Numerical Investigation of Natural Convection of Pine, Olive, and Orange Leaves

Ali Reza Tahavvor, Saeed Hosseini, Nazli Jowkar, Behnam Amiri

***Abstract*—**Heat transfer of leaves is a crucial factor in optimal operation of metabolic functions in plants. In order to quantify this phenomenon in different leaves and investigate the influence of leaf shape on heat transfer, natural convection for pine, orange and olive leaves was simulated as representatives of different groups of leaf shapes. CFD techniques were used in this simulation with the purpose to calculate heat transfer of leaves in similar environmental conditions. The problem was simulated for steady state and three-dimensional conditions. From obtained results, it was concluded that heat fluxes of all three different leaves are almost identical, however, total rate of heat transfer have highest and lowest values for orange leaves, and pine leaves, respectively.

***Keywords*—**Computational fluid dynamic, heat flux, heat transfer, natural convection.

I. Introduction

GREEN plants in all of the biological processes use sun light as energy source. It can be argued that the sun is the source of the physiological phenomena. The use of solar energy in photosynthesis and photochemical reactions is the common characteristic of all plants. One of the most important features of plants is thermal equilibrium.

Contributing factors in the heat transfer of leaves comprise absorbed and dissipated energies, evaporation, heat conduction, convection and radiation. Recently, some researchers have begun to study two-dimensional [1] and tree-dimensional heat transfer in a greenhouse ventilation through air temperature difference [2]. Results have shown the effect of air flow speed on ventilation performance using the finite element method. Also, the ventilation conditions are investigated and the results indicate that better ventilation dos not always lead to better efficiency of system [3].

Designing a method for controlling the parameters that affect evaporation and transpiration of plants is of significant importance for the management and protection of agricultural products, particularly for greenhouse products. For this purpose, two factors are considered to be important; First, optimization of weather conditions by controlling input values such as energy of solar radiation, water and nutrient solutions and Second, the development of alternative methods of pest management such as insects and fungi that largely depends on the environmental circumstances. The main challenge for the optimal control of greenhouse climate conditions includes maintaining the desired temperature and humidity conditions for plant development. Excessive moisture can lead to aggregation of water on the leaf surface which, in turn, may lead to contamination by pathogenic fungi. Recently, with the aim of improving control methods to maintain favorable conditions and paying more attention to micro-biological pest management, some researches on the impact of the climate heterogeneity on plant activity as well as the influence of the vent configurations on the efficiencies of ventilation on flow rate and air temperature has been conducted [4].

Different simulation tools, such as the methods used in computational fluid dynamics, are used to investigate the influence of the environmental conditions on plants. Computational Fluid Dynamics (CFD) is now widely used to simulate the heat and mass transfer in passive and active surfaces and boundary layer flows. In an active surface like the surface of a leaf, ventilation and transpiration models should be considered in leaf boundary layers. Fatnassi et al. [5] provide a simple model, based on classical microclimate measurements for the determination of inside air speed, ventilation and crop transpiration rates. It was shown that their approach allows for a precise estimation of ventilation and transpiration rates using only simple measurement devices such as temperature and air humidity sensors.

Recently lots of researchers have investigated natural convection heat transfer within different cavities, vertical cylinders, porous plate channels and rectangular enclosure having finite thickness walls, through numerical simulation [6]-[11]. Jacobsl et al. [12] applied a dew simulation model to simulate leaf wetness distribution considering information on the above-canopy wind speed, air temperature, humidity and net radiation as well as the within-canopy temperature and humidity. Richards [13] estimated dewfall on a maple leaf and an artificial surface, such as a roof, using a computed surface energy balance (which includes a roof subsurface heat flux), latent heat fluxes, and an inferred surface water balance.

To the best of our knowledge, so far, there is no comprehensive study to compare heat transfer in broadleaf and coniferous trees and fully investigate the effect of leaf shape on plant heat transfer. No doubt, different vegetation with different leaves have a completely different influences on the temperature and other environmental conditions. The aim of

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this work is to determine the extent of heat transfer and effect of orange, olive and pine leaves as three different types of plants with different geometry and shape on the environment.

II. Governing Equations

The governing set of equations of natural convection heat transfer around a leaf includes the equations of continuity, momentum and energy conservation. General form of these equations in unsteady state, three-dimensional, compressible and with viscosity conditions are as follows.

Continuity equation:

$$\frac{D\rho}{\mathrm{Dt}} + \nabla.\rho \mathrm{V} = 0 \tag{1}$$

Momentum equation:

x direction:

$$\rho\frac{Du}{Dt} = -\frac{\partial p}{\partial x} + \frac{\partial t_{xx}}{\partial x} + \frac{\partial t_{yx}}{\partial y} + \frac{\partial t_{zx}}{\partial z} + \rho f_x \tag{2}$$

y direction:

$$\rho\frac{Dv}{Dt} = -\frac{\partial p}{\partial y} + \frac{\partial t_{xy}}{\partial x} + \frac{\partial t_{yy}}{\partial y} + \frac{\partial t_{zy}}{\partial z} + \rho f_y \tag{3}$$

z direction:

$$\rho\frac{Dw}{Dt} = -\frac{\partial p}{\partial z} + \frac{\partial t_{xz}}{\partial x} + \frac{\partial t_{yz}}{\partial y} + \frac{\partial t_{zz}}{\partial z} + \rho f_z \tag{4}$$

Energy equation:

$$\frac{\partial y}{\partial t}\left[\rho\left(e+\frac{V^2}{2}\right)\right] + \nabla.\left[\rho\left(e+\frac{V^2}{2}\right)V\right] = \rho q^{\cdot} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) - \frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y} + \frac{\partial(u\tau_{zx})}{\partial z} + \frac{\partial(v\tau_{xy})}{\partial x} + \frac{\partial(v\tau_{yy})}{\partial y} + \frac{\partial(v\tau_{zy})}{\partial z} + \frac{\partial(w\tau_{xz})}{\partial x} + \frac{\partial(w\tau_{yz})}{\partial y} + \frac{\partial(w\tau_{zz})}{\partial z} + \rho f.V \tag{5}$$

If the buoyant force is the only body force in these equations, then the value of this force is equal to per unit volume, in which g is the gravitational acceleration. So the momentum equation in the z direction (perpendicular to the surface) is changed as:

$$w\frac{\partial u}{\partial z} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + v\frac{\partial^2 u}{\partial y^2} \tag{6}$$

In the absence of any body force in the y direction, the momentum equation in this direction will change as:

$$\frac{\partial p}{\partial \mathrm{y}} = 0 \tag{7}$$

In the stationary region out of boundary layer, u=0 , and the momentum equation in the x direction is changed as:

$$\frac{\partial p}{\partial \mathrm{z}} = -\rho_\infty \mathrm{g} \tag{8}$$

By substitution we have:

$$u\frac{\partial \mathrm{u}}{\partial \mathrm{x}} + \mathrm{v}\frac{\partial \mathrm{v}}{\partial \mathrm{y}} = \mathrm{g}\left(\frac{\Delta\rho}{\rho}\right) + \mathrm{v}\frac{\partial^2 \mathrm{u}}{\partial \mathrm{y}^2} \tag{9}$$

In which $\Delta\rho = \rho_\infty - \rho$. This term is used in all points of boundary layer of natural convection. The first term in the equation is the buoyant force which causes flow due to the density variation. The origin of this variation can be demonstrated by entering the volumetric thermal expansion coefficient as:

$$\beta = -\frac{1}{\rho}\left(\frac{\partial P}{\partial T}\right)_{\mathrm{p}} \tag{10}$$

The above equations show the relation between buoyant force, which is the causative factor of flow, and temperature difference. So, the set of governing equations are:

$$\begin{cases} \frac{\partial u}{\partial \mathrm{x}} + \frac{\partial \mathrm{v}}{\partial \mathrm{y}} + \frac{\partial w}{\partial \mathrm{z}} = 0 \\ u\frac{\partial \mathrm{u}}{\partial \mathrm{x}} + v\frac{\partial \mathrm{v}}{\partial \mathrm{y}} = g\beta(\mathrm{T}-\mathrm{T}_\infty) + v\frac{\partial^2 \mathrm{u}}{\partial \mathrm{y}^2} \\ u\frac{\partial \mathrm{T}}{\partial \mathrm{x}} + v\frac{\partial \mathrm{T}}{\partial \mathrm{y}} = \alpha\frac{\partial^2 \mathrm{T}}{\partial \mathrm{y}^2} \end{cases} \tag{11}$$

Viscous dissipation can be neglected due to the negligible amount of velocity gradient. It should be noted that the thermal expansion coefficient β has a key role in natural convection, and for ideal gas, it can be calculated as:

$$\rho = \mathrm{P/RT} \tag{12}$$

$$\beta = -\frac{1}{\rho}\left(\frac{\partial y}{\partial x}\right)_p = \frac{1}{\rho}(\mathrm{P/RT^2}) = \frac{1}{\mathrm{T}} \tag{13}$$

III. Numerical Modeling

Recent achievements in flow modeling give us the ability to predict weather parameters in the environments like greenhouses [14]. These techniques are powerful tools for the simulation of different climatic conditions [15].

In this work, before any simulation, a set of measurements have been taken with the aim of choosing a representative leaf geometry for each plant. 10 leaves from the upper region of the tree, 10 leaves from the middle region and 10 leaves from the bottom of the tree are used as samples. Leaf areas were measured using leaf area meter device. Length and width and thickness of leaves are also measured with digital micrometer. For each plant type, after calculation of mean values for each dimension, a leaf, which has the nearest dimensions to the mean values, is selected as the representative leaf for the study. The results of these measurements are shown in Table I.

TABLE I
LEAVES SPECIFICATION

	Area mm^2	Width mm	Length mm	Thickness mm
Pine	158	1.3	125.4	0.5
Olive	717	10.7	70.1	0.45
Orange	3789	51.3	101.9	0.24

In order to simulate the problem, the governing equations should be solved for three-dimensional steady-state case considering heat sources on the leaf surface. In the simulation, the leaves are placed in a flow field. Fluid begins moving from the stagnation point above the leaf and boundary layer expands. In this problem, the gravity force is in the direction of fluid motion. The velocity of input flow which comprise of dry air and water vapor, can vary depending on the environment. The governing equations are solved using the finite volume method and SIMPLE algorithm is used for pressure velocity relation [16].

Environmental variables like temperature, vapor pressure deficit, leaf water potential, and ambient CO concentration are investigated to simulate response of plant stomata to environmental conditions, especially as an aid to climate management [17]-[23]. As a result of insignificant variation of environmental parameters in the simulation, the effect of these variations on stomatal resistance is negligible. Thus, it is convenient to neglect stomatal resistance model. Leaf geometry and solution field are shown in Fig. 1. In Fig. 2, boundary conditions of the problem are defined.

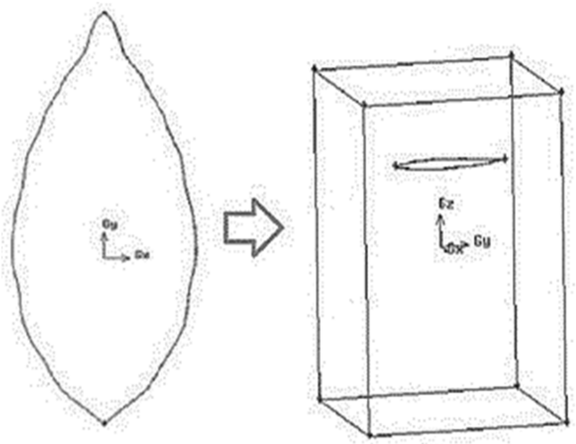

Fig. 1 Leaf geometry and solution field

Setting the boundary conditions has a key role in solving the governing equations. Input and output pressure boundary conditions are considered equal to the ambient pressure. Furthermore, with the symmetry assumption, only half of the leaves are built in the model. The input boundary conditions are shown in Table II.

TABLE II
INPUT BOUNDARY CONDITIONS

Density(kg/m^3)	1/166066
Pressure(Pascal)	101325
Temperature (K)	299
Viscosity (kg/m-s)	1/841e^{-05}
Ratio of specific heats	1/4

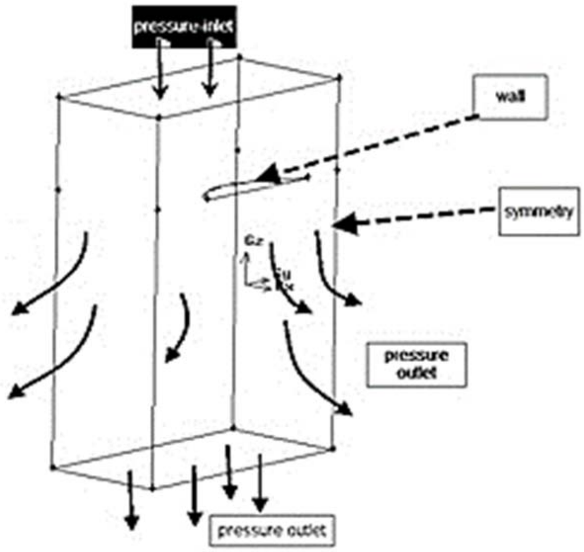

Fig. 2 Boundary conditions

IV. Results and Discussions

Neural In order to achieve grid independent answers in leaves modeling, 11 grids for three different types of leaves with different dimensions and geometries have been studied. The sizes of the computational grids are specified in Table III.

TABLE III
QUANTITY OF GRID NODES

	A	B	C
Pine	390096	460636	540000
Olive	156672	239904	291375
Orange	141570	178024	220500

Grid structure of models of orange, olive and pine leaves is shown in Figs. 3-5.

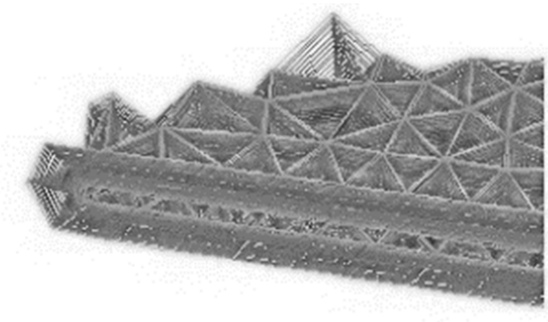

Fig. 3 Grid structure of orange leaf

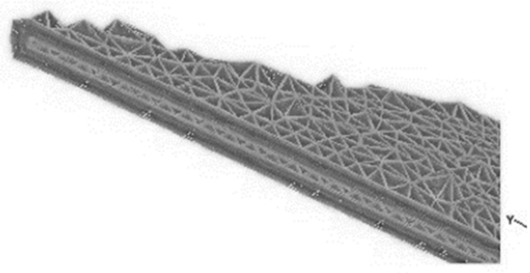

Fig. 4 Grid structure of olive leaf

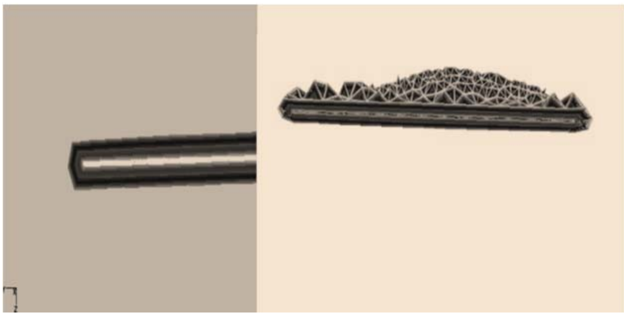

Fig. 5 Grid structure of pine leaf

After solving the equations and determination of the temperature field around each leaf, heat transfer flux can be calculated. The heat flux of orange, olive and pine leaves in different networks are presented in Table IV.

TABLE IV
HEAT FLUX

	A	B	C
Pine	-0.23399319	-0.23493199	-0.23665448
Olive	-0.14549758	-0.14597628	-0.14625486
Orange	-0.20022398	-0.20043902	-0.20057569

As can be seen in Table IV, obtained results are grid independent results and so the accuracy of the results is acceptable. Considering heat flux for each leaf, total heat transfer of leaves are calculated and presented in Table V.

TABLE V
HEAT FLUX AND HEAT TRANSFER

	Heat Flux	Heat Transfer
Pine	-0.2354369675.	-0.0316
Olive	-0.1458678564	-0.0675
Orange	-0.2003548625	-0.554

The remarkable conclusion of the achieved results is that the heat flux in all of the leaves is almost identical, and does not depend on the geometry of the leaf. However, it should be noted that total heat transfer also depends on surface area. Thus, plants can control the rate of heat transfer in accordance to the environment weather conditions using their leaves shape. Thus, as a direct consequence of the difference in heat transfer of different leaves, in environments with orange trees vegetation daytime temperature will be higher in comparison to the environments with olive and pine trees vegetation. Of course, this result also can be concluded from the comparison of surface area to volume ratio in different leaves.

Considering the surface area to volume ratio in leaves and with an analogy to fins in heat exchangers, it can be concluded that orange leaves have highest and pine leaves have lowest rate of heat transfer in this group of plants.

As the surface area of the leaf increases the total heat transfer increases and it is directly related to the surface area of the leaves.

V. CONCLUSIONS

- Heat flux in the leaves of orange, olive and pine are almost identical and independent of the shape of the leaf.
- The rate of heat transfer for orange leaves is higher than that for the olive leaves.
- By comparing the ratio of surface area to volume in leaves, a quite similar behavior to the blades of heat transfer equipment can be observed.
- Environments with pine trees vegetation experience lower increase of ambient temperature over daytime in comparison to environments with orange and olive trees.

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