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A CFD Analysis of Heat and Mass Transfer in greenhouses: An Introduction

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Abstract: Greenhouses are mainly used with a purpose of improving the environmental conditions in which plants are grown. The parameters that affect the growth of plants inside greenhouse, such as air temperature and relative humidity are controlled appropriately. They are done so efficiently to retain relatively low levels of solar energy; but without specialized ventilating and cooling systems, they will quickly fry a crop during high temperature periods. Over the past few decades CFD has been a useful tool in development of numerical models that improve the understanding of the interaction of the gases and vapors constituting micro-climate inside greenhouses. It is however, necessary to perform a CFD analysis to show us the trends, strengths and weaknesses in the use of this tool. This paper discusses an introduction of CFD analysis of airflow and climate inside greenhouses, analyzing the issues that help us understand how it has evolved, as well as trends and limitations on their use.

Keywords: CFD, Convection, Greenhouse, Heat and Mass Transfer, Modeling

1. Introduction

The branch of fluid mechanics that apply the numerical analysis methods and algorithms to solve and analyze fluid flow problems is known as computational fluid dynamics (CFD). In CFD, are used computers to perform the calculations required to simulate the interaction of fluids with surfaces defined by the boundary conditions, [2, 3, 7]. CFD is a tool that has been used in recent years to develop numerical models that improve our understanding of the interaction of variables that make up the climate inside greenhouses. Greenhouses are structures with walls and roof made chiefly of transparent material where the inside climatic conditions are regulated to maximize plants yields. These structures range in size from small sheds to industrial-sized buildings depending with either financial ability or size of land available. Inside a greenhouse, solar radiation passes through the transparent material of roof and walls and is absorbed by the floor, earth, and contents, which become warmer and re-emit the energy as longer-wavelength infrared radiation, [1, 6]. The heat transfer in a greenhouse occurs through convection, conduction or radiation. Convection is the transfer of heat through circulation and mixing of warm air with colder air. Conduction is the movement of heat between or through objects such as a metal rod or a greenhouse covering material. Radiation is the movement of heat from a warm to a colder object without the need for a medium such as air (convection) or direct contact between or through objects (conduction). When the air outside is colder, a greenhouse loses heat through conduction across the covering material. The amount of heat loss depends on the conductive characteristics of the covering material. Outside air in contact with the warmer covering material is continuously mixed to remove heat through convection. Air exchange or infiltration through greenhouse cracks, small openings and gaps around doors, equipment and other greenhouse features, is another form of convective heat transfer. Although radiation is important for solar heating of a greenhouse, thermal radiation is of minor importance for heat loss from a greenhouse. The materials used for greenhouse the roof and walls do not transmit infrared radiation, and therefore the infrared cannot escape by radiative mode; also since the structure is closed, heat produced cannot escape by convection, so the temperature inside the greenhouse rises, [4, 6].

Convective heat transfer is the transfer of heat from one place to another by the movement of fluids. Convection is usually the dominant form of heat transfer in liquids and gases. Convection can either be forced by movement of a fluid by means other than buoyancy forces or by natural buoyancy forces that are responsible for fluid motion when the fluid is heated. The convection heat transfer mode comprises transfer due to molecular motion of fluid particles. Such motion, in the presence of a temperature gradient, contributes to heat transfer. Because the molecules in aggregate retain their random motion, the total heat transfer is then due to the superposition of energy transport by random motion of the molecules and by the bulk motion of the fluid. By analogy, mass transfer by convection involves the transport of material between a boundary surface and a moving fluid or between two relatively immiscible, moving fluids. There are two different cases of convective mass transfer, either, mass transfer takes place only in a single phase either to or from a phase boundary, or mass transfer takes place in the two contacting phases as in extraction and absorption, [8, 10].

In the current trend of greenhouses cultivation, the aim is to extend production season so as to maximize their use and increase production and profitability. When the plants' natural growth conditions are altered, there arise demands for cooling and ventilation systems to avoid imbalances. The airflow and its influence on the variables that constitute the greenhouse climate create a dynamic in temporal and non-linear relationship, which can be expressed by using a system of the Navier-Stokes equations. In the last decade, there have been an increase in the use of numerical methods based on CFD in developing models that help us understand relationships between variables that make up the climate and behavior of airflow in the ventilation of greenhouses. This paper discusses an introduction of CFD modeling of airflow and climate inside greenhouses, analyzing the issues that help us understand how it has evolved, as well as trends and limitations on their use, [5, 7].

2. Materials and Methods

2.1. Governing Equation

The CFD technique numerically solved the Navier-Stokes equations and the mass and energy conservation equations (which govern any fluid flow and is a non-linear set of differential equations that describes the flow of a fluid whose stress depends linearly on flow velocity gradients and pressure). Mathematical formulations of these governing equations may be interpreted by considering the concept of a control volume; which is a specified volume in space through which air can flow in and out. In differential formulations, the equations apply Stokes' theorem to yield an expression which may be interpreted as the integral form of the law applied to an infinitesimal volume at a point within the flow.

a) Equation of Conservation of mass

The rate of change of fluid mass inside a control volume must be equal to the net rate of fluid flow into the volume, i.e.,

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = 0 \tag{1}$$

where, ρ is the fluid density, u is the flow velocity, and t is time, [11].

b) Equation of conservation of momentum

This equation applies Newton's second law of motion to the control volume, requiring that any change in momentum of the air within a control volume be due to the net flow of air into the volume and the action of external forces on the air within the volume. The differential form of the momentum conservation equation is as follows. Here, both surface and body forces are accounted for in one total force, F, [11].

$$\frac{Du}{Dt} = F - \frac{\nabla p}{\rho} \tag{2}$$

c) Conservation of energy

Although energy can be converted from one form to another, the totally energy in a given closed system remains constant.

$$\rho \frac{Dh}{Dt} = \frac{Dp}{Dt} + \nabla.(k \nabla T) + \Phi \tag{3}$$

where, h is enthalpy, k is thermal conductivity of the fluid, T is temperature, and Φ is viscous dissipation function, [11].

In addition to the conservation equations, perfect gas equation relating the pressure and other thermodynamic variables for the fluid is required to completely specify the problem. The equation is,

$$p = \frac{\rho R T}{M} \tag{4}$$

where p is pressure, ρ is density, R is the gas constant, M is molar mass and T is the temperature, [6].

2.2. Simplifying the Governing Equations

The equations can be simplified in a number of ways, all of which make them linear and easier to solve. All the quantities presented by the governing equations are time and space dependent. Nevertheless, for fluid flow problems relevant to ventilation characterized by low velocity fields and low gradients of transported quantities, some of the physical properties are assumed to be constant. Most flow fields can be described with Cartesian coordinates system. For convective and ventilation situations, determination of the velocity, temperature and humidity fields is essential for understanding the climate in greenhouses, [9].

These governing equations can be solved by either of the following methods;

a) Finite volume method (FVM) which is a common approach used in CFD codes, as it has an advantage in memory usage and solution speed, especially for large problems, high Reynolds number turbulent flows, and source term dominated flows. In the finite volume method, the governing partial differential equations are recast in a conservative form, and then solved over discrete control volumes. This discretization guarantees the conservation of fluxes through a particular control volume,

b) Finite element method (FEM) is used in structural analysis of solids, but is also applicable to fluids. However, the FEM formulation requires special care to ensure a conservative solution. The FEM formulation has been adapted for use with fluid dynamics governing equations. Although FEM must be carefully formulated to be conservative, it is much more stable than the finite volume approach. However, FEM can require more memory and has slower solution times than the FVM, and

c) Finite difference method (FDM) has historical importance and is simple to program. It is currently only used in few specialized codes, which handle complex geometry with high accuracy and efficiency by using embedded boundaries or overlapping grids, [7].

2.3. Convective Heat Transfer

The basic relationship for heat transfer by convection is:

$$q = hA(T_a - T_b) \quad (5)$$

where, q is the heat transferred per unit time, A is the area of the object, h is the heat transfer coefficient, T_a is the object's surface temperature and T_b is the fluid temperature, [8].

2.4. Mass Transfer

The mass transfer is determined using the equation of the form

$$N_A = h_m\left(C_s - C_A\right) \quad (6)$$

The molar flux N_A is measured relative to a set of axes fixed in space. The driving force is the difference between the concentration at the phase boundary, C_s (a solid surface or a fluid interface) and the concentration at some arbitrarily defined point in the fluid medium, C_A. The convective mass transfer coefficient h_m is a function of geometry of the system and the velocity and properties of the fluid similar to the heat transfer coefficient, h. [8]

2.5. Ventilation and Cooling

Inside greenhouses, light and considerable amounts of heat are trapped and enclosed which results to a demand for specialized ventilation and cooling equipment, without which they will quickly fry a crop during high light periods. To achieve this, controlled ventilation is required for greenhouse cooling to remove heated greenhouse air and introduce just the right amount of dry air to sustain the evaporative cooling rate, without causing an unwanted rise in vapor pressure deficit and air temperature. The ventilation system should be designed to remove heat evenly from all parts of the greenhouse, with no ‘hot spots’. The ventilation method used can either be natural, where farmers rely on wind and stack action, or mechanical ventilation, where electric automated gadgets are applied. In areas with extremely high temperatures and very dry air, it may be possible to maintain cooler air temperatures than outdoors by taking advantage of the combined effects of evaporative cooling equipment and crop transpiration, [4, 5].

3. CFD Modeling

3.1. Theory

Mass and heat may also be transported from one place to another by diffusion or heat conduction, respectively. Random molecular motion induces diffusive fluxes even if the fluid is at rest. The modeling of the flux function should reflect the nature of the involved transport processes. Convective effects arise when fluids flow and transport the quantities of interest downstream. In general, the transport of conserved quantities from regions of high concentration into regions of low concentration may be caused by random molecular motion or turbulence. Molecular diffusion represents the natural tendency of a physical system towards equilibrium; whereas turbulent dispersion is due to unresolved eddies that enhance the macroscopic mixing rate. The corresponding mathematical models look the same but the coefficients differ by orders of magnitude. In what follows, both molecular and turbulent mixing will be referred to as ‘diffusion’, [10, 11].

3.2. Initial and Boundary Conditions

The same differential equation may describe an amazing variety of flow patterns, so some additional information is required to complete the problem statement. In practical applications, the processes to be investigated take place in a concrete geometry (e.g., in turbines, chemical reactors, heat exchangers, car engines etc.) during a finite interval of time. The choice of the domain and of the time interval to be considered is dictated by the nature of the problem at hand, by the objectives of the analytical or numerical study, and by the available resources. Another important aspect is the choice of initial and/or boundary conditions that lead to a well-posed problem, [10, 11].

3.3. CFD Simulations

The Matlab software will be used for this study where three-dimensional simulations are to be carried out. Both buoyancy and thermal effects are the main target if the study. The ground characteristics are generally dynamic and the air was assumed real and as an ideal gas, [12, 13].

4. Conclusion

The accuracy of the heat transfer model is mainly affected by the simplification through assumption of some variables as being constant and by omitting other forms of heat fluxes in the model. In this case heat transfer by conduction and radiation are assumed as negligible inside the greenhouse. The mathematical models developed on this basis provide valuable information about the complex system and the ability to perform a variety of simulation enables us to analyze the sensitivity of the system to individual parameters changes.

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