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Fluid Mechanics of Agricultural Systems

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3.1 Introduction

Agriculture is the production of food and goods through farming and forestry. In the beginning of the twenty-first century, one-third of the world’s workers were employed in agriculture. Nevertheless, agricultural production accounts for less than 5% of the gross world product (Wikipedia, 2010). Since its beginning, roughly 10,000 years ago, agriculture was significantly developed. In particular, during the industrial revolution, which took place from the eighteenth to the nineteenth century, major changes were taking place in agriculture as well as in other fields of life.

Agricultural production is usually classified into two categories: extensive and intensive. Extensive agriculture is crop cultivation using small amounts of labor and capital in relation to the area of land being farmed. The crop yield in extensive agriculture depends primarily on the natural fertility of the soil, the terrain, the climate, and the availability of water. On the other hand, intensive agriculture is associated with high inputs of capital, labor, and technology. The ultimate goal of intensive agriculture is to increase yield (quantity and quality) relative to the farmed land area in an attempt to meet the increasing demand of the growing world population.

One example of intensive agriculture is protected cultivation which became highly popular in agricultural production in the past decades. Here crops are cultivated in some kind of protected environment, usually a greenhouse, screenhouse, or a horizontal shading screen. These structures aim at protecting the crop from external hazards while allowing meticulous supply of resources for optimal production.

Plants need light, water, and carbon dioxide for photosynthesis and carbohydrate production. Besides, optimal production will be achieved by plants under specific conditions of air temperature and humidity. The greenhouse is one of the most sophisticated facilities for agricultural production. Its walls and roof are made of impermeable transparent material like glass or plastic which allows the penetration of radiation to the crop. Due to its relatively high isolation from the outside, climate control is possible and implemented in many greenhouses. Thus, conditions for optimal crop production may be achieved. The screenhouse is a structure which covers the whole plantation or orchard with a porous screen extending over the roof and the sidewalls. The screenhouse protects the crop from invasion of insects, high wind speeds, and supra-optimal solar radiation, usually allowing sufficient ventilation. Screens of different hole sizes and colors have different protection capabilities. Thus, screenhouses may provide passive climate control. Horizontal shading screens deployed over plantations mainly provide wind and radiation protection of the crops. With open sidewalls, much higher ventilation rates are realized and protection level is lower than screenhouses and greenhouses.

In greenhouses, light penetrates through the transparent cover and water is supplied by the irrigation system. However, to supply sufficient CO₂ for photosynthesis, greenhouses are usually ventilated by exchanging the inside air with external fresh air at a certain rate. Ventilation also removes excess moisture.
which may cause certain plant diseases and deteriorate production. Ventilation may be natural, in which case the driving force for airflow is either external wind or buoyancy due to temperature differences between inside and outside. Ventilation may also be forced through the use of mechanical fans which usually suck inside air outside. To keep the inside environment at certain ranges of temperature and humidity, more sophisticated climate control systems are also employed in greenhouses. These may include cooling/heating, humidifying/dehumidifying, and lighting/shading systems.

For ventilation purposes greenhouses are usually equipped with windows. The size and duration of windows openings are controllable and depend on the outside climatic conditions and crop requirements. To avoid the penetration of insects into ventilated greenhouses, openings are usually equipped with insect-proof screens. These screens have very tiny holes with a size smaller than the size of the anticipated insect. While these screens are efficient in insect exclusion, they inhibit air flow through the opening thus impeding ventilation and affect microclimate (Teitel, 2001). Therefore, knowledge of the properties of flow through openings with and without screens is essential for a proper design of greenhouse ventilation systems.

In recent years, the area of cultivation under screen constructions is steadily increasing mainly in Israel, some Mediterranean countries, and around the world. Major purposes for cultivation under screens are shading from supra-optimal solar radiation, improving the thermal climate (e.g., for frost protection), exclusion of insects (with insect-proof screens, Tanny et al., 2003), changing the solar spectrum for induction of light-mediated processes (e.g., use of colored screens), providing shelter from wind and hail, and saving of irrigation water. The use of insect-proof screen houses is expanding rapidly because of the increasing demand for produce grown with reduced use of pesticides and the relatively low costs associated with screenhouses compared to fully climate-controlled greenhouses.

In screenhouses, the passive climate control is determined by the screen properties, that is, the screen material, the shape and size of holes, the screen color, and the shading level. In these structures, both sidewalls and roof are covered with a screen. For common horizontal winds over flat terrains, flow through screens will prevail across the screenhouse sidewalls, whereas over the roof the flow will be along the screen (Tanny and Cohen, 2003, Tanny et al., 2009). Hence, these two configurations were studied in past years.

Obviously, the analysis of microclimate, ventilation, or heat and mass exchange is involved with a variety of fluid mechanics principles. Therefore, in this chapter we will review several topics related to fluid mechanics in greenhouse, screenhouse, and shading screen systems. In particular, we will discuss greenhouse natural and forced ventilation, screenhouse ventilation, and flow through and along screens. The chapter will not cover all the relevant literature on these issues. Instead, it will present and highlight certain topics which, according to the view of this author, nicely demonstrate how fluid mechanics principles can be employed for better analysis and design of agricultural systems.

### 3.2 Greenhouse and Screenhouse Ventilation

#### 3.2.1 General

Greenhouse ventilation may be either natural or forced. Natural ventilation, which may be defined as ventilation driven by the natural forces of wind and temperature, is a reliable, low-maintenance and energy-efficient method to keep temperature, humidity, and CO₂ concentration inside greenhouses within suitable limits for optimal crop production. The main attraction of natural ventilation is that the airflow within the greenhouse is driven by two naturally occurring forces, namely, the buoyancy force and the wind force. The buoyancy force, also known as the “stack” or “chimney” effect, results from temperature differences between the internal and external environment; warm, less dense air rises and flows out through openings at high levels and draws cooler ambient air in through openings at lower levels. Wind-driven flow through a building depends on the locations and sizes of the openings and may enhance or hinder the stack-driven flow depending upon the wind speed and direction. The disadvantage of natural ventilation is its dependence on natural resources, the availability of which is not always predictable. Also, in certain climates natural ventilation may not be sufficient to induce optimal conditions for crop production, and more sophisticated approaches of climate control are required.

Forced ventilation is generated by operating mechanical fans that suck the air out of the greenhouse, induce small negative internal pressure which causes the inflow of external fresh air. Forced ventilation is controllable in terms of flow rates, operation time and duration, and locations of inlets and outlets. The design of a forced ventilation system should also take into account the drag induced by the canopy elements (stems and leaves) on the airflow through the greenhouse. In many situations in hot and arid climates, forced ventilation is combined with evaporative cooling, supplied either by a wet pad or a fogging system. Wet pads introduce additional airflow resistance and should be taken into account in the design of a forced ventilation system.

#### 3.2.2 Greenhouse Natural Ventilation

Systems for greenhouse natural ventilation consist of openings which can be closed or opened. Greenhouses are usually equipped with either roof openings or side openings or both (Figure 3.1).

An important parameter in greenhouse design is the ventilation rate, \( G \) (m³ s⁻¹). In naturally ventilated greenhouses, ventilation may be driven by buoyancy and wind. The ventilation rate can be determined either through an energy balance analysis of the greenhouse, or by application of the Bernoulli equation. For a greenhouse equipped with side and roof openings, natural ventilation is governed by the displacement ventilation mode (Linden, 1999) where outflow of less dense air occurs through high-level openings and inflow of external denser air takes place.
through low-level openings. For this situation, the ventilation rate is (Katsoulas et al., 2006)

$$G = C_d \left( 2 \frac{\Delta T_{w0}}{T_w} h \right) + \left( \frac{A_r}{2} \right) C_w u^2$$  \hspace{1cm} (3.1)

When only roof openings are opened, the governing ventilation mode is mixing ventilation. In this case, exchange flow between inside and outside takes place through a single upper opening. For greenhouses equipped with roof openings only, the ventilation rate is (Katsoulas et al., 2006)

$$G = \frac{A_T}{2} C_d \left( 2 \frac{\Delta T_{w0}}{T_w} \frac{h}{4} \right) + C_w u^2$$  \hspace{1cm} (3.2)

In Equations 3.1 and 3.2, $A_R$, $A_S$, $A_T$ are the roof, sides, and total openings’ surface area (m$^2$), $g$ is the gravitational acceleration (m s$^{-2}$), $u$ is the outside wind speed (m s$^{-1}$), $C_d$ is the discharge coefficient of the openings, $C_w$ is the wind effect coefficient, $\Delta T_{w0}$ is the temperature difference between inside and outside (K), $T_o$ is the outside air temperature (K), and $h$ is the vertical distance between the midpoints of side and roof openings (m) in Equation 3.1 and half of the vertical height of the roof opening in Equation 3.2.

The buoyancy effect would be significant in greenhouses equipped with roof and side openings (e.g., Figure 3.1) because of the relatively large vertical distance between openings. In this situation, displacement ventilation would prevail. If only roof or side openings are employed, this effect will be relatively small since the mixing ventilation mode would be dominant and exchange flow will take place through a single opening. In the latter case with an upper opening, relatively high-turbulence intensities were observed in the shear layer between the inflow and outflow (Tanny et al., 2008), which may decrease the ventilation efficiency.

Wind-induced ventilation is driven by the pressure field developed around the structure. The ventilation rate would depend on the wind and structure properties and the interrelation between them. For example (Hunt and Linden, 2004), openings located at a high level on the windward side of the greenhouse and at low level on the leeward side allow a wind-driven flow from high to low level, opposite to the buoyancy-driven flow. In such a case, the wind and buoyancy-driven ventilation flows will oppose each other and ventilation would be insufficient. Hence, proper orientation of the greenhouse openings is required such that both natural ventilation modes would assist each other. Therefore, commonly, greenhouses are positioned such that high-level openings are leeward and low-level openings are windward, relative to the prevailing wind direction at the site.

Many studies investigated natural ventilation of greenhouses in an attempt to characterize the different ventilation modes under a variety of operating conditions and greenhouse structure configurations. One question of interest is the relative dominance of the wind and stack effects. Kittas et al. (1997) investigated an experimental greenhouse in southern France and have demonstrated that the wind effect predominates on the stack effect for $u' / \sqrt{\Delta T_{w0}} > 1$. For low wind velocities and under typical temperature differences in this study (~5 K), the roof and side ventilation system became more efficient than roof openings only for low wind velocities (<2.5 m s$^{-1}$). Kittas et al. (1997) have also tested the ventilation models (Equations 3.1 and 3.2) and by fitting measured and modeled ventilation rates obtained $C_d \sqrt{C_w} = 0.2 \pm 0.01$. Boulard et al. (1997a) obtained $C_d \sqrt{C_w} = 0.18$ for a greenhouse with roof openings only, and Teitel and Tanny (1999) reported on $C_d \sqrt{C_w} = 0.11$ also for a roof ventilated greenhouse. The different value obtained in the latter study as compared to earlier literature was explained mainly by different greenhouse configuration and differences in the wind directions relative to the greenhouse openings.

Apart from the overall ventilation rate, research was focused on the detailed flow patterns within and through the openings of naturally ventilated greenhouses. This information is of practical importance in identifying regions that are less ventilated within a large greenhouse, which may cause nonuniform production and even damage to the crop.

Boulard et al. (1996) applied the eddy correlation technique to determine the heat flux through greenhouse roof openings. They deployed a one-axis ultrasonic anemometer and a fine-wire thermocouple at the plane of the vent and measured air velocity and temperature at a frequency of 5 Hz. Moving the system along the 32 m long vent allowed them to identify separate regions of inflow and outflow through the same vent and to verify their measurements by mass balance closure. Boulard et al. (1996) also compared values of $C_d \sqrt{C_w}$ using measured mean and turbulent mass fluxes through the openings and those obtained by ventilation measurements using the tracer gas technique in the same greenhouse. They obtained good agreement between the two approaches over a wide range of wind speeds. Using a
three-axis ultrasonic anemometer, Boulard et al. (1997b) have demonstrated that external wind blowing in parallel to a long roof opening gave rise to inflow at the downwind end of the vent and outflow at the windward end. Within the greenhouse, the air followed a spiral flow pattern.

Teitel and Tanny (2005) studied the effect of external wind direction, relative to the greenhouse, on the flow patterns through continuous vertical roof openings. Using sonic anemometers, they measured simultaneously mean and turbulent flow at the two edges of a roof opening. When the wind was not perpendicular to the plane of the openings, there was outflow and inflow at the windward and leeward edges of the openings, respectively (Figure 3.2). However, when the wind was blowing from the back of the openings and nearly perpendicular to the plane of the openings, the mean air velocity through the openings was reduced but the turbulent component was almost unchanged.

Shilo et al. (2004) extended earlier eddy correlation measurements by applying simultaneous high-frequency humidity measurements at the openings using a Krypton hygrometer. This allowed them to measure both sensible and latent heat fluxes through the openings. In addition to the air mass balance, they analyzed the energy balance from which they determined the ventilation rate. For a semi-commercial greenhouse equipped with roof openings covered with insect-proof screens, good agreement was obtained between ventilation rates measured by the tracer gas technique and those deduced from the energy balance. Internal flow patterns measurements showed that under conditions of leeward ventilation (i.e., roof openings facing the leeward direction) the direction of air velocity at plant level was opposite to that of the external wind.

A more recent advancement in the study of greenhouse ventilation is the use of CFD (computational fluid dynamics) for such systems. This can assist in greenhouse design for optimal ventilation depending on external climatic conditions. The effect of ventilation configuration of a tunnel greenhouse with crop on airflow and temperature patterns was numerically investigated by Bartzanas et al. (2004) using a commercial CFD code. The numerical model was first validated against experimental data with good qualitative and quantitative agreement between the numerical results and the experimental measurements. Then, the CFD model was used to study the consequences of four different ventilator configurations on the natural ventilation system. An interesting finding of the simulations was that while the mean air temperature at the middle of the tunnels varied from 28.2°C to 29.8°C, for an outside air temperature of 28°C, there were regions inside the tunnels 6°C warmer than outside air. An example of velocity contours in one of the configurations studied by Bartzanas et al. (2004) is given in Figure 3.3.

Boulard and Wang (2002) utilized a commercial CFD package (CFD2000) to predict the heterogeneity of plant transpiration in a tunnel greenhouse lettuce crop. The crop was simulated as a porous medium (using the Darcy–Forshheimer equation) exchanging latent and sensible heats with its environment. The radiative and convective heterogeneity in two vertical sections of the tunnel predicted by the CFD model was validated against the experimental results obtained by several solar radiation sensors and sonic anemometers. The validated model was finally used to predict the transpiration flux of a mature lettuce crop in the tunnel. The predicted crop transpiration was in close agreement with the measured value. It was demonstrated that the crop transpiration strongly varied with the location in the tunnel. Specifically, they showed that crop transpiration was lower by about 30% on the northern side of the greenhouse due to lower solar radiation reaching the plants at this region. Such analyses have important implications in the management of greenhouse crops and demonstrate the usefulness in using CFD tools.

3.2.3 Greenhouse Forced Ventilation

If the natural ventilation system is unable to provide the required inside climatic conditions, forced ventilation systems are applied. These include exhaust fans, usually installed at one side wall with inlet openings at the opposite wall. In warm-arid climates, wet pads, installed at the inlet sidewall, or fogging systems are used to cool down the greenhouse air through evaporative cooling.

**FIGURE 3.2** Air velocity, normalized with respect to external wind speed, through two edges of a greenhouse roof opening as a function of external wind azimuth. Openings spanned 32 m along the north–south direction with their plane facing the east. Azimuth of 270° indicates wind perpendicular to the opening plane. Positive values of velocity indicate outflow and vice versa; solid line—the southern edge of roof opening; dashed line—the northern edge of roof opening. (From Teitel, M. and Tanny, J., *Flow Turbul. Combust.*, 74(1), 24, 2005, Figure 3c. With permission.)

**FIGURE 3.3** Computed contours of the air velocities of a tunnel greenhouse with side openings only. Tunnel width (from left to right) is 8 m. Tunnel length (perpendicular to the page) is 20 m. (From Bartzanas, T. et al., *Biosyst. Eng.*, 88(4), 479, 2004, Figure 5. With permission.)
In forced ventilation systems, the airflow along the greenhouse crop may generate horizontal gradients in temperature, humidity, and CO₂ concentrations, which induce non-uniform climatic conditions inside the greenhouse. Such gradients were modeled and measured by Kittas et al. (2003) who reported a temperature gradient of up to 8°C along the 60 m distance from pads to fans. Along with the measurements, Kittas et al. (2003) developed a model based on the energy balance of the greenhouse. Components affecting the temperature distribution along the greenhouse crop were: ventilation rate, crop transpiration, percentage of shading (of the downstream half of the greenhouse), water evaporation from the pad, and heat-loss coefficient of the greenhouse cover. Sensitivity analysis showed that increasing the ventilation rate, that is, fan flow rate, and shading the downstream half of the greenhouse contributed to a smaller horizontal temperature gradient.

Vertical temperature distributions were studied experimentally and using a numerical thermal model by Li and Willits (2008a, b). Measurements were conducted in a fan-ventilated greenhouse equipped with cooling pads that could be turned on or off. Vertical temperature profiles were measured by five thermocouple and relative humidity sensors installed at five levels above the ground. Air velocities were measured by a hand-held anemometer, at 55 sampling points and at three cross sections. In their study, Li and Willits (2008a) distinguished between mean canopy velocity, that is, air velocity within the canopy, and greenhouse mean velocity which is the mean of all measurements at the three cross sections.

Figure 3.4 shows the ratio of mean canopy velocity to mean greenhouse velocity, as a function of the ratio of canopy frontal area to greenhouse cross-section area. An interesting finding of this figure is that with relatively small plants ($A_c/A = 0.2$) and lower ventilation rate, the canopy velocity was higher than mean greenhouse velocity. Li and Willits (2008a) explained that this was possibly because at low ventilation rates, higher velocities were recorded near the ground since the cooler airstream from outside tended to slide along the ground due to its higher density relative to the warmer inside air. Thermal stratification (defined as the temperature difference between top and bottom temperatures) within the fan-ventilated greenhouse was found by Li and Willits (2008a) to increase with increasing solar radiation and when the wet pad was operating. The stratification decreased with increased ventilation rate and due to the presence of plants, as compared to an empty greenhouse. Li and Willits (2008b) developed a theoretical thermal model which essentially verified the experimental observations of temperature stratification in the greenhouse.

### 3.2.4 Natural Ventilation of Screenhouses

Unlike greenhouses, screenhouses do not have definite openings. Instead, the whole structure is covered by a porous screen, through which air can flow in and out at various locations. Forced ventilation of screenhouses is therefore impractical and natural ventilation is the only feasible ventilation mechanism.

Tanny et al. (2003) conducted a field study in a commercial fine mesh screenhouse in which pepper was grown. Screenhouses of this type use high mesh screens to mechanically exclude insect penetration and thus avoid potential fruits diseases. Simultaneously, however, these screens inhibit ventilation due to the small holes and high resistance to airflow. Hence, it is of importance to study ventilation rate and microclimatic properties of such screenhouses. Tanny et al. (2003) utilized water vapor as a tracer and applied two physical principles, namely, the flux-gradient ratio and mass conservation of water vapor to estimate the air exchange rate through the screenhouse. The resulting measured air exchange rate increased linearly with the external wind speed (Figure 3.5) and was in good agreement

![FIGURE 3.4 Ratio of canopy velocity to mean velocity ($u_c/u_m$) as a function of the ratio of canopy area to greenhouse cross-section area ($A_c/A$) for two ventilation rates (LV = 0.041 m² m⁻² s⁻¹; HV = 0.087 m³ m⁻² s⁻¹). The second-order polynomial curves were fitted from three data points. (From Li, S. and Willits, D.H., Trans. ASABE, 51(4), 1443, 2008a, Figure 3. With permission.)](image)

![FIGURE 3.5 Air exchange rate at the center of the screenhouse (open diamonds) as a function of the external wind speed, $u$, together with the theoretical air exchange rate (solid line) estimated theoretically for an open pepper field. Closed circles: greenhouse exchange rate measured by Fatnassi (2001). $X_c$ and $X_o$ are air exchange rates in the screenhouse and in the open field, respectively. (From Tanny, J. et al., Biosyst. Eng., 84(3), 331, 2003, Figure 9a. With permission.)](image)
FIGURE 3.6 (a) Wind vectors outside and above the screenhouse. Each arrow represents a measuring period of 15 min and corresponds to the times of the inside measurements on the right. The concentric circles indicate the wind speed in m s\(^{-1}\). (b) Wind vectors inside the screenhouse. Each vector corresponds to a location along the central axis of the screenhouse from west to east: 1–13 m from western edge; 2–30, 3–57, 4–78, and 5–102 m from western edge. The concentric circles indicate the wind speed in m s\(^{-1}\). (From Möller, M. et al., Acta Hortic., 614, 445, 2003, Figures 10 and 11. With permission.)

with earlier results by Fatnassi (2001) for a plastic greenhouse fitted with insect-proof screens at its openings.

Measurements of air velocity and direction inside and above the same screenhouse (Möller et al. 2003) revealed a complex flow pattern with a counter-flow (to the atmospheric conditions) in the windward western region of the screenhouse and a concurrent flow along its easterly region, as depicted in Figure 3.6. This flow pattern can be explained by the curvature of external wind streamlines at the leading edge of the structure and the induced lower pressure at this region as compared to the higher pressure at the leeward easterly edge.

In a more recent study, Tanny et al. (2006) applied the eddy covariance technique to investigate turbulent fluxes of water vapor and sensible heat in a large banana screenhouse. They showed that turbulent properties within the screenhouse, in the air gap above the plants and below the screen, were favorable for such measurements. For example, they showed that velocity spectra decay rates were very close to \(-5/3\), the value typical of the inertial sub-range in steady state turbulent boundary layers. Average turbulence intensity for all the data collected was 0.49, a value which marginally supports the validity of Taylor’s hypothesis of frozen turbulence. The water vapor flux measured by Tanny et al. (2006) was again used to calculate the ventilation rate of the screenhouse. Results showed a linear increase with the external wind speed and general agreement with literature results.

3.3 Flow along and through Porous Screens

3.3.1 General

The use of porous screens in agriculture became widely popular in recent years. The main two applications are (1) the deployment of screens in greenhouse roof and side openings to exclude insects and (2) crop cultivation inside screenhouses or under horizontal shading screens. In the first case, since greenhouse openings are usually vertical or slightly inclined, the screen is perpendicular or inclined at some angle to the airflow. In the second application, a flow parallel to the screen takes place over much of the cultivated area. In this chapter, we first discuss flow along screens, mostly related to the screenhouse cultivation practice. Discussion of flow through screens will follow.

3.3.2 Flow along Screens

Covering a crop with a screen reduces the vertical exchange of heat, mass, and momentum between the crop and the free atmosphere. Besides incident radiation, these transport processes are the major factors influencing the crop microclimate. A major goal of recent studies (Tanny and Cohen, 2003, Tanny et al., 2009) was to investigate how screens modify the turbulence characteristics of the wind. Tanny and Cohen (2003) measured vertical profiles of wind and temperature above a small shading screen covering few citrus trees. From these profiles, and by fitting the data to a log-linear profile, they were able to estimate the friction velocity and other boundary layer properties.

When the boundary layer flow along the screen is neutrally stable, the logarithmic wind profile equation is

\[
    u(z) = \frac{u_*}{k} \ln \left( \frac{z - d}{z_0} \right)
\]  

(3.3)

where

- \( u \) is the wind speed (m s\(^{-1}\))
- \( z \) is the height above the ground (m)
- \( u_* \) is the friction velocity (m s\(^{-1}\))
- \( k \) is the von Karman constant (= 0.41)
- The parameter \( d \) is the zero plane displacement (m), that is, the distance that the canopy or the screen “displaces” the wind profile above the ground
- \( z_0 \) is the roughness length (m), which is a scaling length for a particular surface
When the boundary layer is not neutral, a modification of the aforementioned equation should be applied to take into account the stabilizing or destabilizing effect of the temperature profile. This modification results with a log-linear profile where the effect of buoyancy is characterized by the bulk Richardson number, \( R_i \), defined as

\[
R_i = \frac{(g/T)(\partial T/\partial y)}{\Delta u/\Delta z}
\]  

(3.4)

where

\( \Delta u/\Delta z \) is a representative constant wind speed gradient, calculated over the boundary layer above the canopy.

\( \partial T/\partial y \) is the variation of temperature with horizontal mean velocity within this boundary layer.

The purpose of past studies was to evaluate the friction velocity from mean wind speed and temperature profile measurements under different conditions of atmospheric stability and to compare the results for flow over orchards covered with screens and over uncovered orchards. Results of such analyses have shown that horizontal screen covers reduced the friction velocity (Figure 3.7) and roughness length and increased the aerodynamic resistance and zero-plane displacement in comparison with an uncovered plantation. Results under unstable conditions were in agreement with a numerical calculation by Louis (1979). The results also exhibited the decay of turbulence at \( R_i \approx 0.2 \), in agreement with the well-known stability criterion of stratified shear flows (Turner, 1979). The modifications in flow properties along screens may be partially responsible for the reduced transport of water vapor from the crop to the atmosphere which may allow lower irrigation by the growers and thus increase the water saving.

Tanny et al. (2009) further elaborated the aforementioned analysis by comparing the results mentioned earlier for a small shading screen above a citrus orchard with measurements over a larger screenhouse (110 m \times 60 m) in which pepper was grown. The analysis showed that under stable conditions the boundary layers in both configurations had almost similar properties. Under unstable conditions, however, more significant differences were observed presumably due to the differences in screen and crop types, and different available fetch in the two experiments.

### 3.3.3 Flow through Screens

Screens inhibit airflow through increased resistance, that is, increased pressure drop. The pressure drop across a screen, \( \Delta P \), can be calculated by the Bernoulli's equation:

\[
\Delta P = 0.5 \rho K U^2
\]

(3.5)

where

\( \rho \) is fluid density
\( K \) is pressure loss coefficient
\( U \) is mean upstream velocity

Many research works were devoted to the characterization of \( K \) as a function of screen and flow properties, part of them within the general engineering context, for example, Brundrett (1993) and Turner (1969).

Within the context of insect-proof screens used to protect agricultural crops, Teitel and Shklyar (1998) studied experimentally and numerically the pressure drop across such screens. They conducted pressure drop measurements in a wind tunnel and carried out numerical simulations using a commercial finite element program. Presenting the pressure loss coefficient as a function of the thread Reynolds number for a given screen porosity (defined as open area divided by total screen area) suggested that \( K \) also depended on the weave texture. In particular, it was shown that as the distance between adjacent threads increases, the pressure drop becomes less dependent on the detailed weave texture.

Flow patterns of different weave configurations were also investigated by Teitel and Shklyar (1998). An example is presented in Figure 3.8, where the velocity vectors downstream two intersecting threads (designated as cylinders 1 and 2) are shown. It can be observed in the figure that the vertical flow patterns immediately downstream the screen induce a region with backflow; this may assist in the process of insect exclusion.

A recent comprehensive review by Teitel (2007) considered different approaches in characterizing the flow resistance induced by screens. The general equation describing flow through a porous medium can be written as:

\[
\frac{\mu}{k} u + \rho \left( \frac{Y}{k U^2} \right) \frac{\partial u}{\partial x} = \frac{\partial P}{\partial x}
\]

(3.6)

where

\( \mu \) is the dynamic viscosity
\( u \) is upstream fluid velocity
\( k \) is permeability
\( Y \) is inertial factor of the screen.
Values of skewness and flatness were significantly different from those for a Gaussian distribution. Skewness was mostly negative, indicating strong negative turbulent motions. Velocity flatness values suggested that the outflow was more intermittent than the inflow for both screened and unscreened openings. Spectral analysis showed that installing screens on the greenhouse openings reduced the turbulence energy density at low frequencies, and increased the decay rate of turbulence, apparently due to the smaller scales generated by the screen. Positive co-spectra of velocity and temperature, estimated for openings with and without screens, indicated turbulent heat transfer from the greenhouse to the external surroundings in both cases. The quadrant analysis showed that with screens, the contribution of the different quadrants to the turbulent heat flux were similar at the two edges of the opening while without screens there was a more pronounced difference between the two edges. This, again, indicated on the more uniform microclimate induced by the screens.

Integral length scales calculated by Teitel and Tanny (2005) for the flow through the roof openings resulted with values of 0.7–0.84 m for the inflow and 0.12–0.31 m for the outflow. The scale for the inflow was commensurate to the height of the roof opening. The calculations showed only a relatively small difference between integral length scales with and without screens deployed at the openings. This result was not surprising since screens are expected to mainly affect the small scales of the flow.

In an attempt to compensate the effect of screens in inhibiting greenhouse ventilation, various screen configurations have been...
applied in greenhouse openings. The use of inclined or concen-
tina-shaped screens (Bailey, 2003) increases the actual flow area and thus may compensate for the reduced flow due to the higher pressure drop across the screen. An experimental and CFD simulation of flow through vertical and inclined screens was recently conducted by Teitel et al. (2009). In the experiments, a sub-tunnel with a cross section 280 × 280 mm and 1.2 m long was placed on the floor of a larger wind tunnel. Tested screens were mounted on the side of the sub-tunnel facing the upstream flow. Screens were deployed at inclination angles of 45°, 90°, and 135° between the upstream direction and wind-tunnel floor. In addition, three screen porosities were examined at each inclination angle. Vertical profiles of velocity were measured downstream of the screens using an omnidirectional hot-wire sensor. In the simulations, the ANSYS-CFX-11 software package was utilized, with the addition of the pressure drop expression of Equation 3.6 as a source term to the momentum equation. Following Fatnassi et al. (2006), Teitel et al. (2009) used a porous medium with a larger thickness than a real screen, but with similar air-flow transmission characteristics, to avoid discontinuities in the meshing of the simulation domain.

Results by Teitel et al. (2009) showed that inclined screens generate a non-uniform downstream velocity profile. Generally, good agreement was obtained between the velocity measurements and the simulations. Positioning the screen at 45° caused more air to penetrate into the sub-channel, thus somewhat increasing the mass flow rate as compared to the 135° inclination (Figure 3.9). With 135° inclination, more air could escape above the sub-channel and mass flow rate was somewhat smaller. The effect of screen porosity on mass flow rate through the screen was more pronounced than the effect of screen inclination. Increasing the porosity from 0.4 to 0.62 nearly doubled the mass flow rate, as shown in Figure 3.9. Teitel et al. (2009) also calculated the forces on the screen induced by the flow, which is an important consideration in the design of the greenhouse structure.

### 3.4 Summary

A wide variety of fluid mechanics principles and tools are commonly applied in the study of agricultural systems. These tools are mainly aimed at improving the understanding and hence the design and performance of such systems. For example, fluid mechanics studies deal with non-uniform climatic conditions inside agricultural structures which may reduce the total yield. Insufficient ventilation in greenhouses or screenhouses may result in CO₂ shortage which may deteriorate photosynthesis and production. The reduced friction velocity of the flow along screens indicates smaller exchange between plants and atmosphere which may lead to increased water saving. It must be recalled that the ultimate goal in the design of an agricultural system is increasing the profitability of the growers to facilitate sufficient supply of food in affordable prices for the growing world population.

This chapter focused on some applications of fluid mechanics in protected cultivation since this has been a widespread adopted technology in agricultural production in many regions of the world in the past few decades. The chapter did not cover all topics related to fluid mechanics in agricultural systems. Some topics that were not covered here are fluid mechanics of irrigation systems (e.g., sprinklers, drip irrigation systems), water distribution in the root zone within the soil (i.e., flow in porous media), microclimate of livestock buildings, transport of solutes and nutrients in agricultural soils, and more. A much more comprehensive review is required to cover these topics.

### References


