# Chapter 10
# Air Distribution and Its Uniformity

**Ying Zhang and Murat Kacira**

**Abstract** Air distribution system in plant factories with artificial lighting (PFALs) is responsible for the air exchange and replacement to create desired growing conditions for plants. Combined effects of multitiers, heat from supplemental lighting, improper air conditioning, and air distribution system design can lead to environmental nonuniformity in PFALs. The principle for the design of air distribution system is to understand the physics of wind and how crops response to wind. This chapter describes how wind affects the photosynthesis and transpiration processes of crops by briefly explaining the theory of leaf boundary layer and boundary layer resistance. Then an example application of improving air movement to prevent plant physiological disorder (e.g., tipburn in lettuces) is introduced. For the design of air distribution system, the overall control with mixing ventilation systems and the localized control with cooling fans and perforated air tubes are described. Finally, several indices for assessment of ventilation performance are defined such as air exchange effectiveness, local mean age of air, efficiency of heat removal, and coefficient of variation.

**Keywords** Boundary layer · Boundary layer resistance · Air movement · Air distribution system · Cooling fan · Perforated air tube · Air exchange effectiveness · Local mean age of air · Efficiency of heat removal · Coefficient of variation · Simulation · Computational fluid dynamics

## 10.1 Introduction

The operational costs and resource-use efficiency in multitier-based plant factory systems can be improved by appropriate production-system design modifications for key technologies and control strategies while considering the crop-specific minimum

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environmental requirements such as light, air temperature, air velocity and flow pattern, $CO_2$, and uniformity of these variables.

Majority of the plant factories with artificial lighting have been constructed inside a pre-existing warehouse building with multilayer production shelves. It is observed that the main focus with the existing system designs has been using the internal building space to achieve higher biomass production without considering detailed engineering design fundamentals for air conditioning systems, uniformity of the environment, efficient delivery of $CO_2$, shelf spacing, smart lighting system and shelf designs, and interaction of crop and surrounding climate in terms of heat and mass transfer processes. Therefore, lack of detailed engineering analysis in the system design can lead to inefficient use of resources (i.e., energy, $CO_2$, water), nonuniform environment, higher system costs, and limit production quality, yield, and profitability.

Due to the limited and uneven air circulation inside each shelf and large production domain, the environment in multitiered plant factories with artificial lighting may not be uniform. This can limit the production quality, yield, and speed. Thus, the resource consumption is increased as the growing period is extended. It is necessary to properly design crop production, air conditioning, and air distribution systems in plant factories under sole source lighting for providing desired airflow patterns, boundary layer thickness, sufficient air current speed for optimal heat and gas exchanges, improving uniformity of the environment, and efficient delivery of $CO_2$.

The importance of proper air distribution in conditioned space is often underestimated. Air movement around crops in PFALs has a major impact on crop growth and physiology. Determining an optimized multitier system design requires exhaustive onsite studies and experimentation, labor, and time to analyze various configurations, design variables, and operational strategies to address the challenges indicated above. Thus, using computer modeling and simulation-based approach is a more advantageous and time-, cost-, and labor-efficient way once a validated model is developed to determine key design features and variables in detail and to recommend design optimization leading to improved resource-use efficiency. In this chapter, the mechanics of interaction between crop and surrounding climate and other important factors are discussed, some of the air distribution system alternatives are considered and evaluated, and localized climate control concept is proposed, with results and illustrations based on computer modeling-based approach and analysis on airflow uniformity in plant factory system.

### *10.1.1 Leaf Boundary Layer and Leaf Boundary Layer Resistance*

Leaf boundary layer (LBL) is a thin layer of still air adhering to the leaf surface generated by air friction. Airflow within the boundary layer can be laminar,

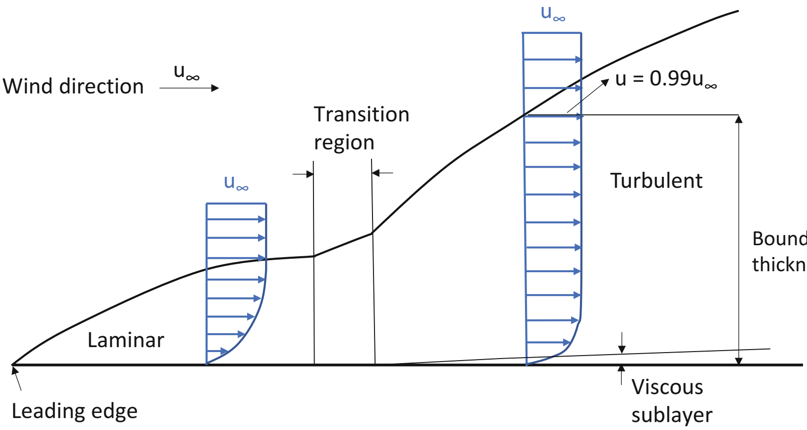
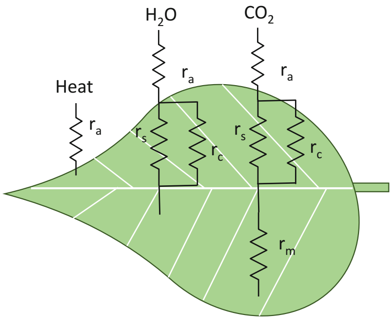



**Fig. 10.1** Schematic illustration of airflowing over a smooth flat plane, indicating the transition from laminar to turbulent flow

**Fig. 10.2** Resistances for gas and heat exchange at leaf surface: boundary layer resistance ($r_a$), stomatal resistance ($r_s$), cuticular resistance ($r_c$), and mesophyll resistance ($r_m$)




turbulent, or transitional, which depends on the turbulence of the impinging airstream and characteristics of the leaf (Van Gardingen and Grace 1991). Figure 10.1 illustrates airflowing over the top of a flat leaf, showing the transition from laminar to turbulent flow. The arrows indicate the relative speed and the direction of airflow. Within laminar boundary layer or laminar sublayer, air movement is parallel to the leaf surface. Heat and gas transfer occurs by molecular diffusion in the laminar boundary layer. Turbulent flow is characterized by unsteady eddying motions in all sizes. The eddies assist heat and gas transfer in turbulent boundary layers. In nature, wind profile is not laminar. The flapping motion of leaves with the wind, the roughness of leaf surfaces, the veins, and serrations all affect the development of airflow and lead to a turbulent boundary layer (Van Gardingen and Grace 1991).

The exchange of heat and mass between crop and the atmosphere must overcome various resistances at leaves (Fig. 10.2). Photosynthesis can be considered a process of $CO_2$ diffusion from the air to chloroplast. The resistances to $CO_2$ diffusion are from mesophyll, cuticular, stomata, and boundary layer (Gaastra 1959). Transpiration is the transport of water and minerals from roots to leaves. Water vapor must diffuse through LBL and then be removed by moving air. The resistances in the diffusion pathway of water vapor are cuticular, stomata, and LBL, whereas only the leaf boundary layer resistance (LBLR) plays a role for heat transfer. Air movement plays a vital role affecting the heat and mass transfer between crop and its surrounding by changing the boundary layer thickness and therefore positively or negatively affects crop growth.

LBLR is the resistance in the pathways for energy and gas fluxes to and from leaf surface, which is directly related to the leaf boundary layer thickness (LBLT). The LBLT is the normal distance to leaf immediately from leaf surface to a point where the flow velocity closes to the free stream value. It is influenced by the characteristics of leaves (such as leaf size, shape, and roughness) and air movement. The average LBLT next to a flat leaf can be defined as the approximate equation below (Nobel 2009):

$$\delta^{bl} = 4.0\sqrt{\frac{l}{v}}$$

where $l$ is the mean length of leaf in the downwind direction in m, $v$ is the ambient wind speed in m $s^{-1}$, and $\delta^{bl}$ is the average LBLT in mm. The factor 4.0 (mm $s^{-0.5}$) and the exponent 0.5 vary with different leaf shapes and sizes. Generally, the average LBLT is directly proportional to the mean length of the leaf in the downwind direction and inversely proportional to the ambient wind speed.

### 10.1.2 Effects of Air Current Speed and Air Current Direction on Photosynthesis or/and Transpiration

Insufficient air circulation decreases photosynthesis (Pn) and transpiration (Tr) by suppressing the gas and water diffusion in the leaf boundary layer and thus limits plant growth and development (Yabuki 2013). Kitaya (2005) assessed the effect of air current speed on Pn and Tr of a seedlings canopy and single leaves of cucumber. For the seedlings canopy, Pn and Tr increased, respectively, by 1.2 and 2.8 times when the air current speed was increased from 0.02 to 1.3 m $s^{-1}$. Similarly, Pn and Tr of the single leaves increased, respectively, by 1.7 and 2.1 times when the air current speed was increased from 0.005 to 0.8 m $s^{-1}$. The results showed that enhancing the wind current speed has a positive effect on photosynthesis and transpiration. It was reported that as air current speed increases from 0.005 to 0.1 m $s^{-1}$, the decrease of LBLR is proportional approximately to the minus 0.37 power of the air current speed. Wind affects transpiration not only by reducing LBLT but also by removing the moist air close to the surfaces of leaves. When the moist air at boundary layer is replaced with drier air, the water potential gradient between stomata and ambient environment increases, and the transpiration rate is enhanced.

Air current direction has been shown to have a great influence on the transpiration of plants. Kitaya et al. (2000) studied the effect of vertical and horizontal air currents on transpiration rate for a model plant canopy. The speed of the downward air current was controlled in the range of 0.1 to 0.3 m $s^{-1}$. The results showed that the evaporation rates were 2 and 2.7 times greater in the vertical airflow than in the horizontal airflow at air current speeds of 0.15 and 0.25 m $s^{-1}$, respectively. Compared to a horizontal airflow, vertical airflow can effectively decrease LBLT at canopy surface and thus increase the diffusive rate of water vapor at boundary layer. Forced air movement with vertically downward air currents was recommended for a closed plant culture system with a large amount of plants at a high density.

### *10.1.3 Effects of Air Current Speed and Air Current Direction on Tipburn Prevention*

In order to produce high-quality crops continuously, proper growing conditions for the crop must be maintained in the production space. In an indoor production system, due to the limited and uneven air circulation across a shelf and large production domain, air temperature over the crop canopy can deviate by several degrees from that of A/C unit set points, and the environment also may not be uniform thereby limiting production quality, yield, and rate. The appropriate air current speeds for enhancing gas exchanges by leaves were more than 0.3 m $s^{-1}$ in the vicinity of the leaves (Kitaya et al. 1998). Lack of vertical airflow and limited capacity to create proper boundary layer dynamics, especially when the shelf height (head space) is limited, may result in crop physiological disorders (i.e., nutrient deficiency-induced tipburn with lettuce).

Tipburn is considered as a symptom of calcium deficiency-related disorder, and it is characterized by browning margins in lettuces. Calcium is an essential plant nutrient for strengthening plant cell walls. Calcium uptake from the roots to the leaves of plants is passive and is driven by transpiration process. The tipburn symptom may occur at inner and newly developing leaves with low transpiration rate due to the stagnant air at boundary layer even under high transpiration demand conditions despite plenty of supplies of calcium available at root zones. This defect affects the appearance of lettuces and limits its market value.

Goto and Takakura (1992) demonstrated that creating vertical airflow toward the lettuce crop canopy was effective to prevent tipburn. Kitaya et al. (2000) indicated that forced air movement with vertically downward air currents is essential in a closed crop culture system with high cropping densities and the air velocity should be at least 0.3 m $s^{-1}$ just above the canopy boundary layer. Compared to a horizontal airflow, vertical airflow can effectively decrease the thickness of boundary layer at canopy surface and thus increase the diffusive rate of water vapor at boundary layer. Forced air movement with vertically downward air currents was recommended for a closed plant culture system with a large amount of plants at a high density. Shibata et al. (1995) investigated the effect of forced airflow on the growth and occurrence of tipburn in butterhead-type lettuce grown in a plant factory. A $2^3$ factorial experimental design was created with three factors (vertical airflow, horizontal airflow, and no airflow) and two levels for each factor (60% of relative humidity and 80% of relative humidity). Airflow was supplied at the velocity of 0.7 m $s^{-1}$ with either vertical or horizontal direction from air supply systems and achieved the velocity of around 0.5 m $s^{-1}$ at the site of cultivation bed. The study showed that the vertical airflow could effectively prevent the tipburn of lettuces. No tipburn occurred up to 40th day after sowing under vertical airflow conditions. The tipburn symptom was observed without airflow and horizontal airflow at 30th day after sowing. Lee et al. (2013) studied the occurrence of tipburn symptom of two tipburn-sensitive cultivars under four different horizontal airflow rates in an indoor plant factory. One of the reasons for tipburn occurrences at the center is the effect of leaf enclosure. Airflow was generated by three air circulating fans in a horizontal line along the side of the beds in the experiment. It was found that a stable horizontal airflow about 0.3 m $s^{-1}$ significantly reduced the incidence of tipburn and however tipburn was still detected in the inner leaves near harvest at the center of cultivation bed. Compared to the control group without having air supply, 65% and 55% of tipburn were reduced separately for two cultivars under the air current speed of 0.28 m $s^{-1}$.

## 10.2 Air Ventilation/Distribution System in PFALs

### *10.2.1 Air Movement*

Air movement inside and through PFALs can be driven by three forces: wind pressure, buoyancy, and mechanical force. Air infiltration/exfiltration is the unintentional inward or outward movement of air through cracks in the building envelope. It is due to the pressure differences between inside and outside. It depends on wind speed, wind direction, and the airtightness of the building envelope. The level of airtightness in a PFAL can be high with 0.01–0.02 of air change per hour. That means most of the time, the flow of air caused by infiltration/exfiltration in a PFAL is negligible.

Buoyance is the driving force of fluid movement because of the density difference of fluid. It is the pressure generated by molecular collisions in all directions and depends on the kinetic energy of fluid molecules. Denser or cooler fluids have less kinetic energy, and thus less pressure is generated by the fluids. In a PFAL without ventilation, by the force of gravity, cool air with higher density falls, and hot air with lower density rises. This creates an upward buoyant force and the flow of air forms. This also causes spatial temperature gradients in a PFAL.

Air movement is PFALs is mainly driven by mechanical ventilation using fans and air ducts. Typically, air handling units are connected to ductwork. Supply air is distributed by air distribution system to the ventilation space to create a uniform climate of temperature, humidity, $CO_2$, and air motion in production shelves. The design of air ventilation system in PFALs is to properly choose the type, location, and size of the supply air inlet and the return air outlet according to the room geometry, internal heat source, and desired environmental conditions. The characteristics of airflow inside a PFAL are the results of the combination of buoyancy effect and mechanical forces.

## *10.2.2 Air Distribution System*

### 10.2.2.1 Overall Control

Mixing ventilation system is widely used in PFALs to provide air circulation for overall control (OC). The OC here is defined as the general control of air distribution in major areas. The principle is to supply ventilation air at a high velocity (high Reynolds number) to mix and dilute the entire room air to provide mixing and air quality equalization. The inlets usually located in the upper parts of the room supplying air in a jet type (ceiling or wall at high level) (Schiavon 2009). The requirement for outlets is to avoid short-circuiting of supply air. Three examples of air ventilation system are shown in Fig. 10.3. With a jet-type flow, the motion is mainly governed by the initial momentum of the supply air. Therefore, airflow pattern is greatly affected by the location of the inlet whist minimally by the outlet. Airflow pattern is a key factor affecting temperature gradients in the building (Randall and Battams 1979).

#### Side Wall Supply and Extract

In ventilation community, Archimedes number (Ar) is widely used to characterize the direction of the flow (Berckmans et al. 1993). It can be expressed in a general form as (Awbi 2008):

$$Ar = \frac{g\beta \Delta TL}{U^2}$$

where $g$ is the gravity acceleration (m s$^{-2}$), $\beta$ is the thermal expansion coefficient (calculated at the mean temperature between the inlet air and the air close to the wall), $\Delta T$ is the temperature difference between inlet air and the coldest (or hottest) wall of the enclosure ($^{\circ}C$), $L$ is the characteristic dimension of (m), and $U$ is the average velocity at the inlet grid. The equation reveals the relative importance of buoyant and inertia forces by combing the supply air velocity and room temperature difference. For air distribution systems with air supplied from side wall (Fig. 10.3a, b), the jet deflection from the horizontal depends on Ar. As Ar increases, the jet deflection from the horizontal increases (Randall and Battams 1979; Berckmans et al. 1993; Cao et al. 2014).

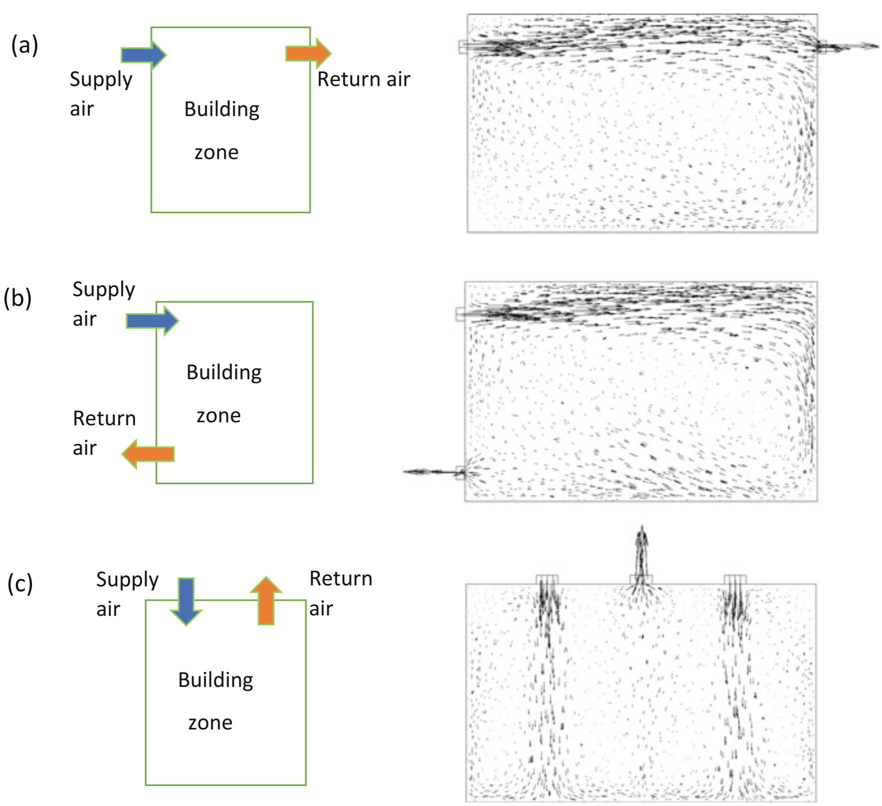



**Fig. 10.3** Examples of mixing ventilation systems (left) and the corresponding airflow pattern (right): (**a**) opposite side walls supply (high) and extract (high), (**b**) one side wall supply (high) and extract (low), and (**c**) ceiling supply and extract

### Ceiling Supply and Extract

The ceiling-based ventilation (Fig. 10.3c) is suitable for large space (Awbi 2015). For this type of mixing ventilation system, a potential flow can be observed along the supply air jet but no clear connective flow around the exhaust outlet (Kikuchi et al. 2003). In a PFAL, a hot aisle/cold aisle air delivery system with alternating inlets with outlets above the aisles can effectively remove the excessive heat form lighting and with uniform air temperature distribution (Fig. 10.4) (Zhang and Kacira 2017). However, for the air velocity distribution, a spatial variation of air current speed can be seen in this air distribution system, with strong airflow closed to the floor and weak airflow in the top levels of production systems. It is common to have a low average air current speed (below 0.3 m $s^{-1}$) at crop canopy surface.

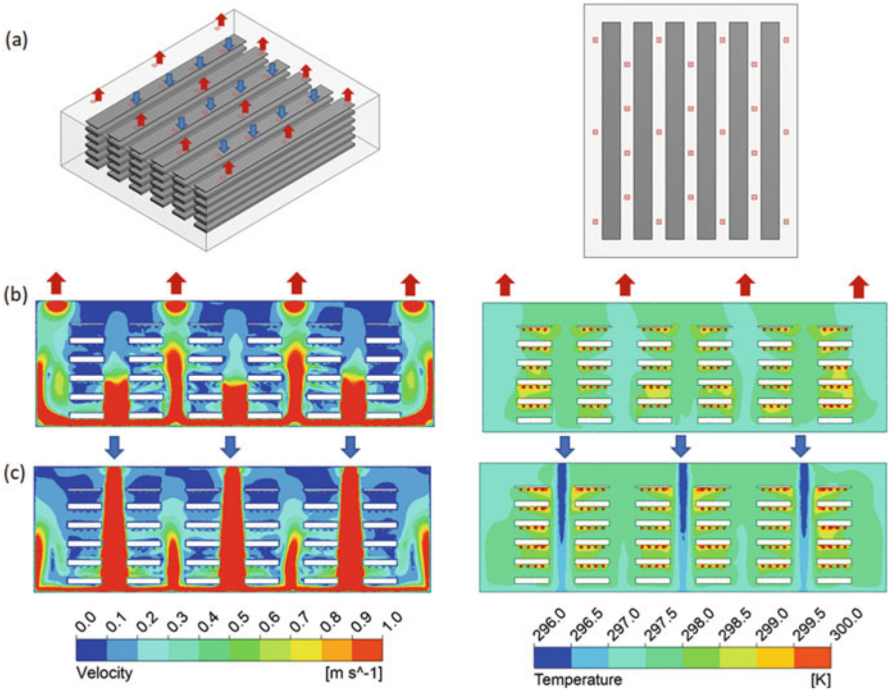



**Fig. 10.4** An example of air ventilation system with ceiling supply and extract vents (Zhang and Kacira 2017): (**a**) the layout of the supply and extract vents, (**b**) the air velocity and temperature distribution at outlet vents, and (**c**) the air velocity and temperature distribution at inlet vents. The analysis and results on air velocity and temperature distributions were obtained using computational fluid dynamics modeling

#### 10.2.2.2 Localized Control

Although mixing ventilation system can help minimize the variation of gas concentration, humidity, and temperature through the room in some degrees (Awbi 2015), the climate uniformity and air movement at crop canopy cannot be insured. With combined effects of multitiers, heat from supplemental lighting, and buoyancy forces, nonuniform air temperature and inadequate air movement at crop canopy can be found even along a single production shelf. These will lead to nonuniform crop growth and crop disorders. Besides, to control the entire space with OC is not efficient in energy. Localized control (LC) is the control strategy to use equipment to enhance air circulation just at crop canopy in each shelf. It can help to improve the climate uniformity, accelerate air movement at crop canopy, and enhance resource-use efficiency.

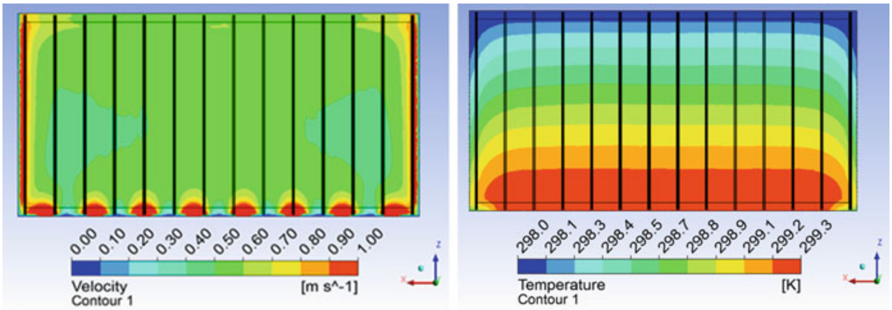



**Fig. 10.5** Top view of air current speed and air temperature distributions on a horizontal plane in the shelf

### Airflow/Cooling Fan

Installing airflow or cooling fan at the end of the shelf or along the length of the shelf is the simplest way as a LC. Figure 10.5 shows the top view of a production shelf equipped with fluorescent lamps and exhaust fans. The exhaust fans are installed at the center of the side wall along the length of the shelf pulling air from the opposite side wall through the shelf. A uniform distribution of air current speed on a horizontal plane in the shelf can be observed. However, the temperature of intake air is increasing by mixing with the hot air closed to the lamps as air passing through the shelf. The air temperature difference from one side to the other side depends on the temperature of intake air, the pathway of the airflow, the sensitive heat released from lamps, and the height of the shelf. Installing fans on the end of the long shelf is not recommended. If we consider the top surface of crop canopy as a big flat leaf, according to the approximate equation for LBLT described in previous section, LBLT increases with the mean length of leaf in the downwind direction. Therefore, the air circulation at the center of the shelf cannot be improved with a large LBLR.

### Perforated Air Tube

For LC, using fans to circulate air downward to provide vertical airflow to crop canopy is not practical. It will lead to a mixing of hot air around lighting with the cool air at leaf surface, increasing the ambient air temperature at leaf surface. Perforated air tube can be used to deliver conditioned air to crop canopy or help air circulation around crop canopy to achieve desired climate uniformity and adequate air movement. The design of a perforated air tube is associated with the size and layout of the production system. The number, size, shape, and spacing of the discharge holes influence the static pressure in the air tube and decide the dissipate rate of jets of air from each hole (Saunders and Albright 1984; Wells and Amos 1994). The aperture ratio for a perforated pipe is defined as the total hole area to dust area. Wells and Amos (1994) reported that an aperture ratio greater than 1.5 will

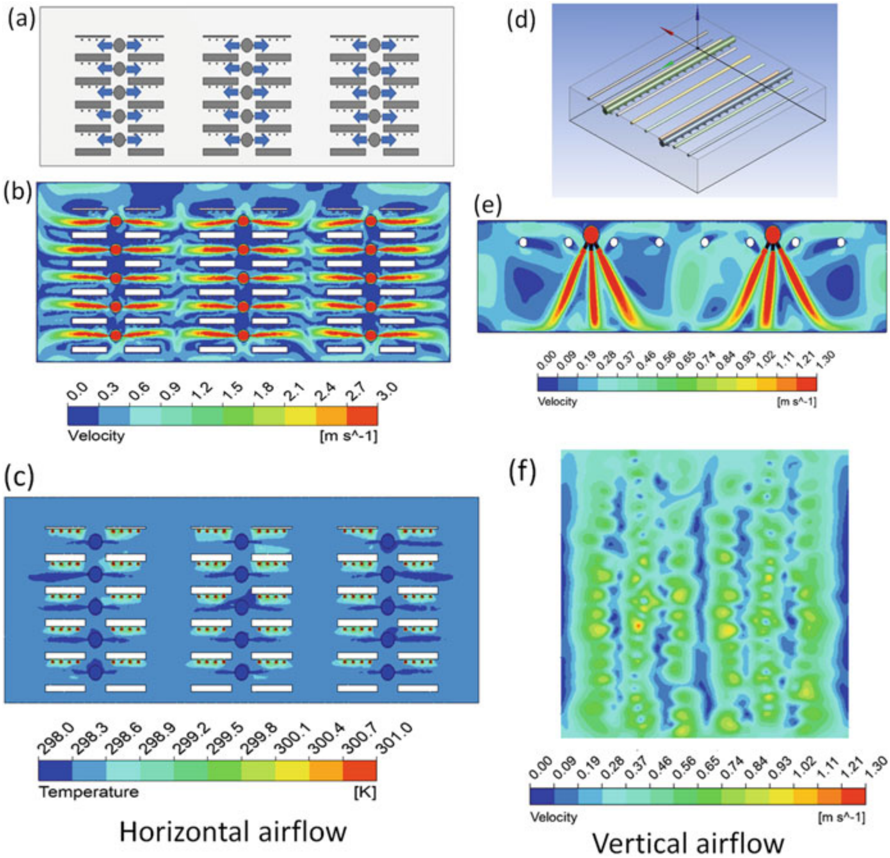



**Fig. 10.6** Examples of the application of perforated air tube for the localized control of air distribution system to provide horizontal airflow (**a**–**c**) (Zhang and Kacira 2017) and vertical airflow (**d**–**f**) in production shelves (Zhang et al. 2016): (**a**) the layout of perforated air tubes (horizontal airflow), (**b**) front view of air velocity distribution (horizontal airflow), (**c**) front view of air temperature distribution (horizontal airflow), (**d**) the layout of perforated air tubes (vertical airflow), (**e**) front view of air jets (vertical airflow), and (**f**) top view of air velocity distribution (vertical airflow)

cause nonuniform duct discharges and an aperture ratio of around one will give the best compromise between uniform discharge and avoiding high inlet pressure. Figure 10.6 shows two examples with perforated air tubes to provide horizontal airflow (left) and vertical airflow (right) to production shelves (Zhang et al. 2016; Zhang and Kacira 2017).

## 10.3 Assessment of Air Distribution System

Ventilation performance can be evaluated by various ways according to the tasks of the ventilation. Efficiency compares the difference between the real and ideal performances. Ventilation efficiency in PFALs can be assessed regarding air change rate, age of air, and heat removal. Climate uniformity is also an important parameter to assess the performance of the air ventilation/distribution system.

### *10.3.1 Air Exchange Effectiveness*

Air exchange effectiveness is the efficiency of the ventilation to change the air in the ventilated space with fresh air. Local (a point in a room) air change effectiveness is half of the ratio of nominal time constant ($\tau_n$) and the room local mean age of air ($\overline{\tau_p}$) (Cao et al. 2014):

$$\varepsilon_a = \frac{\tau_n}{2\overline{\tau_p}}$$

where $\tau_n$ equals to the reciprocal of the air change rate (ACH = Q/V). ACH is equal to the ratio of air supply rate (Q) to the room volume (V).

### *10.3.2 Local Mean Age of Air*

The local age of air is the time taken since the fresh air entered the room or building to reach a designated point (Awbi 2008). The local mean age of air is defined as (Cao et al. 2014):

$$\tau_p = \frac{1}{C(0)} \int_0^\infty C_p(t)dt$$

where $C(0)$ is the initial concentration of the tracer gas and $C_p$is the gas concentration at a certain point in the room at time t. It's common to use mean air velocity to reveal the lack of ventilation within a space. The local MAA distribution is also shown a sensitive parameter, which can be used to detect the stagnant zones, where have the combined accumulation of heat and moisture (Chanteloup and Mirade 2009).

### 10.3.3 Efficiency of Heat Removal

The ventilation efficiency for heat removal can be expressed as (Cao et al. 2014):

$$\varepsilon_t = \frac{T_R - T_S}{T_P - T_S}$$

where $\varepsilon_t$ is the efficiency of heat removal, $T_R$ is the temperature of the exhaust air, $T_S$ is the temperature of the supply air, and $T_P$ is the temperature in the occupied zone. For PFALs, $T_P$ can be the average temperature around crop canopy.

### 10.3.4 Coefficient of Variation

Coefficient of variation (CV), also known as the relative standard deviation (RSD), is a statistical measurement that describes the spread of data respect to the mean:

$$c_v = \frac{\sigma}{\mu}$$

where $\sigma$ is the standard deviation and $\mu$ is the mean. It allows to compare the variates whose scales of measurement are not comparable. It can be used to analyzing the climate uniformity in PFALs, such as air temperature, $CO_2$ concentration, and humidity. Small RSD means less variation in the evaluated variable and higher uniformity. However, since the standard deviation is divided by the mean, with a mean less than unity will lead to a high SCD and often meaningless (Chanteloup and Mirade 2009). For this situation, CV should be carefully used and some further clarification for data interpretation is needed.

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