

A STUDY OF AERODYNAMICS IN AGRICULTURE – MODERN TECHNOLOGIES

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ABSTRACT. *The aerodynamic study on ventilation of agricultural buildings has not been active because of difficulties in conducting field experiment. An engineering approach like aerodynamic analysis should be performed to design and manage the system systematically and scientifically. Moreover, this technology can contribute greatly to the development of overall HVAC system of agricultural buildings suitable for seasonal climates of Korea. This paper introduces the newest scientific and engineering technologies of aerodynamics that can be used to improve or develop structural and ventilating designs. Typical technologies of aerodynamics are large-sized wind tunnel, particle image velocimetry (PIV) technology, and computational fluid dynamics (CFD).*

Keywords. *Aerodynamics, Computational fluid dynamics, Particle image velocimetry, Wind tunnel.*

INTRODUCTION

Most domestic livestock as well as greenhouse facilities in Korea have been quickly modernized during the last decade. However, many of them are not suitable for Korea's natural climate. The ventilation of agricultural buildings such as livestock houses and greenhouses is very important to develop optimum internal environmental condition for animals and plants. Such has not been extensively studied because the invisible airflow should be analyzed. Its magnificent measurement systems and their high accuracy are required for field experiment. As the agricultural buildings have recently been large-scaled for automation and high productivity, it is more required to conduct more systematical ventilation, including airflow analysis, quantitatively as well as qualitatively. Moreover, natural ventilation should be continuously studied.

Ventilation can be defined as deriving external air into the building, and then exhausting its internal dust, gas, and the other harmful organics. It makes the environment agreeable to animals and plants in the buildings resulting to maximized productivity. In livestock houses, while keeping maximum ventilation rate during hot season, optimum air velocity should be maintained to decrease body temperature of the animals. During spring and fall seasons, the effect of external climate change on internal climate should be decreased as much as possible. During cold season, ventilation is decreased considering minimum ventilation rate and energy efficiency as well as preventing incoming cold air from directly reaching the animals. Many greenhouses are empty during hot season in Korea because of serious heat accumulation.

Major internal climate should be suitable, stable, and uniform. This is carefully made by an effective and systematic design of ventilation and building, with main considerations for the external weather and internal target climate. This paper introduces the newest scientific and engineering technologies of aerodynamics that can be used to improve structural and ventilating designs.

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DIFFICULTY OF VENTILATION STUDY

Mainly, the flow field can be analyzed by three methods: experimental, theoretical, and numerical simulation. Experimental methods acquire the most practical data using magnificent measurement systems and their high accuracy. However, it requires magnificent labor, time, space, and cost. Moreover, measuring air velocities directly and overall ventilation rates in agricultural buildings is quite difficult. External wind speed and direction varies constantly, and airflow and its data analysis is difficult to visualize. Because of such difficulties in field experiments, some indirect methods have been used for ventilation study, such as energy & mass balance model, wind-buoyancy effects model, tracer gas tracking, and others. However, most of these can predict only overall ventilation rate. Using these methods is difficult especially in effectively analyzing locally poor environments in buildings.

For structural designs and ventilation improvement, the newest technologies on aerodynamics are used, such as large-sized wind tunnel, and Computational Fluid Dynamics (CFD). The wind tunnel is a device wherein the airflow can be artificially controlled to study flow force on objects, object reaction, vibration, and so on. Even though the wind tunnels have been used for over a century by various engineering studies, quantitative airflow visualization using Particle image velocimetry (PIV) makes the wind tunnel test much more powerful for aerodynamic study. CFD is a science of developing approximate numerical solution to the Navier-Stokes equations over a discretized flow field.

During the last decade, those techniques show significant advantages for aerodynamic study on agriculture compared to field experiments and other indirect methods. First, while maintaining stable and identical boundary conditions, the CFD and wind tunnel tests can easily simulate and change any weather conditions and structural specifications. Second, they can visualize airflow patterns quantitatively as well as qualitatively. Third, unlike Energy balance model and Wind/buoyancy effect models, CFD can compute airflow and all psychrometric conditions of air at any location. Moreover, while most of the indirect methods required extensive instrumentation and high measurement accuracy in well-defined experiments, the aerodynamic technologies can decrease research period greatly and change boundary conditions of weather and structures easily. Designing and developing an overall system of HVAC can easily be performed by airflow visualization, quantitatively and qualitatively. Moreover, design credibility can also be improved according to the optimum design of environmental controlling system and building structure. Ultimately, it saves cost, labor, and time.

NEWEST TECHNOLOGIES OF AERODYNAMICS

Most airflow patterns, forced as well as natural ventilation, are unsteady and has three-dimensional turbulent flow. Also, the internal environment is closely related to the airflow patterns. Recently, aerodynamic approach is considered highly important to precisely predict and then control complicated airflow distributions of turbulent airflow as the current tendency of large-scaled and non-windows. To precisely analyze ventilation problem, precise information on actual airflow distribution is a must. For structural design and ventilation improvement, newest technologies are recently used such as large-sized wind tunnel, PIV, and CFD.

1) WIND TUNNEL

The wind tunnel is a device to produce a controlled stream of air for its effects on moving objects (like aircraft moving through air), or the effects of moving air on stationary objects (such as buildings). Applications of wind-tunnel research range from testing of airframes (the structures of aircraft and

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spacecraft) to research on the boundary layer, turbulence, drag, and lift as well as internal and external airflow distributions of structures. The wind tunnel is used to study the effect of airflow phenomena and airflow patterns on wind force of objects or movement of materials by making airflow artificially. While normal wind tunnel makes continuous airflow by circulating the air movement, other types include the open-return type, closed-return type, and suction type. The different types refer to how airflow is circulated. Compared to field experiment using full-scaled models, the wind-tunnel test can use small-scaled models that can methodically change model shapes or size, and then analyze the data. It entails low cost, and provides for an easy and safe job. Magnificent data is also collected for a short time. However, the scales of model size, time, air velocity and turbulence profiles, and pressure should be carefully considered and then calculated to obtain valid results (Jensen, 1958)



Fig. 1 General view of wind tunnel at National Agricultural Mechanization Research Institute of Rural Development Administration in Suwon

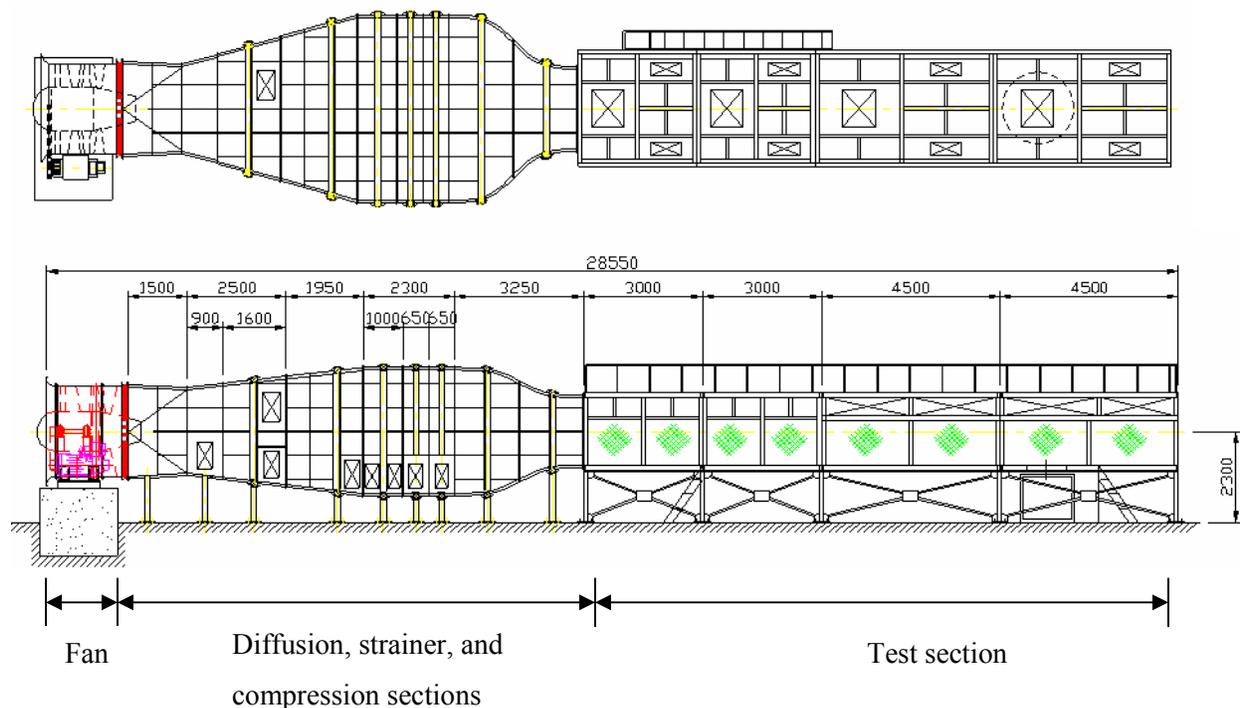


Fig. 2 Plane and side figures of the wind tunnel

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A large-sized wind tunnel was built at National Agricultural Mechanization Research Institute (NAMRI) in Korea on October 24, 2002 (Figs 1 & 2). Table 1 explains in detail that the tunnel is an Eiffel type, and the size of the test section is measured 2.0(W)×1.7(H)×15(L) m. The wind tunnel, including the 15m test section, is 29m long. The height and width of the test section was decided such that 1/20 ~ 1/700 scaled models of agricultural buildings could be tested with this tunnel. The test section is 15m long so that wind profile could be formed easily and stably. The wind tunnel is used mainly as follows.

- Structural design of agricultural buildings
- Ventilation system design
- Decision of large-scaled farm location as well as design
- Study on usage of wind energy in agriculture
- Improvement of pesticide efficiency

Table 1. Specifications of wind tunnel at National Agricultural Mechanization Research Institute in Suwon, Korea

BOUNDARY LAYER WIND TUNNEL	
Type	Eiffel type
Total length	28.5m
Test area	2.0(W)×1.7(H)×15.0(L)m
Wind speed	0.3 ~ 15m/s
Turbulent intensity	Less than 0.5%
Flow uniformity	Within 0.5%
Contraction ratio	4.0 : 1
FAN	
Type	Aerofoil Type Axial Fan
Diameter	2.5m
Maximum speed	Maximum 635RPM
Flow rate	5000 m ³ /min
MOTOR	
Type	DC Motor (Torque Constant Type)
Power	132KW, 60Hz, 3Phase
Maximum speed	Maximum 1150RPM
Voltage	380Voltage

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The body part, from the ventilator to the axial flow section, is built with steel. The sides, bottom and top of the measurement section are made of steel. The entire 15m side of the measurement section is covered with observatory glass. On the part where there is a turntable and a three-dimensional traverse system, its ceiling has an observatory glass. The rectifying screen uses a $\Phi = 0.33\text{mm}$ 20mesh stainless screen, three of which are placed in the diffuser and four in the rectifying section. In addition, a 20cm-long aluminum rectifying grid was installed in the rectifying section of the tunnel. At the center of the diffuser, four electric breathing doors were installed, one on each side. Minimum wind velocity that is controllable with the RPM of a ventilator is 0.3m/s. By using breathing doors, velocity was controlled and lowered. There is a three-dimensional traverse system to measure data in the test section effectively and automatically. Centering around the turntable, it is run in three directions—the air flow direction, the perpendicular to the air flow, and vertical direction. The operation of the ventilator, the turntable, force balance, and the traverse system can be controlled anywhere from two PCs in the control room linked through a network.

2) PARTICLE IMAGE VELOCIMETRY

The ability to see flow patterns in and around a device under investigation often gives insight into a solution to an aerodynamic problem (Barlow et al., 1999). The easiest method to get flow information is flow visualization. It envisions a process of transport phenomena of flow resulting in that invisible space distribution of flow information. Velocity, pressure, density, temperature and others can be visible with the functions of time and space. For the last few decades, most of airflow analysis was done using computer simulation. Domain resolution has been improved, and calculating time has been greatly decreased depending on increased computer capacity. However, it is very difficult to evaluate its accuracy because of non-comparable experimental data. Considering experimental study, conventional point-wise measurement using hot-wired anemometers can only allow local measurement of air velocity and pressure. Using this technique, it is impossible to analyze space variety of turbulent or unsteady airflow rapidly changing. More so, it is difficult to use anemometer sensors because these are difficult to install and natural airflow pattern are likely to be interrupted. To solve this problem, information on overall flow field should be obtained as time function. It was assumed that the PIV could solve the problem.

The flow visualization is mostly a non-contacting method so that it does not disturb the airflow, and accurately visualize overall flow field at certain time. Currently, PIV has been actively studied, and quickly developed as the newest high-end technology of flow analysis. Recently developed PIV systems are Cinematic PIV, Stereoscopic PIV, and Holography PIV for aerodynamic study (Raffel et al., 1998).

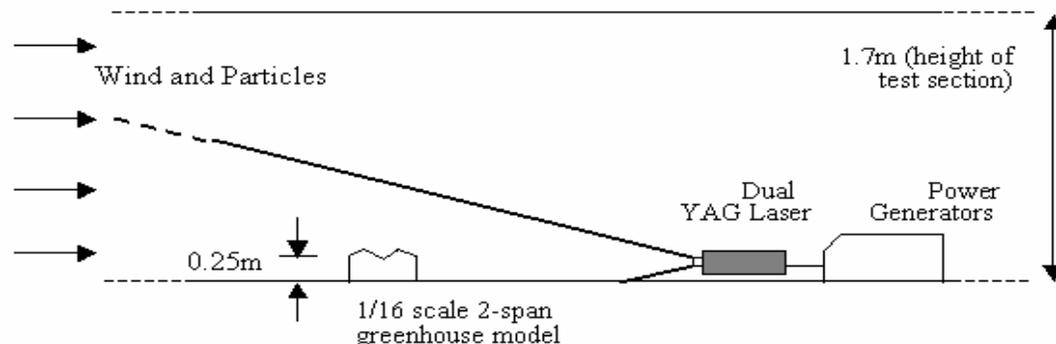
PIV systems measure velocity by determining particle displacement over time using a double-pulsed laser technique. A laser light sheet illuminates a plane in the flow, and the positions of particles in that plane are recorded using a digital or film camera. A fraction of a second later, another laser pulse illuminates the same plane, creating a second particle image. From these two particle images, unique and robust PIV analysis algorithms obtain the particle displacements for the entire flow region imaged, and gives velocity information at hundreds or thousands of locations--quickly, easily, and reliably. Flow properties such as vorticity and strain rates are obtained for the entire region. Other properties, such as mean, turbulence and other higher order flow statistics can also be obtained.

Fig. 3 shows the schematic diagram of the PIV setup in the test section of the wind tunnel. The PIV system included laser and light-sheet optics, an image capture/shifting component, synchronizer,

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and computer hardware/software. Lasers are widely used in PIV because of their ability to emit monochromatic light with high energy density, which can easily be bundled into thin light-sheets for illuminating and recording the tracer particles without chromatic aberrations (TSI/PIV manual, 1999).

1) Front view



2) Top view

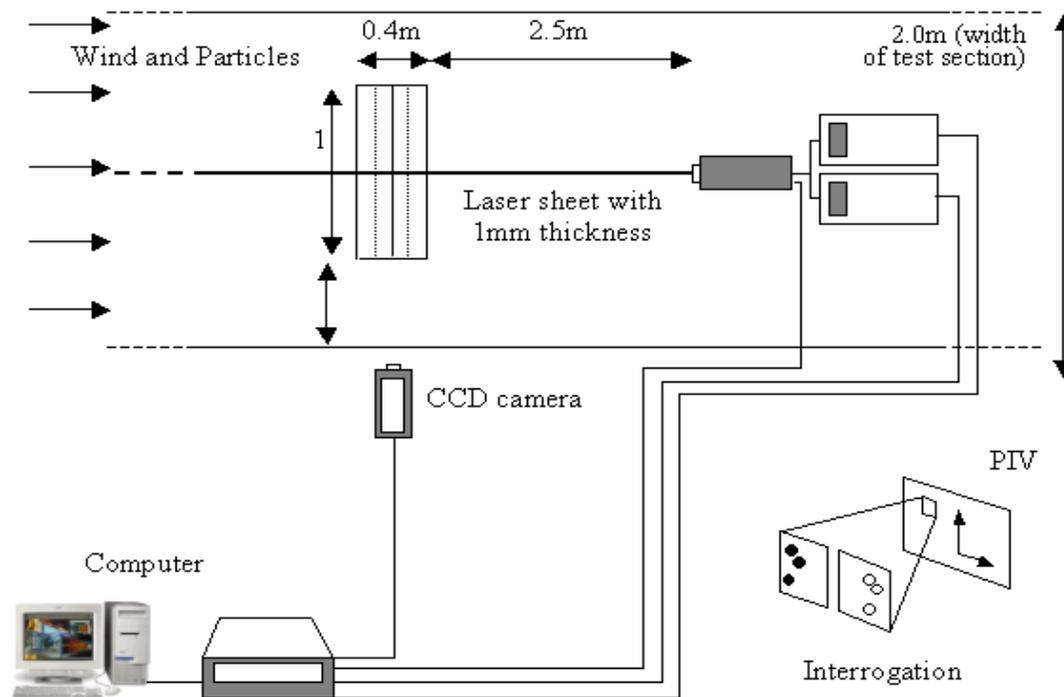


Fig. 3 Schematic diagram of the test section of the wind tunnel including Particle Image Velocimetry (PIV) system. The smoke particles were injected into the building for 1-2 hr before conducting each experiment, to make uniform particle conditions.

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3) COMPUTATIONAL FLUID DYNAMICS (CFD)

Numerical simulation has recently been on spotlights with the development of the computer industry. The typical numerical analysis using computer for aerodynamic study is Computational Fluid Dynamics (CFD). CFD model has recently become one valuable tool for analyzing natural ventilation systems. The CFD models predict distributions of internal airflow, air temperatures, and humidity and show the functionality of structural characteristics. However, it is the fact that only few researchers have investigated the validity of the CFD numerical simulations with actual data of airflow because of the difficulties of airflow analysis mentioned before. NAMRI has conducted the wind tunnel and PIV tests to investigate the CFD accuracy and its improvement by comparing their airflow distribution, local air velocity, and local turbulent intensity of the PIV and CFD results.

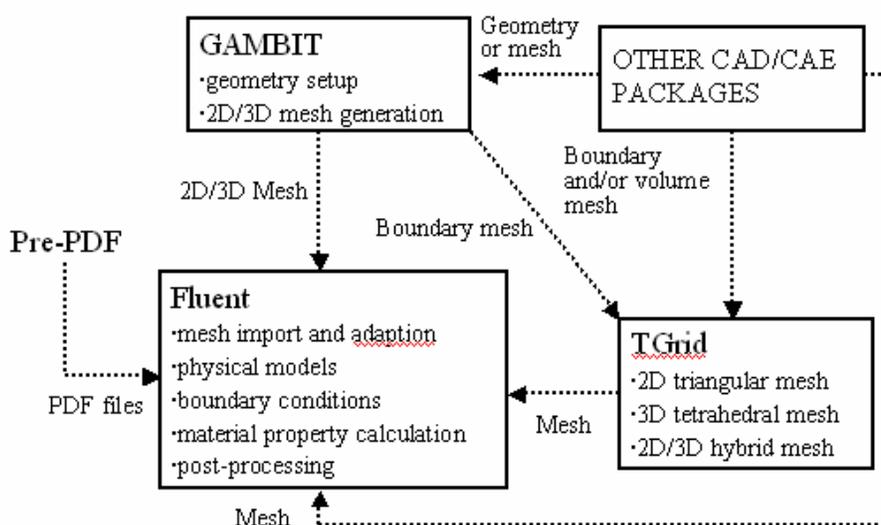


Fig. 4 Basic structure of Fluent CFD program

CFD technique numerically solved the Reynolds-averaged form of the Navier-Stokes equations (Lauder and Spalding, 1974; Fluent manual, 2000) within each cell in the domain. The governing equations were discretized on a curvilinear grid to enable computations in complex and irregular geometries. The Reynolds-averaged process is considered the instantaneous fluid velocity to be the sum of a mean and a fluctuating component of turbulence (Hinze, 1975; Bennet et al., 1995). Since the high-frequency and small scale fluctuations of turbulent flow could not be directly quantified, turbulence numerical modeling related some or all of the turbulent velocity fluctuations to the mean flow quantities and their gradients.

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fluctuations to the mean flow quantities and their gradients. The governing equations of mass, momentum, and energy used in Fluent are briefly described in Equations (1), (2), and (4), respectively.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (1)$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i \quad (2)$$

where P is the static pressure, τ_{ij} is the viscous stress tensor, and g_i is the gravitational acceleration. Considering several assumptions, Equation 2 can be changed as follows.

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial}{\partial x_i} \left(k \frac{\partial T}{\partial x_i} \right) - \frac{\partial}{\partial x_i} \sum_{j'} h_{j'} J_{j'} + \frac{\partial P}{\partial T} + u_i \frac{\partial P}{\partial x_i} + \tau_{ij} \frac{\partial u_i}{\partial x_j} \quad (6)$$

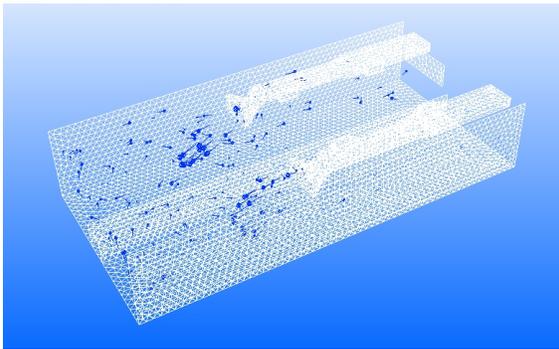
where T is the temperature, $J_{j'}$ is the flux of species j' , and k is the mixture thermal conductivity. The stress τ_{ij} is given by:

$$\tau_{ij} = \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] - \frac{2}{3} \mu \frac{\partial u_l}{\partial x_l} \delta_{ij} \quad (3)$$

where μ is the molecular viscosity and the second term on the right hand side is the effect of volume dilation.

Fig. 5 shows the time-dependent CFD airflow and relative humidity dilution in a mechanically ventilated piglet house.

a) Internal airflow



b) Internal relative humidity dilution

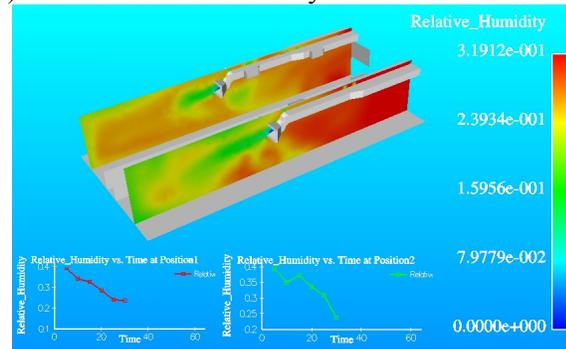


Fig. 5 CFD airflow and relative humidity dilution in a forced ventilated piglet house

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