Computational fluid dynamics for non-experts: Development of a user-friendly CFD simulator (HNVR-SYS) for natural ventilation design applications

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Measuring the ventilation rate is crucial to ensuring the control of thermal comfort, energy saving, and emission of pollutants in greenhouses and animal houses. This is more difficult in naturally ventilated (NV) buildings because of the dynamic and complex air flow patterns caused by wind and buoyancy effects. In this study, a user-friendly computational fluid dynamics (CFD) simulator is developed to analyse internal airflow patterns and ventilation rates of NV buildings, with the initial focus on agricultural buildings. The user-friendly CFD automation program, developed using the freely available open-source OpenFOAM and ParaView visualization toolkit, is aimed at non-CFD experts to help them obtain practical CFD solutions quickly. Users simply input building and ventilating configurations, outdoor wind conditions, topographical conditions, and information regarding plants or animals through user-friendly graphical user interfaces. General CFD processes are automated, and the quality of each process is controlled. After executing the program, a three-dimensional interactive visualization module is used for post-processing. It can ensure the flexibility and manageability of the model by automating predeveloped procedures in a user-interactive manner, thereby reducing time and effort. This paper describes the development process of automation interfaces.

Nomenclature			
A_c	Surface area of the animal (m^2)	r_s	Stomatal resistance of the leaf ($s\ m^{-1}$)
A_p	Cross-sectional area projected in the direction of the airflow (m^2)	r_t	Total resistances on both sides of the leaf ($s\ m^{-1}$)
B	Size of inner box (m)	S_ϕ	Source term for the time scalar
C_1	Parameters related to viscous (m^{-2})	S_T	Source term for the sensible heat generation by animals or plants ($K\ s^{-1}$)
C_2	Parameters related to inertial resistances (m^{-1})	S_U	Source term for the kinematic pressure loss by animals or plants ($m\ s^{-2}$)
C_d	Drag coefficient	T	Temperature (K)
C_p	Specific heats of air ($J\ kg^{-1}\ K^{-1}$)	T_{ref}	Reference temperature (K)
C_{pl}	Specific heats of leaves ($J\ kg^{-1}\ K^{-1}$)	T_a	Temperature of air (K)
C_μ	Dimensionless constant	T_{avg}	Average absolute temperature of the surface temperature and bulk temperature (K)
d	Characteristic dimension of the animal (m)	T_{bd}	Temperature of body core (K)
D_{max}	Maximum saturation deficit	T_c	Temperature of hair-coat surface (K)
D_{sat}	Saturation deficit of air	ΔT	Mean difference between the surface temperature and bulk temperature ($^{\circ}C$)
D_t	Diffusivity of the time scalar ($m^2\ s^{-1}$)	T_{flr}	Temperature of floor (K)
E_c	Latent heat loss from the skin ($W\ m^{-2}$)	T_l	Temperature of leaf (K)
E_r	Latent heat loss from the respiratory tract ($W\ m^{-2}$)	t_l	Thickness of the leaf (m)
F_d	Drag force acting on an animal ($kg\ m\ s^{-2}$)	T_{mid}	Average temperature between the skin and the outer surface of hair-coat (K)
G	Gravitational acceleration ($m\ s^{-2}$)	T_m	Average temperature K between the radiant temperature of the enclosure T_r and the hair-coat temperature T_c (K)
h	Crop height (m)	T_r	Temperature of radiant enclosure (K)
H	Height (m)	T_s	Temperature of skin (K)
H_a	Animal height (m)	U	Velocity ($m\ s^{-1}$)
h_g	Geostrophic plane height of the ABL (m)	ν	Kinematic viscosity ($m^2\ s^{-1}$)
k_a	Thermal conductivity of air ($W\ m^{-1}\ K^{-1}$)	ν_T	Kinematic turbulent viscosity ($m^2\ s^{-1}$)
K_c	Extinction coefficient	v_o	Velocity induced by the buoyancy effect
L	Characteristic length of the leaf (m)	V_z	Volume of the animal zone in the building (m^3)
L	Length (m)	W	Width (m)
LA_{lv}	Volumetric leaf area density ($m^2\ m^{-3}$)	w_a	Humidity of air
l_c	Coat depth (m)	w_l	Humidity of leaf
l_{cw}	Depth of wind penetration in the hair-coat (m)	β	Thermal expansion coefficient (K^{-1})
M	Net rate of heat storage in metabolic reactions	ϵ	Emissivity
n_a	Number of animals in the building	κ_{eff}	Effective thermal diffusivity ($m^2\ s^{-1}$)
N_u	Nusselt number	Λ	Latitude of the position ($^{\circ}$)
P	Kinematic pressure ($m^2\ s^{-2}$)	Λ	Latent heat of water evaporation ($J\ kg^{-1}$)
P_c	Coat penetration parameter (m^{-1})	μ_t/μ	Turbulent viscosity ratio
P_{sat}	Saturation pressure of air (Pa)	ρ	Density of the air ($kg\ m^{-3}$)
Q_a	Convective heat loss from the hair-coat surface to the air ($W\ m^{-2}$)	ρC_p	Volumetric specific heat of air ($J\ m^{-3}\ K^{-1}$)
Q_c	Heat losses from the skin to the hair-coat surface ($W\ m^{-2}$)	ρ_l	Density of the leaves ($kg\ m^{-3}$)
Q_{flr}	Heat losses from the skin to the floor ($W\ m^{-2}$)	σ	Stefan–Boltzmann constant ($W\ m^{-2}\ K^{-4}$)
Q_r	Radiative heat loss from the hair-coat surface to the air ($W\ m^{-2}$)	ϕ	Time scalar (s)
Q_t	Heat losses from the body core to the skin ($W\ m^{-2}$)	Ω	Angular velocity of the Earth's rotation ($rad\ s^{-1}$)
R	Proportion of the animal's trunk exposed to the air	ABL	Atmospheric Boundary Layer
R_d	Radius of computational domain (m)	BBSFA	buoyant Boussinesq Simple Foam AM
$R(z)$	Solar radiation at height z ($W\ m^{-2}$)	BBSFP	buoyant Boussinesq Simple Foam PM
r_a	Aerodynamic resistance of leaf ($s\ m^{-1}$)	DEM	Digital Elevation Model
r_b	Thermal resistance of the boundary layer on the hair-coat surface ($m^2\ K\ W^{-1}$)	GUIs	Graphical User Interfaces
r_{bt}	Thermal resistance of body tissue ($m^2\ K\ W^{-1}$)	LMA	Local Mean Age
R_c	Solar radiation absorbed by the leaf at the Height of z_c ($W\ m^{-3}$)	LMR	Local Mean Residual Lifetime
r_c	Thermal resistance of hair-coat ($m^2\ K\ W^{-1}$)	low Re	Low Reynolds Number
r_{flr}	Thermal resistance of floor ($m^2\ K\ W^{-1}$)	NV	Naturally Ventilated
R_{net}	Net solar radiation at the top of the crop	pvPython	ParaView Python Script
r_r	Radiative resistance of the boundary layer on the hair-coat surface ($m^2\ K\ W^{-1}$)	RANS	Reynolds-Averaged Navier–Stokes
		RNG	Renormalization Group ory

STL	Stereolithography	VB	Visual Basic
SYS	Simulate Yourself	VTK	Visualization Toolkit

1. Introduction

With the rapidly increasing global population, food security demands safer and more food production from limited resources, with less environmental impact (EuropeanCommission, 2008). Natural ventilation is important for indoor livestock and plant production systems, as it allows the indoor climate to be managed with minimal energy. For this reason, natural ventilation has been studied over the last two decades (Bjerg, Norton, et al., 2013; Bournet & Boulard, 2010; I.; Lee, 1998; I.; Lee, Sase, Okushima, Ikeguchi, & Park, 2002; I.; Lee & Short, 2000; I.; Lee & Short, 2001; I.; Lee, Short, Sase, & Lee, 2000; I.; Lee, Short, Sase, Okushima, & Qiu, 2000).

The estimation of ventilation rates has always been a fundamental requirement in assessing the ventilation capacity of naturally ventilated (NV) buildings and has resulted in aerial emissions. However, as indoor agricultural systems are enlarging to take advantage of economies of scale, it is more challenging to maintain proper indoor air flows against unpredictable weather conditions, especially in terms of wind speed and direction (Kacira et al., 2004). Uncertain ventilation rates reduce the quality of indoor environment and cause uncontrolled emissions of air pollutants to the neighborhood (Behera, Sharma, Aneja, & Balasubramanian, 2013; Hong, Lee, Hwang, Seo, Bitog, Kwon, Song, Moon, Kim, & Ko, 2011; Hong, Lee, Hwang, Seo, Bitog, Kwon, Song, Moon, Kim, Ko, et al., 2011; Skjøth & Geels, 2013; Takai et al., 2013).

Many methods have been developed to measure the ventilation rate of NV structures. Direct measurements use a range of anemometers but are primarily available for a limited number of point measurements over wide ventilation openings (Buggenhout, Ozcan, Vranken, Van Malcot, & Berckmans, 2007). Indirect measurements using the tracer gas method and energy balance theory are being widely used, but the imperfect mixing of indoor air and microclimate result in inaccurate results (Ozcan & Berckmans, 2010; Wang, 1998). Such measurement techniques are still being actively used despite their insufficient accuracy (25% errors on average) or inconvenience owing to bulky equipment (Buggenhout et al., 2007). Therefore, there is an increasing need for more accurate and convenient ventilation rate determination using numerical methods.

Computational fluid dynamics (CFD) simulation has been used to predict the complicated mechanisms of natural ventilation because of its advantage in predicting complex air flow patterns (Hong et al., 2017; Hong et al., 2008; I.; Lee et al., 2013; S.; Lee, Lee, & Kim, 2018; Norton, Sun, Grant; Fallon, & Dodd, 2007). While CFD simulations have been used in many different ventilation analyses, their results vary vastly in accuracy according to the researchers' skills and abilities. A modeller's skill in mesh design and problem understanding affect the final results significantly (Norton, Sun, Grant, Fallon, & Dodd, 2007), as the airflows are driven by the complexity of

the building configuration and local terrain. Moreover, CFD simulations are, to some extent, sensitive to the application for which the simulations are developed. In addition, if some changes in building shapes or ventilation configurations are required, the CFD model requires a re-design of mesh and geometry as a preprocessing, and a completely new simulation should be performed to adapt to those changes. Hence, CFD simulation requires relatively heavy workloads, which only CFD experts can manage; consequently, it is used primarily for research purposes rather than for practical use (Ai & Mak, 2014; Wakes, Maegli, Dickinson, & Hilton, 2010). CFD tools should, however, be made accessible to non-experts, such as farmers or agricultural building advisors/developers, to enable better building design in the agricultural industry.

This paper presents the development of a user-friendly CFD software that allows the practical use of the CFD technique in agricultural NV building design for non-experts. The ultimate goal is to develop an easy-to-use CFD simulator that automates all general pre-, main-, post-processing of CFD procedures for nonprofessional CFD users who wish to test their agricultural buildings by themselves (Hong, Exadaktylos, & Berckmans, 2014). The CFD calculation included in the software enables the natural ventilation flows that are wind-driven and buoyancy-driven and includes the effects of animals or plants on indoor thermal imbalance, thus resulting in airflows and the effect of terrain around the target building.

2. HNVR-SYS: general aspects

This study developed a handy natural-ventilation-rate (HNVR) calculator, named "simulate yourself (SYS)." The HNVR-SYS is an application program to automate the pre-, main-, and post-processes of CFD simulations and to analyse the ventilation performance of NV agricultural buildings. Figure 1 presents the framework of the SYS tool. It consists of graphical user interfaces (GUIs) that handle open-source OpenFOAM CFD packages (Open Field Operation and Manipulation, ver. 2.1, OpenFOAM Foundation) and the ParaView (v. 3.12, Kitware) visualisation toolkit (VTK) libraries, which were used for CFD simulations and visualisation, respectively. OpenFOAM and ParaView VTK were selected for this study because they are free and open-source software that enables spin-off program applications to be produced. The OpenFOAM was available on the Linux operating system, but the original codes and new solvers developed in this study were cross-compiled to be operated on the Windows system that is more user-friendly.

The automation routines were developed using Microsoft Visual Basic (VB). It provides the GUIs for users to enter the input data and control options, manage CFD calculations, and return the simulation results. The simulated results are displayed by a three-dimensional interactive visualisation that is realised by the VTK libraries and controlled by the ParaView

Fig. 1 – Framework of the CFD automation processes.

Python script (pvPython). Parallel computing solutions are also available for scientific purposes.

3. Materials and methods

This section describes the details of the CFD simulation and information regarding the automation processes. When users provide information upon a building structure, terrain, plants or animals, wind conditions, and simulation conditions, the program executes the scripted routines described in this section.

3.1. OpenFOAM CFD

OpenFOAM is a C++-based open-source CFD package developed on the Linux platform. It is distributed under the GNU General Public Licence by the OpenFOAM Foundation, allowing for free use, modification, and redistribution. The package includes preprocessing utilities for mesh generation and modification, parallel processing utilities for data decomposition and reconstruction, and main solvers for incompressible, compressible, and buoyancy flows. In this study, OpenFOAM 2.1.x was used and cross-compiled using the MinGW-w64 cross-compiler and source code patch supported by Symscape (<http://www.symscape.com>) on Manjaro Linux (ver. 0.8.10).

The basic structure for an OpenFOAM case is a file–folder system. The OpenFOAM case consists of several files that contain all simulation data such as mesh information, simulation configuration, and computed results. Its proper handling enables the automation of CFD processes.

3.2. Meshing strategy

Meshing was comprised of four steps as described in (Hong et al., 2017) using SnappyHexMesh utility (Fig. 2). First, the building structure and terrain surfaces were modelled as STL (stereolithography) files (Fig. 3). The second step was to create an initial computational domain that surrounds the building and terrain surfaces and create an initial background mesh on the domain. The third step was to split the initial mesh into a finer mesh using the “snappyHexMesh” utility of the OpenFOAM. The final step was to improve the mesh quality for accurate simulation results.

Fig. 2 – Meshing processes using SnappyHexMesh utility: a) initial background mesh, b) cell-splitting by surfaces and regions, and c) improvement of the mesh quality around surface geometries.

3.2.1. Building and terrain modelling

A building structure given by users is modelled by STL files that describe the surface geometry of a three-dimensional object in the form of a combination of triangulated surfaces. The easiest method for the triangulation was to change each wall into a regular grid of quadrilateral face elements and subsequently split the quadrilateral elements diagonally into

Fig. 3 – Sketches showing computational domain, its background meshing, and building geometry in STL format. B is the size of the inner box and determined as $B = 2\sqrt{W^2 + L^2} + 10$. The radius of the computational domain (R_d) was designed as $R_d = B\sqrt{2}/2 + 50$.

pairs of triangular faces. When ventilation openings exist on the wall, triangular faces located in the openings were omitted from the STL file.

The terrain is modelled from a digital elevation model (DEM) that should be given by a user. A dataset of the DEM is a two-dimensional array; therefore, by simply connecting each adjacent data point, the DEM becomes a grid of quadrilateral face elements. The remaining triangulation procedures are the same as the case of building structures.

3.2.2. Computational domain and meshes

Creating a computational domain and meshes was described in detail by (Hong et al., 2017). The size of the domain and meshes is dependent on the size of the building to achieve sufficient surrounding volume. For most agricultural buildings, the size of the computational domain satisfies the recommended domain size, which is generally $5H$ in height and $15H$ in length (Bjerg, Cascone, et al., 2013; Tominaga et al., 2008). An inner box of size B and $(H+5)$ is created at the centre of the domain to yield finer meshes around the target building.

A cylindrical domain was built as the computational domain and was initially filled with structured hexahedron cells. The “blockMesh” and “snappyHexMesh” utility of the OpenFOAM were used to create meshes, as shown in Fig. 4. A user-defined terrain surface can also be included in the

Fig. 4 – Process of splitting cells in the computational domain using snappyHexMesh utility.

computational domain before the refinement stages and treated the same as the building walls. After the refinement stages, the cells beneath the terrain surface were removed because they were not required for the air flow calculation.

The mesh size can be selected by users among 10 pre-defined mesh levels (Hong et al., 2017). The mesh size of the lowest level is four times the overall mesh, and eight times for near-wall meshes larger than those of the highest level. Every refinement process halves the mesh size. After the refinement stages, the “checkMesh” utility of the OpenFOAM is executed to detect bad-quality cells that are subsequently removed from the mesh to avoid numerical errors using the “setSet” and “subsetMesh” utilities (Ivchenko, 2011).

3.3. Numerical schemes

The governing equations to solve the airflows are the steady-state Reynolds-averaged Navier–Stokes (RANS) equations. The used numerical schemes are the same as those in (Hong et al., 2017). The turbulence quantities are modelled by two-equation $k-\epsilon$ models, which are the standard $k-\epsilon$ model, the RNG (renormalisation group theory) $k-\epsilon$ model, the realisable $k-\epsilon$ model, and the low Reynolds number (low Re) $k-\epsilon$ model.

The RANS equations combined with the energy equation are solved by the “buoyant Boussinesq Simple Foam” solver, which describes the buoyant and turbulent flows of incompressible fluids and the Boussinesq approximation. In this study, new solvers, “buoyantBoussinesqSimpleFoamAM” (BBSFA) and “buoyantBoussinesqSimpleFoamPM” (BBSFP) were developed to produce more realistic simulation results for animals and plants, respectively. The new solvers modified the “buoyantBoussinesqSimpleFoam” solver by adding the source terms to the energy and momentum equations to realise the heat generation and momentum sink from animals and plants, respectively.

The equations used for the BBSFA and BBSFP solvers are the momentum equation (1), continuity equation (2), and energy equation (3).

$$\nabla(UU) - \nabla(\nu_T \nabla U) = -\nabla p - [1 - \beta(T - T_{ref})]g + S_u \quad (1)$$

$$\nabla \cdot \mathbf{U} = 0 \quad (2)$$

$$\nabla(UT) - T\nabla U - \nabla(\kappa_{\text{eff}} \nabla T) = S_T \quad (3)$$

where U is the velocity (m s^{-1}), ν_T is the kinematic turbulent viscosity ($\text{m}^2 \text{s}^{-1}$), p is the kinematic pressure ($\text{m}^2 \text{s}^{-2}$), β is the thermal expansion coefficient (K^{-1}), g is the gravitational acceleration (m s^{-2}), T is the temperature (K), T_{ref} is the reference temperature (K), κ_{eff} is the effective thermal diffusivity ($\text{m}^2 \text{s}^{-1}$), S_U is the source term for the kinematic pressure loss by animals or plants (m s^{-2}), and S_T is the source term for the sensible heat generation by animals or plants (K s^{-1}).

The source term, S_U , is derived by the Darcy–Forchheimer equation.

$$S_U = - \left(\nu C_1 + \frac{1}{2} U C_2 \right) U \quad (4)$$

where, C_1 and C_2 are the parameters related to viscous and inertial resistances (m^{-2} and m^{-1}), respectively.

The source term, S_T , was calculated using different forms in the BBSFA and BBSFP solvers because animals and plants involve completely different energetic and physiological mechanisms, as explained in section 3.4.

3.4. Sensible heat generation

Sensible heat generation by animals and plants are calculated from their energetic balance models. Latent heat transfer owing to respiration or transpiration is also involved in the total energy balance, but air humidity is not modelled in this program because water vapour and latent heat do not affect the airflow patterns significantly compared to thermal effects.

A few mathematical models described the processes of heat transfer from animals to their surroundings based on the physics of heat transfer (Norton, Grant, Fallon, & Sun, 2010; Turnpenny, McArthur, Clark, & Wathes, 2000). For plants, especially the tomato crop, energetic activities were described in (Boulard et al., 2004; Boulard & Wang, 2002; Demrati et al., 2007; Wang & Boulard, 2000). The details of the mathematical modelling of sensible heat generation by animals and plants can be found in Appendices A and B, while equation (5) was used to describe the source term, S_T .

$$S_T = \begin{cases} \frac{A_c n_a Q_a}{\rho C_p V_z} & , \text{ for animals} \\ \frac{2LAI_v (T_l - T_a)}{r_a} & , \text{ for plants} \end{cases} \quad (5)$$

where A_c is the surface area of the animal (m^2), n_a is the number of animals in the building, V_z is the volume of the animal the zone in the building (m^3) calculated by the product of the floor area and the animal height (H_a), LAI_v is the volumetric leaf area density ($\text{m}^2 \text{m}^{-3}$), T_l and T_a are the temperatures of leaf and air, respectively (K), and r_a is the aerodynamic resistance of leaf (s m^{-1}).

3.5. Momentum loss

The existence of animals and plants reduces the momentum of airflows passing through the animal zone or plant zone. C_1

and C_2 are factors that determined the effect on the flow resistance. In a turbulent flow, the pressure decrease owing to viscous resistance is small compared to the pressure decrease by inertial resistance and can be neglected (Sase, Kacira, Boulard, & Okushima, 2012). Therefore, the momentum sink is almost dependent on the inertial resistance.

The momentum loss in the animal-occupied zone is described by simple physical concepts. When wind flows to an animal, the amount of drag force acting on the animal can be simply calculated as

$$F_d = \frac{1}{2} \rho v^2 C_d A_p \quad (6)$$

where F_d is the drag force acting on an animal (kg m s^{-2}), C_d is the drag coefficient, and A_p is the cross-sectional area projected in the direction of the airflow (m^2).

When the air exerts a force on the animal, the animal simultaneously exerts an identical force but in the opposite direction of the airflow, as described by Newton's third law. When n_a animals exist in a zone with a volume of V_z , the total force acting on the air that correspond to the momentum loss with respect to time is calculated in a unit volume as follows:

$$S_U = - \frac{n_a F_d}{\rho V_z} = - \frac{n_a A_p}{2V_z} C_d v^2 \quad (7)$$

Similarly, the inertial resistance of a plant is estimated from the drag coefficient of the plant using Wilson's equation that describes the relationship between the drag coefficient of the plant and the pressure loss (Wilson, 1985) (Wilson, 1985).

$$S_U = - LAI_v \cdot C_d v^2 \quad (8)$$

This yields the relationship between C_d and C_2 .

$$C_2 = \begin{cases} \frac{n_a A_p}{V_z} C_d & , \text{ for animals} \\ 2LAI_v C_d & , \text{ for plants} \end{cases} \quad (9)$$

3.6. Boundary conditions

For boundary conditions within the atmospheric boundary layer (ABL), vertical profiles of the wind speed and turbulence quantities can be designed in two forms, which are non-uniform profiles or uniform constant values. When the wind speed and turbulence kinetic energy, k , are given as a constant value that does not vary over the ABL, the given values are used as a fixed value for each inlet boundary condition. The turbulence dissipation rate at the inlet boundaries is set as (Burton, Jenkins, Sharpe, & Bossanyi, 2011; Burton, Sharpe, Jenkins, & Bossanyi, 2001):

$$\varepsilon = \rho C_\mu \frac{k^2}{\mu} \left(\frac{\mu_t}{\mu} \right)^{-1} \quad (10)$$

where, C_μ is the dimensionless constant of 0.09, and μ_t/μ is the turbulent viscosity ratio that is assumed as 100.

When a log profile is provided for the wind speed as shown in (11), the friction velocity, u_* , is calculated by a user-defined reference wind speed and used to design the vertical profiles of turbulence quantities. The vertical distributions of the mean wind speed, the turbulence kinetic energy and its dissipation rate, and the turbulent viscosity for the inlet

boundaries are shown as follows (Burton et al., 2001) (Burton et al., 2001):

$$U(z) = \frac{u_*}{K} \ln\left(\frac{z + z_0}{z_0}\right) \quad (11)$$

$$k(z) = \frac{u_*^2}{\sqrt{C_\mu}} \left(1 - \frac{z}{h_g}\right)^2 \quad (12)$$

$$\varepsilon(z) = \frac{u_*^3}{K(z + z_0)} \quad (13)$$

$$\mu_t(z) = u_* K z \left(1 - \frac{z}{h_g}\right)^4 \quad (14)$$

where h_g is the geostrophic plane height of the ABL that is calculated as

$$h_g = \frac{u_*}{12\Omega \sin(|\Lambda|)} \quad (15)$$

where Ω is the angular velocity of the Earth's rotation ($7.2722 \times 10^{-5} \text{ rad s}^{-1}$), and Λ is the latitude of the position.

The boundary conditions at the inlet, outlet, top, ground, and building walls are set as shown in Table 1. The side boundary of the cylindrical domain is divided into 16 parts representing the 16 wind directions. When the wind direction is given, the windward 8 parts are set up as inlet while the leeward 8 parts are set up as outlet.

3.7. Calculating LMA and LMR

The local mean age (LMA) and local mean residual lifetime (LMR) were used to evaluate the efficiency of ventilation (Kwon et al., 2011). During the ventilation process, fresh air can reach any point through various pathways. The LMA of air at a given point refers to the average time of streams that the fresh air travels from the inlet to the point, while the LMR of air is the average time of streams that the old air at the given point reaches the exit.

After obtaining a convergent solution for the velocity, the LMA and LMR are calculated by the method proposed by Park, Lee, and Hong (2014). In this method, the distribution of the LMA is calculated by solving the passive scalar transport equation for the time scalar, φ , with the uniform production of the time scalar over the ventilation space as shown in (16).

$$\frac{\partial \varphi}{\partial t} + \nabla(U\varphi) - \nabla(D_T \nabla \varphi) = S_\varphi \quad (16)$$

where φ is the time scalar (s), D_T is the diffusivity of the time scalar ($\text{m}^2 \text{s}^{-1}$), and S_φ is the source term for the time scalar.

Assuming that the time scalar is transported in the opposite direction to the airflow, i.e., the air travels from the outlets to inlets, the solutions of the time scalar transport equation imply the distribution of time that air travels from the outlets to the internal positions, corresponding to the LMR. Therefore, the LMR is calculated by replacing U with $-U$ in the second term of (16), which is the convection term, and by solving the revised scalar transport equation. The two equations for the LMA and LMR are introduced into a new solver, "ageOfAirFoam" developed in this study.

3.8. Management of simulation

Creating the OpenFOAM case is the fundamental procedure for CFD simulation. The OpenFOAM case consists of three folders, each of which contains the files with proper file names and are written with the syntax rules of the OpenFOAM. To create the OpenFOAM case, data obtained from the inputs are written in the right locations of the files.

As shown in Fig. 5, the wind conditions given by users are used to build the boundary conditions. Each involved quantity, such as velocity, pressure, turbulent quantities, and energy, is defined by individual files, and all files are placed in the "0" folder. The building geometry and terrain data are modelled as STL files in the subfolder of the "constant" folder. Some constants to be used in the governing equations and parameters to calculate the source terms for heat and momentum owing to animals or plants are also written in the "constant" folder. The "system" folder includes files related to the meshing techniques, selected numerical schemes and algorithms, calculation time and conditions, and parallel processing. Apart from the files above, some files are included in the OpenFOAM case to automate the simulation processes.

Based on the OpenFOAM case file, the CFD simulation was conducted through a typical procedure, i.e., mesh generation and poor mesh removal (section 3.2), solution initialisation and inlet boundary condition revision, primary calculations (section 3.3~3.6), and LMA and LMR calculations (section 3.7), as shown in Fig. 5. Each step is executed by executing the suitable OpenFOAM utility.

Among the CFD procedures, the mesh generation, primary calculations, and LMA and LMR calculations can be performed by parallel computing. When parallel processing is activated, additional actions are performed before and after each step. Before the step, the computational domain and all data fields were decomposed into the desired number of partitions. Decomposition was performed using the hierarchical method

Table 1 – Boundary conditions for velocity (V), pressure (p), turbulence kinetic energy (k), turbulence dissipation rate (ε), turbulent viscosity (μ_t), and temperature (T) at inlet, outlet, top, ground, and building structures.

	Inlet	Outlet	Top	Ground	Building
V	Fixed value	Outlet	slip	Fixed value (U = 0)	Fixed value (U = 0)
P	Zero gradient	Fixed value	slip	Zero gradient	Zero gradient
k	Fixed value	Zero gradient	slip	Wall function	Wall function
ε	Fixed value	Zero gradient	slip	Wall function	Wall function
μ _t	Calculated	Calculated	Calculated	Wall function	Wall function
T	Fixed value	Outlet	slip	Zero gradient	Zero gradient

Fig. 5 – CFD simulation and automation pipeline.

in which the domain is split into the specified number of pieces in the x-, y-, and z-directions. Meanwhile, the partitions are reconstructed as before after the mesh generation or when the calculations are completed. Parallel computing is performed by the freely available MPICH2 (version 1.4.1p1, <http://www.mpich.org/>).

4. HNVR-SYS: primary functionalities

This section briefly describes the primary modules and user interfaces available in HNVR-SYS. Figure 6 presents several GUIs that comprise the program. A complete overview and more details of the program are provided in the HNVR-SYS tutorial and documentation.

4.1. Inputs and options for CFD simulation

The automation tool requires information about the geometry, ABL, and simulation methodology that should be provided before it runs. The geometrical information contains dimensions of a building structure and its ventilation openings, terrain map and its information, and animals/plants data if they exist in the building. The ABL information includes the wind speed as a constant value or a log profile, wind direction, turbulence level, and ground roughness. The simulation information involves the controls of mesh generation, CFD computation, and parallel computing environment.

The inputs that should be provided or selected by the users are as follows.

Fig. 6 – HNVR-SYS graphical user interfaces.

- Building: Selectable between six building types, dimensions of walls and roof, roof slope ratio or curvature, eave length, and ventilation opening size and location.
- Terrain (optional): DEM file or DEM image file, terrain size, highest/lowest elevation (if a DEM image file is given), location, and direction of the building.
- Animals/plants (optional): Animal type (cattle, pigs, poultry) and data presented in Table 2; plant data presented in Table 3.
- Wind conditions: Wind direction (16 directions), wind speed (log profile is selectable), reference height (if a log profile is selected), turbulence kinetic energy (or turbulence intensity), ground roughness.

Simulation controls: Mesh size, meshing technique (poor-quality correction, adding layer), turbulence model (among four k- ϵ models), numerical schemes (GAMG, PCG, smooth-Solver, PBICG), relaxation factors, number of computation steps, number of computing nodes (if parallel processing is activated).

4.2. Result visualization

The simulation results are analysed in two aspects. One is to show the ventilation rates at each ventilation opening and the overall ventilation rate. The other is to visualise airflow patterns in and around the building, and the distributions of any physical properties in the building. The visualisation tool was coded in Python to render the simulation results in the VTK format as a three-dimensional visual object.

The visualisation application creates a view window and represents the building outline and, if desired, the terrain surface in the view window. It also creates a slice to show variable values over a plane on which the LMA, LMR, velocity, pressure, temperature, turbulence quantities, and airflow

Table 3 – Parameters and their default values for plant modelling. The values are from Boulard et al. (2004); Hong (2008) but are user definable.

Parameter	Default values (cattle/pigs/poultry)
LAI	3
h_p	1.8
L	0.25
T_{ai}	298.15
w_a	40%
R_{net}	600
a	2.7
b	1/17.5
K_c	0.75
$r_{s, min}$	30
D_{max}	1000
ρC_p	1220 at 20 °C
C_d	0.26
Relaxation	0.2
# iterations	25

vectors are found, as shown in Fig. 7. The sliced plane can be bounded into the building and extended to the exterior of the building; the location and direction of the slice are also controllable using a keyboard and mouse. The view window allowed for users to perform manipulations interactively, such as zoom in, zoom out, rotate, and move the viewpoint using the mouse.

4.3. Procedure to use HNVR-SYS

A CFD problem can be solved by the basic procedural steps as follows. 1) Determine the important features of the problem that a user wishes to solve. 2) Select the building type, and input the dimensions of the building and its ventilation openings. 3) If applicable, load a DEM file to create a terrain surrounding the building. Establish the direction of the

Table 2 – Parameters and their default values for animal modelling. The values are from Turnpenny, Wathes, Clark, and McArthur (2000) but are user definable.

Parameter	Default values (cattle/pigs/poultry)
A_c	$0.09 m_b^{0.67} / 0.086 m_b^{0.67} / 0.081 m_b^{0.67}$, while m_b is the mass (liveweight) of the animal (kg)
m_b	500/70/1
d	$2\sqrt{\frac{A_c}{4\pi}}$ by assuming the animal as a sphere
H_a	1.45/0.65/0.45
T_{bd}	38 °C/39 °C/41 °C
p	1800/1800/500
c'	$2.4 \times 10^{-5} / 2.4 \times 10^{-5} / 9.1 \times 10^{-6}$
r_t	147/130/250
r_{fir}	85 for concrete
E_c	7/10/5
E_r	10/20/5
k_a	0.0257 at 20 °C
B	0.48
m	0.25
ϵ	1
ρC_p	1220 at 20 °C
C_d	1
Relaxation	0.8
# iterations	9
n_a, T_r, T_{fir}	should be given

Fig. 7 – Three-dimensional visualisation of the simulation results by the Paraview Python script.

building. 4) If applicable, select the internal object between animals and plants, and assign physiological parameters to them. 5) Input the wind speed, turbulence kinetic energy, and ground roughness for the inlet boundary conditions. Activate or deactivate the log profile option. 6) Select the mesh size among 10 levels. 7) Establish the calculation time. 8) If applicable, activate the parallel processing, and set the number of computing nodes. 9) If applicable, more technical options can be established in the advanced tap, such as the turbulence model, mesh options, numerical schemes for discretisation, and relaxation factors. 10) Execute the CFD processes by clicking the “auto process” button or by clicking four separate buttons sequentially. 11) Examine the simulation results.

In step 2, only six building types are available, but more structural types will be included in the program in the future. Although the simulation is automatically performed by the program, it is open to the user’s intervention because all files and folders of the OpenFOAM case are freely accessible.

5. Examples of HNVR-SYS applications

The developed program was used, as part of a validation study, to examine the accuracy of the OpenFOAM simulations by [Hong et al. \(2017\)](#). In its current state, the program comprises three building types, and [Hong et al. \(2017\)](#) compared the simulation results with wind tunnel measurements. The OpenFOAM simulations yielded good agreement with the measured air velocities. Two examples given below show further validity of the developed program with regard to the prediction of ventilation rate and indoor air temperature.

5.1. NV greenhouse

In the first example, an even-span greenhouse of size 9 m (W) $\times$ 45 m (L) $\times$ 4.95 m (H) was modelled. The building contained two continuous side vents and angled roof vents, as shown in [Fig. 8](#). [S. Lee et al. \(2018\)](#) calculated the ventilation

rates according to various wind directions (0° , 45° , and 90°) and wind speeds (1.0 , 2.5 , and 5.5 m s^{-1}) using a commercial CFD code and validated the simulated results through wind tunnel measurements. The same structure and wind conditions were modelled using the HNVR-SYS with a mesh level of three and the RNG $k-\epsilon$ turbulence model; the results are in good agreement with those by [S. Lee et al. \(2018\)](#), showing an average relative error of 11.8% and an RMSE error of 0.43 min^{-1} ([Fig. 9](#)).

5.2. NV dairy barn

In the second example, an NV dairy barn studied by [Samer et al. \(2011\)](#) was tested. The dairy barn of size 34.2 m (W) $\times$ 96.15 m (L) $\times$ 10.73 m (H) was ventilated primarily through adjustable curtains on the long sidewalls and open ridge slots, and accommodated 364 dairy cows. [Samer et al. \(2011\)](#) measured the air temperatures and ventilation rates in the summer, among which five consecutive measurements were compared to the simulation. HNVR-SYS was used to model the dairy barn where all the inputs were the same as the experimental conditions of [Samer et al. \(2011\)](#). Wind speed varied from 0.3 to 3.5 m s^{-1} in the measurement, and the average wind speed of 1.9 m s^{-1} was tested in the simulation. [Figure 10](#) shows the comparison of the indoor air

Fig. 8 – Schematic diagram of the even-span greenhouse ([S. Lee et al., 2018](#)).

Fig. 9 – Comparison of ventilation rates obtained by the reference (S. Lee et al., 2018) and HNVR-SYS of this study. WD stands for wind direction, and 90° indicates the wind blowing perpendicular to the side vent.

temperature increase owing to heat generation by animals and the ventilation rates between five measurements and HNVR-SYS result. The air temperature was less increased in the simulation, and this may be because other heat sources besides animals' body heat were not considered in the simulation. In the summer, air temperature near the ground is generally higher than that measured at weather stations due to solar radiation. While the hot air might enter the barn through the side openings, the simulation considered the air temperature measured at the weather stations as the outdoor air temperature, which would not heat up the barn up to the desired level. The simulated ventilation rate was also slightly smaller than the ones measured by the tracer gas method. It was because the experimental barn opened gates and doors at the front side of the barn through summer seasons, which is a practice for common naturally-ventilated barns to allow more ventilation air flows into the barn. Notwithstanding the slight underestimates, the simulated results were still within the range of measured values, indicating that the HNVR-SYS produced a reasonable approximation of heat generation by animals, the corresponding indoor air temperature, and the ventilation rate of the naturally-ventilated barn.

Fig. 10 – Comparison of indoor air temperature rise and ventilation rate between the reference (Samer et al., 2011) and HNVR-SYS result.

In the two examples, results obtained by HNVR-SYS were in good agreement with those in the references. In particular, a remarkable benefit from HNVR-SYS was that the program reduced time and effort by automating the mesh generation, which is the most time consuming part for engineering problems generally. Only a few hours were required to complete the CFD computation from scratch, while a few days are required for any CFD tool to complete the pre-, main-, and post-processes.

6. Conclusions and further developments

In this study, an automatic simulation tool using CFD for non-experts was developed to predict the ventilation rate of NV buildings. OpenFOAM and ParaView VTK were used for CFD simulation and visualisation, respectively, because they are free and open-source software. The simulation tool, HNVR-SYS, was developed using Microsoft VB and Python to automate the general processes of the CFD simulation, such as the building geometry, meshing and computing, and GUIs for users. The GUI allowed the user to easily design the structure and surrounding terrain, and create wind conditions that were subsequently used to build the boundary conditions of the simulation model automatically.

HNVR-SYS provides general users, such as farmers, companies, and researchers, with quick and practical solutions to simulate the ventilation process without any help from CFD experts but with the advantage of ensuring a similar level of accuracy by the predeveloped procedures and reduced time and effort. It can model the effect of a terrain shape on the atmospheric boundary layer and natural ventilation easily, and simulate the effect of animals or plants in a thermal environment and buoyancy-driven ventilation.

This study proposed a new simulation idea for encouraging people from CFD technique. While CFD is still a highly technical method, further development of CFD automation would enable non-CFD experts to apply aerodynamic knowledge to their various fields of research. The first step can be using ventilation prediction in a mechanically ventilated agricultural building, which still accounts for the majority of agricultural buildings. The emission of NH_3 and dust from animal houses and their dispersion to downwind communities is becoming a serious concern and can benefit from the program. More building types that are typically used should be included in the program to be further developed. Moreover, validation tests should be conducted persistently.

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Appendix A. Heat Source from Animals

The heat transfer from animals can be described in three layers: the layer between the body core and the skin, the layer between the skin and the hair-coat surface, and the layer between the hair-coat surface and the air. When an animal is in thermal equilibrium, heat is transferred in the first layer through the body tissue and blood by conduction, and convection. In the second layer, heat is transferred through the hair-coat by conduction, convection, and radiation. Heat is also transferred in the form of latent heat from the skin. In the third layer, heat is transferred to the air by convection and radiation. Apart from the three layers above, the animal can lose its body heat through its respiratory tract and through a direct contact with the floor.

The rate of heat transfer depends upon the temperature difference, resistance to heat flow, and additional heat transfers, as shown in (A-1).

$$Q = (T_1 - T_2) / r + Q_3 \quad (\text{A-1})$$

Table A1 – List of heat losses and related variables in heat transfer processes from animals.

Heat loss (Q) from 1 to 2	Temperature at 1 (T ₁)	Temperature at 2 (T ₂)	Thermal resistance (r)	Additional term (Q ₃)
Q _t	T _{bd}	T _s	r _{bt}	E _c
Q _c	T _s	T _c	r _c	
Q _a	T _c	T _a	r _b	
Q _r	T _c	T _r	r _r	
Q _{flr}	T _s	T _{flr}	r _{bt} + r _{flr}	

In Table A1, Q_t, Q_c, and Q_{flr} are the heat losses from the body core to the skin, from the skin to the hair-coat surface, and from the skin to the floor (W m⁻²). Q_a and Q_r are the convective heat loss and radiative heat loss from the hair-coat surface to the air, respectively (W m⁻²). T_{bd}, T_s, T_c, T_a, T_r, and T_{flr} are the temperatures of the body core, skin, hair-coat surface, surrounding air, radiant enclosure, and floor (K). r_{bt}, r_c, and r_{flr} are the thermal resistances of the body tissue, hair-coat, and floor (m² K W⁻¹). r_b and r_r are the thermal resistance and radiative resistance of the boundary layer on the hair-coat surface, respectively (m² K W⁻¹). E_c is the latent heat loss from the skin (W m⁻²).

The resistances, r_t and r_{flr}, are the characteristics of an animal, while r_c, r_a, and r_r are influenced by the surrounding air conditions.

$$r_b = \frac{d}{k_a N_u} \quad (\text{A-2})$$

$$r_r = \frac{1}{4\sigma\epsilon T_m^3} \quad (\text{A-3})$$

$$r_c = \frac{l_c - l_{cw}}{\rho C_p} \left(\frac{(T_s - T_c)^{0.53}}{14.5 \times 10^4} + \frac{k_a}{\rho C_p} + \frac{16\sigma T_{mid}^3}{\rho C_p (3p_c)} \right)^{-1} \quad (\text{A-4})$$

where d is the characteristic dimension of the animal (m), k_a is the thermal conductivity of air (W m⁻¹ K⁻¹), and N_u is the Nusselt number. The Nusselt number can be obtained from N_u = B Gr^m for free and natural convection flows. Monteith and Unsworth (Monteith & Unsworth, 2008) assigned B = 0.48 and m = 0.25. The Grashof number was calculated as Gr = gTd³/ν²T̄. ν is the kinematic viscosity of air (m² s⁻¹), g is the gravitational acceleration (m s⁻²), ΔT is the mean difference between the surface temperature and bulk temperature (°C), and T̄ is the average absolute temperature of the surface temperature and bulk temperature (K). T_m is the average temperature (K) between the radiant temperature of the enclosure (T_r) and the hair-coat temperature (T_c), σ is the Stefan–Boltzmann constant (5.670373 × 10⁻⁸ W m⁻² K⁻⁴), and ε is the emissivity. For the indoor animals, T_r can be assumed to be the average temperature of the walls and floor (Turnpenny et al., 2000b). l_c is the coat depth (m), l_{cw} is the depth of wind penetration in the hair-coat (m), ρC_p is the volumetric specific heat of air (approximately 1220 J m⁻³ K⁻¹ at 20 °C), p_c is the coat penetration parameter (m⁻¹) that is the “projected area of hair on the plane of the skin per unit skin area, for a unit depth of coat,” which are approximately 500 m⁻¹ for sheep and 1800 m⁻¹ for cattle, and T_{mid} is the average temperature between the skin and the outer surface of hair-coat (K).

On the assumption that steady heat flows from and to each region of the body without any heat storage in any layer, two equations can be derived. Because two unknown variables, T_s and T_c, exist, equations (A-1), (A-5), and (A-6) are solved by an iterative method to generate successive approximations to the solutions for T_s and T_c.

$$Q_t = R(Q_c + E_r) + (1 - R)Q_{flr} \quad (\text{A-5})$$

$$Q_c = Q_a + Q_r \quad (\text{A-6})$$

where R is the proportion of the animal's trunk exposed to the air, and E_r is the latent heat loss from the respiratory tract (W m⁻²).

When the solutions are convergent, the rate of sensible heat flux from the animal to the air is derived as follows:

$$S_T = \frac{A_c n_a Q_a}{\rho C_p V_z} \quad (\text{A-7})$$

where A_c is the surface area of the animal (m²), n_a is the number of animals in the building, and V_z is the volume of the animal zone in the building (m³) calculated by the product of the floor area and the animal height (H_a).

Appendix B. Heat Source from Plant

The thermal activity of plants can be described in a single energy balance equation.

$$R_c = \frac{dR(z)}{dz} \Big|_{z_c} = 2LAI_v \cdot \rho \cdot C_p \cdot \frac{T_1 - T_a}{r_a} + 2LAI_v \cdot \rho \cdot \lambda \cdot \frac{w_1 - w_a}{r_t} + LAI_v \cdot t_l \cdot \rho_l \cdot C_{pl} \cdot \frac{dT_l}{dt} + M \quad (\text{B-1})$$

where R_c is the solar radiation absorbed by the leaf at the

height of z_c ($W m^{-3}$), $R(z)$ is the solar radiation at height z ($W m^{-2}$), LAI_c is the volumetric leaf area density ($m^2 m^{-3}$), ρ and ρ_l are the densities of the air and leaves, respectively ($kg m^{-3}$), C_p and C_{pl} are the specific heats of air and leaves, respectively ($J kg^{-1} K^{-1}$), λ is the latent heat of water evaporation ($2500000 J kg^{-1}$), T_l and T_a are the temperatures of leaf and air, respectively (K), w_l and w_a are the humidities of leaf and air, respectively (mass fraction: mass of water/mass of air), r_a is the aerodynamic resistance of leaf ($s m^{-1}$), r_t is the total resistances on both sides of the leaf ($s m^{-1}$), t_l is the thickness of the leaf (m), and M is the net rate of heat storage in metabolic reactions, e.g., photosynthesis or respiration.

The primary source is the indoor solar radiation that is a function of the height above the floor. The absorbed solar energy in the leaves is exchanged with the nearby air in forms of sensible and latent heat.

$$R(z) = R_{net} \cdot \exp\left(-K_c \cdot LAI \cdot \frac{h-z}{h}\right) \quad (B-2)$$

where R_{net} is the net solar radiation at the top of the crop, K_c is the extinction coefficient, and h is the crop height (m).

The first and second terms in the right side of equation (B-1) represent the sensible and latent heat exchanges at the leaves, respectively. These exchanges occur through the leaves' stomata. Because tomato leaves contain stomata on both sides, the ratio of the upper stomatal resistance face of the leaf by that underneath was introduced. The ratio (AA) depends primarily on the stomatal aperture and on the solar radiation at the crop level; and Boulard et al. (2004) suggested 2.7 and 1/17.5 for constants a and b , respectively.

$$AA = \ln(a + b \cdot R_{net}) \quad (B-3)$$

The total resistance of the leaf is calculated as follows:

$$r_t = \left(\frac{1}{r_a + r_s} + \frac{1}{r_a + AA r_s}\right)^{-1} \quad (B-4)$$

where r_s is the stomatal resistance of the leaf ($s m^{-1}$).

The aerodynamic resistance on the leaf is affected by the leaf boundary layer and depends on the shape of the leaf and air velocity near the leaf.

$$r_a = 305 \sqrt{\frac{L}{v + v_0}} \quad (B-5)$$

where L is the characteristic length of the leaf (m). The velocity induced by the buoyancy effect (v_0) depends on the shape and surface temperature of the leaf and is calculated as

$$v_0 = \frac{\sqrt{g \cdot |T_l - T_a| \cdot L \cdot 0.5}}{\sqrt{T_l}} \quad (B-6)$$

The aerodynamic resistance for water vapour exchange is known to be 0.93 times that for heat exchange (Goudriaan & Van Laar, 1994).

The stomatal resistance occurs when water vapour or carbon dioxides are diffused through the stomata. It generally ranges from 50 to 10,000 $s m^{-1}$, and depends on the crops. Shaer and Van Bavel (1987) indicated that the stomatal resistance can be 20 $s m^{-1}$ for a tomato crop. Demrati et al. (2007) suggested that the stomatal resistance was primarily calculated by a combination of solar radiation intensity ($f_1(x_1)$)

at the crop level and air saturation deficit ($f_2(x_2)$), or by a combination of solar radiation intensity and leaf temperature:

$$r_s = r_{s, \min} \cdot f_1(x_1) \cdot f_2(x_2) \quad (B-7)$$

$$f_j(x_j) = 1 + a_0 [\exp(a_1(x_j - a_2))]^n \quad (B-8)$$

Table B1 – Climatic factors for aerodynamic resistance of tomato crop (Boulard & Wang, 2002; Demrati et al., 2007).

x_j	a_0	a_1	a_2	n
$R(z)$	1	0.05	49	-1
D_{sat}	0.11	0.34	D_{max}	1

D_{sat} and D_{max} are the saturation deficit of air and the maximum saturation deficit, respectively.

The empirical equation was used to estimate the saturation pressure (Pa) of air.

$$P_{sat} = 610.78 \times \exp\left(\frac{17.25 \times (T_a - 273.15)}{237.8 + (T_a - 273.15)}\right) \quad (B-9)$$

The third and fourth terms in the right hand of equation (B-1) are for heat storages of leaves in terms of physical temperature change and metabolic reactions, respectively. The specific heat of the leaves varies from 3500 to 4000 $J kg^{-1} K^{-1}$, but the heat capacity of the leaves is frequently ignored because the energy storage is dominated by the large mass of the soil. The energy use in metabolism tends to be minuscule, and is typically only 1.5–3% of the incoming radiation is used for photosynthesis (Jones & Rotenberg, 2001).

Assuming that all other parameters are provided, the unknown variables are the temperature and humidity of the leaf. To solve the two unknown variables, an additional equation apart from the energy balance equation is derived from the relationship between the temperature and humidity of the leaf by assuming that the inside of the leaf is saturated.

$$P_{l,sat} = 610.78 \times \exp\left(\frac{17.25 \times (T_l - 273.15)}{237.8 + (T_l - 273.15)}\right) \quad (B-10)$$

Two unknown variables and two equations are solved by an iterative method to obtain a convergent solution. From the solution, the source term for the rate of sensible heat generation owing to plants is derived as

$$S_T = 2LAI_v \frac{T_l - T_a}{r_a} \quad (B-11)$$

Appendix C. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biosystemseng.2020.03.005>.

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