SYSTEM INVESTIGATED

Thermal energy balances

Water

A thermal energy balance on the cooling water flowing through the bed of produce can be written

$$\rho_w \varepsilon_w c_w \frac{\partial T_w}{\partial t} + \rho_w c_w u_w \frac{\partial T_w}{\partial x} = D_w \frac{\partial^2 T_w}{\partial x^2} + h_w A f \left(T_{sw} - T_w\right) + h_a A \left(1 - f\right)\left(T_a - T_w\right) \qquad (1)$$

where ρ_w (kg/m^3) and c_w (J/kg.ºC) are respectively the density and specific heat of water. The volume fraction of water in the bed of produce is ε_w, and u_w

(m/s) is the Darcian, superficial or phase average velocity of the water, defined as the volume flow rate of water divided by the cross-sectional area of the bed when it is not occupied by the produce. h_w (W/m^2.ºC) and h_a (W/m^2.ºC) are respectively the heat transfer coefficients between the water and the produce and the interstitial air and the produce. D_w (W/m.ºC) represents the thermal dispersion coefficient and A (1/m) is the surface area of the produce per unit volume of the bed of horticultural produce. The surface of the produce is not entirely wetted, and that fraction that is wetted is known as the wetting efficiency, f.

Interstitial air

It is likely that the mass flow rate of air through the bed of produce is negligible and limited to that entrained by the water used to spray the produce. However, since we are considering a three-phase system we must consider the presence of the air. The heat balance on the interstitial air is expressed as

$$\rho_a \varepsilon_a c_a \frac{\partial T_a}{\partial t} + \rho_a c_a u_a \frac{\partial T_a}{\partial x} = D_a \frac{\partial^2 T_a}{\partial x^2} + h_a A f \left(T_w - T_a\right) + h_a A\left(1 - f\right)\left(T_{sa} - T_a\right) \quad (2)$$

Figure 2. Refrigerated water being sprayed onto bed of horticultural produce in a commercial hydrocooler

where the subscripts suggest meanings analogous to those ascribed in the formulation of equation 1. T_{sa} is the surface temperature of the produce in contact with the interstitial air.

Heat transfer within the produce

Heat transfer is deemed to occur within the individual pieces of horticultural produce by the mechanism of thermal conduction. The pieces of produce are assumed to be spherical so that governing equation is

$$\rho_s c_s \frac{\partial T_s}{\partial t} = k_s \left(\frac{2}{r} \frac{\partial T_s}{\partial r} + \frac{\partial^2 T_s}{\partial r^2} \right) + \rho_s S\left(T_s\right) \quad (3)$$

where ρ_s (kg/m^3) and c_s (J/kg.ºC) are the density and specific heat of the horticultural produce respectively and k_s (W/(m.ºC)) is its thermal conductivity. The radial distance from the centre of the produce is signified by r (m). Equation 3 contains the source term $\rho_s S\left(T_s\right)$ (W/m^3) arising from the heat of respiration. It is a function of the of the local temperature within the produce T_s. The boundary conditions on equation 3 are

$$T_s = T_{sw} \text{ at } r = R \quad (4)$$

and

$$\frac{\partial T_s}{\partial r} = 0 \text{ at } r = 0 \quad (5)$$

where R is the radius of the produce.

PARAMETERS THAT AFFECT THE PERFORMANCE OF HYDROCOOLERS

Before equations 1, 2 and 3 can be solved we must evaluate parameters such as the liquid/solid and air/solid heat transfer coefficients, the bed-specific area, thermal dispersion coefficient and so on. The primary aim of hydrocooling is to reduce the temperature of horticultural produce and it is likely that the heat transfer coefficients are important in governing the overall rate of cooling. In this work we use the correlations presented by Larachi *et al*. [7] for the water/solid heat transfer coefficient; it is also shown that the rate of heat transfer between the produce and the interstitial air is negligible.

A secondary objective of hydrocooling is to reduce the concentration of pathogens on the surfaces of the produce. This is achieved by irrigating the produce with water that is not only cold, but which also contains a disinfectant such as bromochlorodimethylhydantoin that is efficacious over a wide range of pH. The disinfection is likely to be enhanced if a very high fraction of the surface area of the produce is wetted. An estimate of the wetting efficiency, f, is therefore a useful parameter in determining the operating conditions of a hydrocooler. As one might expect, the wetting efficiency also plays a role in calculating the average heat transfer coefficient between the produce and the water.

Traditionally, it is believed that some horticultural produce, such as strawberries, should not be cooled in a hydrocooler because they become wet and this gives rise to the growth of spoilage phytopathogens. Instead, it is usually recommended that fruit such as strawberries be air-cooled.

However, some evidence is emerging (Bliss, [8]) that disinfectant-containing water remaining in the interstices of pieces of fruit after they have been cooled may increase the shelf life of soft fruit. This is because the disinfectant offers some residual protection against spoilage organisms. It is therefore perhaps useful to be able to estimate the amount of water remaining after hydrocooling. One method of calculating this is to subtract the dynamic hold up of water from the total hold up. The latter quantity is envisaged as having two components, namely water that is static, or trapped, in the interstices between the individual pieces of produce and that water that is continuously being replaced by flowing water. This fraction of flowing water is known as the dynamic hold up. In practice, the distinction between static and dynamic hold up may be a little blurred because dispersive processes impact on all regions of the liquid. However, it can be argued that static hold up is closely related to the residual water that remains in a bed of porous media that has been irrigated and then drained. Thorpe (2006) demonstrates that for the bed of horticultural produce studied by him the difference between the total and dynamic hold ups is very similar to the static hold up précised by van der Merwe *et al*. [9].

Thermal dispersion in the liquid phase can be several orders of magnitude greater that thermal conductivity of water. Thermal dispersion is intimately related to the hydrodynamics of the flow over the solids and it results in thermal energy being smeared as the water flows through hydrocoolers. Kaviany [10] points out that our knowledge of two-phase flows through porous media is incomplete. He further remarks that our knowledge of thermal dispersion is *even* more inconclusive (Kaviany's emphasis). In this analysis we obtain an order of magnitude estimate of the thermal dispersion coefficient using a model of an idealised system proposed by Saez *et al*. [11].

The methods used to calculate the parameters that define the performance of hydrocoolers are described in the source materials cited in this paper, and they have been summarised by Thorpe [6].

The volume fraction, ε_w, of water in the bed of produce

Larachi *et al*. [12] present the following expression for the total liquid hold-up, ε_w, in an irrigated bed of porous medium

$$\varepsilon_w = (1-\varepsilon_s)\left(\frac{E_1 f^2}{\phi^2}\frac{\mathbf{Re}_w}{Ga_w} + \frac{E_2 f}{\phi}\frac{\mathbf{Re}_w^2}{Ga_w}\right)^{1/3} \qquad (6)$$

in which ε_s is the volume fraction of the bed of horticultural produce being cooled. E_1 and E_2 are the coefficients of the linear and quadratic terms in Ergun's [13] equation which are taken to be 150 and 1.75 respectively. Re_w and Ga_w are the water Reynolds and Galileo numbers respectively and they are defined in the Nomenclature. ϕ is the sphericity of the particles defined by Gan *et al*. [14] as the ratio of surface area of sphere having the same volume of object to the actual surface area of the object

.

The wetting efficiency, *f*

Larachi *et al.* [15] combined an Artificial Neural Network with dimensional analysis (ANN-DA) to obtain an expression for the wetting efficiency, *f*, in terms of five dimensionless groups. They are used to form six normalised input groups, U_i, thus

$$U_i = \mathbf{log}_{10}\left(a_i N_i^{bi}\right) \qquad i = 1,2,3,4,5. \qquad (7a)$$

$$U_6 = 1 \qquad (7b)$$

where N_i is the i^{th} dimensionless group and a_i and b_i are coefficients determined by fitting the model to experimental data. Hidden layer variables, H_j,, are expressed by

$$H_j = \frac{1}{1+\mathbf{exp}\left(-\sum_1^6 \omega_{ij} U_j\right)} \qquad j = 1,2,3,4,5,6,7. \quad (8a)$$

$$H_8 = 1 \qquad (8b)$$

The normalised output is obtained from the hidden layer by means of the function

$$S = \frac{1}{1+\mathbf{exp}\left(-\sum_1^8 \omega_j H_j\right)} \qquad (9)$$

Values of S enable the wetting efficiency, *f*, to be determined directly from the expression

$$f = 0.83S + 0.17 \qquad (10)$$

Larachi *et al*[12] demonstrate that the dynamic hold up in beds of irrigated produce can be determined using a correlation similar to that used to calculate the wetting efficiency.

The thermal dispersion coefficient

Saez *et al*. [11] present an analysis of thermal dispersion that is based on beds of porous media that have a simplified geometry, but that are amenable to rigorous analysis. The analysis results in the following closed form expression for the dispersion coefficient, D_w

$$D_w = \frac{Pe_w^2}{24}\varepsilon_a \varepsilon_w \left[\frac{37}{180} + \frac{5}{12}\varepsilon_a \varepsilon_w + \frac{\beta_1 - \beta_2}{\beta_3}\right] \qquad (11)$$

The Peclet number, Pe_w, is defined by

$$Pe_w = 6\varepsilon_w \delta_w \frac{\langle u_w \rangle^w}{\alpha_w} \quad (12)$$

and β_1, β_2 and β_3 are functions of the physical properties of the phases within the system and the operating conditions. $\langle u_w \rangle^w$ is the intrinsic phase average velocity of the water and it is the average velocity of water in a film of thickness δ_w flowing over the produce. The wetting phase fraction or saturation of the bed, ε_w, and the porosity, ε_a, can be calculated from the operating conditions, physical properties of the phases and the geometry of the bed using standard analyses such as that presented by Bird *et al*. [16].

Water/produce heat transfer coefficient

Heat transfer coefficients are presented in terms of surface averages that may be denoted as $\langle h_w \rangle_{sw}$. The surface over which the heat transfer is averaged is that of the entire item of produce and not only the wetted area thus

$$\langle h_w \rangle_{sw} = \frac{1}{A} \int_{(1-f)A} h_w dA \quad (23)$$

in which A is the surface area of the produce in a representative volume of bed, and h_w is the point heat transfer coefficient between the liquid water and the produce.

We shall show later that the terms involving heat transfer and thermal dispersion in the intergranular air are negligible.

Larachi *et al*. [7] has developed a correlation for the heat transfer coefficient $\langle h_w \rangle_{sw}$ that is based on an analysis of 1259 published data points. The method is analogous to that used to calculate the wetting efficiency, f, and dynamic hold-up, h_d. The Nusselt number, Nu, is obtained from an output parameter, S, by means of the following expression

$$Nu = 10^{(3.4849S + \log_{10}(0.43495))} \equiv 0.43495 \times 10^{3.4849S} \quad (24)$$

From the definition of Nusselt number

$$\langle h_w \rangle_{sw} = \frac{k_w}{d_p} Nu \quad (25)$$

Bed-specific area of the produce

The bed-specific area, A, of the horticultural produce is defined as the area of the produce per unit volume of bed, i.e.

$$A = \frac{\text{Area of produce in the bed}}{\text{Volume of the bed}} \quad (26)$$

Heat of respiration

In this exploration of the performance of hydrocoolers a specific horticultural product is not studied, but it is important that we incorporate in the heat conservation equations 3 a realistic function, $S(T_s)$, that accounts for heat of respiration. An equation presented by de Castro *et al*. [17] that describes the respiration of broccoli has been used because broccoli respires quite vigorously hence the model will capture the effects of respiration if they are important. The expression for $S(T_s)$ is

$$S(T_s) = 0.087 \exp(0.1197 T_s) \quad (32)$$

in which the units of $S(T_s)$ are W/kg.

Model reduction

The heat capacitance of the interstitial air is likely to be negligible compared with that of the cooling water and horticultural produce, one consequence of which is that that the term $h_a A(1-f)(T_a - T_w)$ in the heat balance equation 1 is likely to be negligibly small compared with the other terms. If this is the case only two equations need to be solved, namely 1 and 3, and the temperature of the interstitial air, T_a, is not involved. To demonstrate that equation 2 has negligible influence on the analysis we adopt the following reasoning:

Show that the interstitial air approaches thermal equilibrium with the produce and cooling water in a time that is negligibly small compared with the duration of the overall cooling process.

Show that the rate of heat transfer between the interstitial air and the cooling water and produce are of the same order of magnitude.

Demonstrate that the surface of the produce, the air and cooling water approach thermal equilibrium in a time much less than the duration of the overall cooling process.

Use the above results to show that the terms in the thermal energy balance on the air, equation 2, are negligible compared with the corresponding terms in the thermal energy balance on the cooling water and can be ignored.

Much of this analysis hinges on the fact that heat transfer processes in beds of porous media such as horticultural produce occur on several length scales. In the case of broccoli, for example we have the length scale of the florets, that of the stems and the length scale of the box or crate of produce. In the generic horticultural produce studied in this work the two length scales of interest are that of the individual pieces of produce, d_p, and that of the bed of produce, L. To an order of magnitude we have the following relationship

$$h_a \approx \frac{k_a}{d_p/2} \tag{33}$$

where the factor ½ arises because the average distance over which heat flows in the interstices is $d_p/2$, and a bed-specific area, A, is given by

$$A = \frac{6(1-\varepsilon)}{d_p} \approx \frac{3.6}{d_p} \tag{34}$$

The temperature of the interstitial air typically changes from its initial value, i.e. the initial temperature of the produce, $T_{s,initial}$, to a temperature close to that of the water entering the cooler, $T_{w,in}$, so that during the cooling process the temperature change, ΔT_a of the interstitial air can be approximated by

$$\Delta T_a \approx T_{s,initial} - T_{w,in} \tag{35}$$

and since $f > 1 - f$ we can make the order of magnitude approximation, at least during the initial period of cooling

$$h_a A f(T_w - T_a) + h_a A(1-f)(T_{sa} - T_a) \approx h_a A f \Delta T_a \tag{36}$$

along with

$$\frac{\partial T_a}{\partial x} \approx \frac{\Delta T_a}{L} \tag{37a}$$

$$\frac{\partial^2 T_a}{\partial x^2} \approx \frac{\Delta T_a}{L^2} \tag{37b}$$

and

$$\frac{\partial T_a}{\partial t} \approx \frac{\Delta T_a}{\Delta t} \tag{37c}$$

in which Δt is the time associated with the heat transfer process. Using these approximations we can express equation 2 as

$$\rho_a \varepsilon_a c_a \frac{\Delta T_a}{\Delta t} + \rho_a c_a u_a \frac{\Delta T_a}{L} = k_a \frac{\Delta T_a}{L^2} + h_a A \Delta T_a \tag{38}$$

The velocity of air through the bed is very low, probably less than 0.001 m/s, and because the bed is almost stagnant with respect to air the thermal diffusivity, D_a, has reduced to the thermal conductivity, k_a. Making use of equations 33 and 34 to approximate $h_a A$ in equation 38 results in

$$\rho_a \varepsilon_a c_a \frac{\Delta T_a}{\Delta t} + \rho_a c_a u_a \frac{\Delta T_a}{L} = k_a \frac{\Delta T_a}{L^2} + \frac{7.2 k_a}{d_p^2} \Delta T_a \tag{39}$$

Making use of the following approximations

$\rho_a \approx 1$; $\varepsilon \approx 0.4$; $u_a \approx 0.001$; $c_a \approx 1000$; $L \approx 1$; $k_a \approx 0.025$; $d_p \approx 0.025$

we find that

$$\rho_a c_a u_a \frac{\Delta T_a}{L} << \frac{7.2 k_a}{d_p^2} \Delta T_a \tag{40}$$

And

$$k_a \frac{\Delta T_a}{L^2} << \frac{7.2 k_a}{d_p^2} \Delta T_a \tag{41}$$

which means that the advection and dispersion terms are negligibly small. Equation 2 can now be expressed as

$$\frac{\partial T_a}{\partial t} = \frac{h_a A}{\rho_a \varepsilon_a c_a}\left(fT_w + (1-f)T_{sa} - T_a\right) \approx \frac{7.2 k_a}{\rho_a \varepsilon_a c_a d_p^2}\left(fT_w + (1-f)T_{sa} - T_a\right) \tag{42}$$

As an order of magnitude estimate we have

$$\frac{\partial T_a}{\partial t} = O\left(\frac{3.6 \times 2 \times 0.025}{1 \times 0.4 \times 1000 \times 0.05^2} \times \left(fT_w + (1-f)T_{sa} - T_a\right)\right) = O\left(0.18\left(fT_w + (1-f)T_{sa} - T_a\right)\right) \tag{43}$$

The implication of this order of magnitude estimate is that the interstitial air approaches a steady-state after about 1/0.18 ~ 10 seconds (to an order of magnitude) which is much less than the total time of operation of hydrocoolers hence thermal equilibrium may be assumed between the produce and the air. When the steady state has been approached $\partial T_a / \partial t = 0$ and we see from equation 43 that

$$T_a = fT_w + (1-f)T_{sa} \tag{44}$$

We shall now use this equation to compare the magnitudes of the terms $h_a Af(T_w - T_a)$ and $h_a A(1-f)(T_{sa} - T_a)$ with the result

$$\begin{aligned} h_a Af(T_w - T_a) &= h_a Af(T_w - fT_w - (1-f)T_{sa}) \\ &= h_a Af(1-f)(T_w - T_{sa}) \end{aligned} \tag{45}$$

$$\begin{aligned} &h_a A(1-f)(T_{sa} - T_a) \\ &\quad = h_a A(1-f)(T_{sa} - fT_w - (1-f)T_{sa}) \\ &\quad = h_a Af(1-f)(T_w - T_{sa}) \end{aligned} \tag{46}$$

i.e. the two terms are equal in magnitude. We now wish to demonstrate that when a quasi-steady state exists between the horticultural produce and the interstitial air we can write $T_a \approx T_w \approx T_{sa}$. This is achieved by noting that the wetting efficiency, *f*, is typically greater than 0.9 hence the distance between two irrigated regions of the produce is typically $0.1d_p$. Since the rate of cooling of an object by conduction increases with the inverse square of its linear dimensions it follows that the region of produce between rivulets of cooling water are likely to cool about two orders of magnitude more quickly than the piece of produce as a whole. As a consequence we expect that the temperature of the entire surface to approach the temperature of the water. We can therefore write

$$\frac{\partial T_a}{\partial t} \approx \frac{\partial T_w}{\partial t} \tag{47a}$$

$$\frac{\partial T_a}{\partial x} \approx \frac{\partial T_w}{\partial x} \tag{47b}$$

$$\frac{\partial^2 T_a}{\partial x^2} \approx \frac{\partial^2 T_w}{\partial x^2} \tag{47c}$$

Equations 45 to 47 enable us to re-write equation 2 as the following approximation

$$\begin{aligned} &h_a Af(T_w - T_a) \\ &\quad \approx \rho_a \varepsilon_a c_a \frac{\partial T_w}{\partial t} + \rho_a c_a u_a \frac{\partial T_w}{\partial x} - D_a \frac{\partial^2 T_w}{\partial x^2} \end{aligned} \tag{48}$$

Substituting this equation into the thermal energy balance on the water, equation 1, we obtain

$$\begin{aligned} &(\rho_w \varepsilon_w c_w + \rho_a \varepsilon_a c_a)\frac{\partial T_w}{\partial t} \\ &\quad + (\rho_w c_w u_w + \rho_a c_a u_a)\frac{\partial T_w}{\partial x} \\ &\quad = (D_w + D_a)\frac{\partial^2 T_w}{\partial x^2} + h_w Af(T_{sw} - T_w) \end{aligned} \tag{49}$$

which does not contain the temperature of the air, T_a, as a variable. Since

$$\rho_w \varepsilon_w c_w >> \rho_a \varepsilon_a c_a \tag{50a}$$

$$\rho_w c_w u_w >> \rho_a c_a u_a \tag{50b}$$

$$D_w >> D_a \tag{50c}$$

it follows that the thermal energy balance on the cooling water, equation 1, reduces to

$$\begin{aligned} &\rho_w \varepsilon_w c_w \frac{\partial T_w}{\partial t} + \rho_w c_w u_w \frac{\partial T_w}{\partial x} \\ &\quad = D_w \frac{\partial^2 T_w}{\partial x^2} + h_w Af(T_{sw} - T_w) \end{aligned} \tag{51}$$

which is the desired result.

Mass weighted average temperature

Thorpe [6] avers that the mass weighted average temperature, $\langle T_s \rangle^s$, is the preferred measure of the degree of cooling of horticultural produce. In the case of a spherical piece of produce $\langle T_s \rangle^s$ is defined as

$$\langle T_s \rangle^s = \frac{\int_0^R 4\pi r^2 T_s dr}{4\pi R^3/3} \tag{64}$$

SOLUTION PROCEDURE

The temperature profile of the water as it flows through the bed of produce and the temperature distributions within individual items of produce are calculated numerically as detailed by Thorpe [6]. Essentially, the bed is divided longitudinally into discrete elements and the items of produce were also discretised and the thermal energy equation 3 was solved explicitly. It was possible to render the node spacing within the produce non-uniform by defining the distance between successive node radii by

$$dr_i = v dr_{i-1} \tag{65}$$

in which dr_i and dr_{i-1} are the differences in radii of the i^{th} and $(i-1)^{th}$ nodes within the produce, and v is a constant ratio taken in this work to be less than or equal to unity. Convergence studies show that 21 nodes within the produce with $v = 0.9$ and a time step of 0.2 seconds results in a normalised error of the centre temperature of 0.0044 compared with a fully converged solution that occurs when there are 41 nodes and the time step is 0.00625 seconds. The temperature of the cooling water leaving the hydrocooler operating under conditions typical of those used in industry is quite insensitive the to number of nodes in the longitudinal direction. For example, as the number of nodes increases from 6, 11, 21 to 41 the exit temperature increased from 1.8586 ºC, 1.8596 ºC, 1.8600 ºC to 1.8601 ºC respectively. In this study 11 nodes were used.

Physical properties of the produce and water

The physical properties of the water and produce are deemed to be constant and their values have been estimated at a temperature of 5ºC. No specific horticultural produce is modelled in this work but its properties are calculated from a composite of a number of products. Their values are presented along with t heir appropriate sources in Table I and in some cases the values have been interpolated from values at temperatures other than 5ºC.

FACTORS THAT AFFECT THE PERFORMANCE OF HYDROCOOLERS

In this work we examine how some of the less technological, or more fundamental characteristics of the operation of hydrocoolers are affected by the operating conditions. The following conditions were set:

Temperature of the water	2.5ºC
Initial temperature of the produce	25ºC
Diameter of the produce	25mm
Depth of the bed of produce	0.5m

The flow rate of water in the hydrocooler shown in Figure 2 is about 10 kg of water/(m^2.s) which is a typical flow rate employed in commercially available hydrocoolers. This operating condition has been arrived at by trial and error, but the work presented in this paper shows that there may be sound underlying reasons for this choice. Suppose we wish to cool the produce to a temperature of 5°C. If we consider the effects of the flow rate of water on the rate at which the produce cools we can observe from Figure 3 that there are diminishing returns measured in terms of the time to cool the produce as the flow rate of water increases. From a commercial point of view it is important to maximise throughput of produce and it can be seen that if the flow rate of water is 2 kg/(m^2.s) it takes about 11 minutes for the produce to cool, doubling the flow rate to 4 kg/(m^2.s) reduces the cooling time to about 7.5 minutes and a further doubling results in a cooling time of about 5.5 minutes, a reduction of about 2 minutes. When the water flow rate is increased to 16 kg/(m^2.s) the cooling time is about 4.25 minutes. It is possible that a specific flow rate of 10 kg of water/(m^2.s) is close to an optimum that accounts for capital cost of the pumps, pipe size and running cost, but this conjecture needs further study.

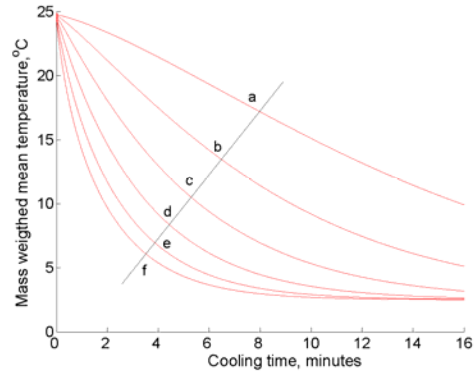

Figure 3 The mass weighted temperature of the produce at flow rates of a) 0.5 kg/(m^2.s), b) 1.0 kg/(m^2.s), c) 2.0 kg/(m^2.s), d) 4.0 kg/(m^2.s), e) 8 kg/(m^2.s), f) 16.0 kg/(m^2.s).

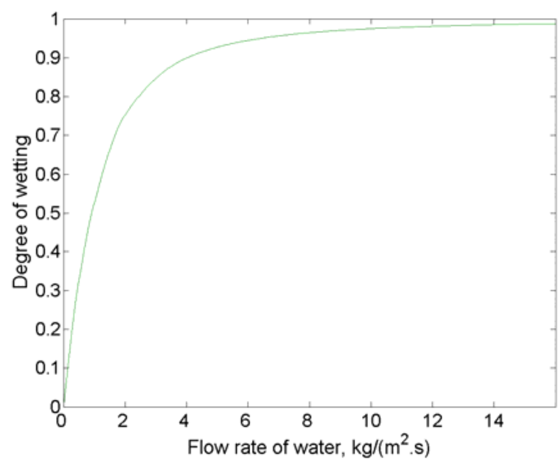

Figure 4. The variation of the degree of wetting with the specific mass flow rate of cooling water.

It has been noted that a high wetting ratio is deemed to be beneficial because it helps to ensure that the surfaces of the produce come into contact with disinfected water. The predicted degree of wetting is shown as a function of the flow rate of water in Figure 4. Again it is seen again that the degree of wetting increases by a relatively small amount when the flow rate exceeds about 10 kg/(m^2.s), which is very similar to the value used in practice. The total hold-up of water, which perhaps has a relatively small impact on the overall

Table I. Physical properties of materials used to explore some of the phenomena that occur in hydrocoolers

Property	Value	Source
Thermal conductivity of produce, k_s	0.595 W/(m.ºC)	Sweat [18]
Thermal conductivity of water, k_w	0.577 W/(m.ºC)	Moran and Shapiro [19]
Specific heat of produce, c_s	4,200 J/(kg.ºC)	Food Science Australia [2]
Specific heat of water, c_w	1,000 J/(kg.ºC)	Wark and Richards, [20]
Density of produce, ρ_s	1,000 kg/m^3	Nahor et al. [21]
Density of water, ρ_w	1,000 kg/m^3	Çengel and Boles [22]
Density of air, ρ_a	1.27 kg/m^3	Ideal gas law
Surface tension of water, σ	0.075	Munson et al. [23]
Viscosity of water, μ_w	17.4×10^{-6} Pa.s	Coulson and Richardson [14]
Viscosity of air, μ_a	1.52×10^{-2} Pa.s	Bird, Stewart and Lightfoot [16]

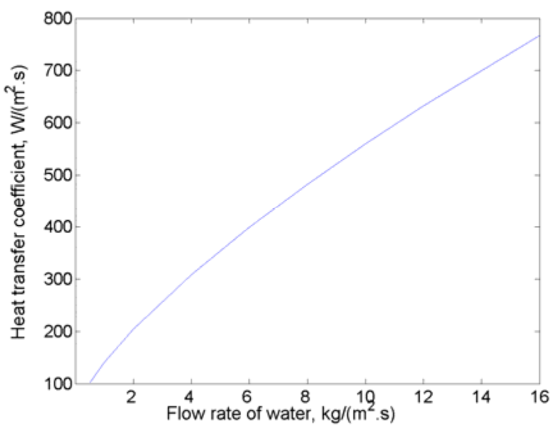

Figure 5. Variation of the heat transfer coefficient between the cooling water and produce with the flow rate of water.

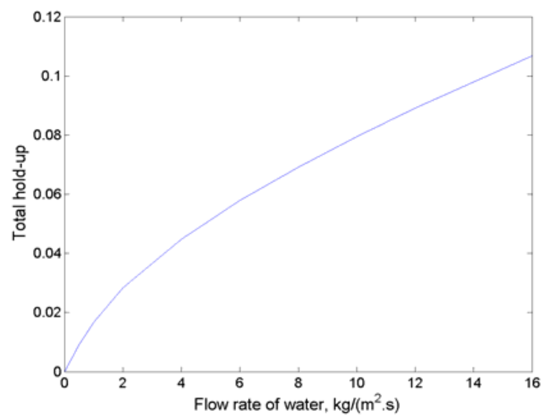

Figure 6. The variation of total hold up of water with the specific mass flow rate of cooling water

performance of hydrocoolers, increases with the mass flow rate of water, as can be observed from Figure 6.

Figure 5 shows the estimated variation of the water/solid heat transfer coefficient within the bed of produce. As expected the heat transfer coefficient increases with increasing flow rate of water. Although the Biot number (Bi = $\langle h_w \rangle_{sw} R/k$) is about 10, numerical experiments indicate that, *ceteris paribus*, the value of the heat transfer coefficient nonetheless has an influence on the rate of cooling of the produce. In addition, the rate of cooling depends on the mean temperature driving force between the water and the produce. The mean temperature driving force increases with the flow rate of water. These two factors, increases in the heat transfer coefficient and the temperature driving force, result in a higher flow rate of water leading to an increase in the overall rate of cooling. Under the conditions studies their influences are more or less equal.

Power requirements to cool produce

Thorpe [6] has shown that the cooling capacity of a hydrocooler can be increased simply by stacking more boxes under the water distribution system. This effectively increases the depth of the beds of horticultural produce but it does not significantly increase the amount of plumbing required. Thorpe [6] estimated that the times to cool produce at the outlet of the hydrocooler to a target of 5ºC takes 5 minutes, 5.5 minutes and 6.5 minutes as the depth of the produce increases from 0.25 m, though 0.5 m to 1 m. This appears very attractive, but it must be realised that the refrigeration capacity must be increased almost proportionally to the depth of the stacks. For example, if the bins have an area of 2m^2 and it is assumed it takes five minutes to load and unload the bins then the cooling capacities are:

To cool a box filled to a depth of 0.25 m: 42kW
To cool a box filled to a depth of 0.50 m: 77kW
To cool a box filled to a depth of 1.00 m: 146kW

Apart from the relative increases in power requirements, absolute values of the cooling power consumption are quite high, particularly for hydrocoolers installed on remote properties that may not have access to mains power supplies. This issue is dealt with by powering water chilling units with transportable diesel-driven electricity generators, recalling also that the coefficient of performance of refrigeration sets is usually two or more. The high power consumption can also be ameliorated by cooling significant quantities of water during periods when the hydrocoolers are not in operation, usually overnight. Phase change materials might also offer the possibility of reducing the peak cooling loads by having their enthalpies considerably reduced overnight, say. These problems, combined with the need to filter and disinfect water recirculated around hydrocoolers, offer many engineering opportunities in an area usually dominated by biologists and agriculturalist.

CONCLUSIONS

Horticultural produce must be cooled as soon after harvest as possible if its freshness is to be preserved. One method of achieving this is to irrigate beds of the produce with chilled water in a process that shares some features of trickle bed reactors. Such systems are known as hydrocoolers. In this work the differential equations that govern these three phase systems have been formulated, and a scaling analysis has been used to show that the equation that governs energy transport in the gas phase is of negligible importance. The equations contain rate parameters such as the water/solid heat transfer coefficient and thermal dispersivity. These parameters may be obtained from contemporary correlations published in the engineering literature and they are used to elucidate factors that affect the performance of hydrocoolers.

The flow rate of water in hydrocoolers is typically 10 kg/(m^2.s), and the analysis presented in this work confirms that this is technologically appropriate. For example, it is shown that the wetting efficiency at this flow rate is over 0.95 which ensures that a high proportion of the produce is irrigated with disinfectant-laden water. The heat transfer coefficient between the chilled water and the produce is shown to increase with increasing flow rate of water. However, there are diminishing returns from increasing the flow rate of water because the rate of heat transfer becomes limited by the intra-particle thermal conduction. Again, this work indicates that 10 kg/(m^2.s) may be technologically a good compromise design flow rate.

Water and energy usage in hydrocoolers is minimised by recycling the chilled water. The recycled water must be potable hence it must be filtered and disinfected in some way, and peak energy usage reduced. These features provide opportunities for applying modern engineering science in an area that is often dominated by biologists and chemists.

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