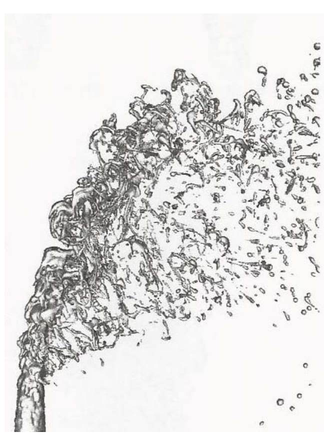
CO2 Dispersion

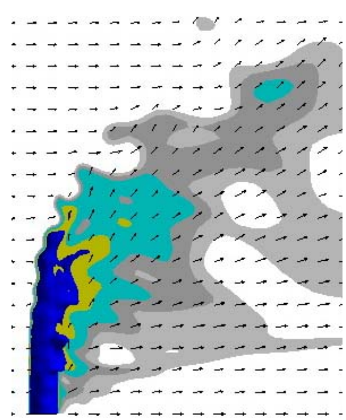
CO_2 gas control within indoor plant growing facilities (small and large) is critical to optimizing plant growth and yield. Multi-gaseous flow characteristics in complex scenes (with obstructions, heat sources, evaporation, plant transpiration, CO_2 sinks, etc) represents complicated fluid dynamic physics. A methodical and documented validation approach should be taken when modeling such physical systems.

A minimal amount of effort reviewing related published research has been undertaken, where ~30 research publications have been reviewed for relevance and quality (see reference list). Unfortunately, there is minimal research readily available (modeling or experimental) for complex indoor plant growth facilities focused on CO_2 management. However, the identified research is fairly current and several publications appear to be promising cases for validation studies.

The first validation case selected involves modeling a pure CO_2 jet introduced into a simple computational domain with a crosswind. The publication presents multiple CFD simulations and experimental results. At first glance, this case seems to be a simple and straight forward validation problem for CO_2 dispersion. However, the physics are actually quite complex as modeling multi-species gas requires special treatment (e.g., mass conservation, turbulence modeling, body-force treatment, etc). In addition to the multi-gas aspect, the high speed jet (2cm diameter at 8.8 m/s) into an air cross-wind also presents some challenges related to computational modeling.

Adaptive Research has completed a validation study of a similar physical model with air and water jets. This validation effort (part of a 90K engineering contract for an aerospace company), proved to be a computational challenge matching experimental results (see figure right and Appendix A of this document).





Selected Research for Validation/Verification

The following three research publications have been selected for validation cases, as the research publications present experimental and CFD simulation results of key physics related to CO2 dispersion. The research publications are also current (2008, 2016, and 2017).

Primary focus has been on Case I (to-date) as the physical aspects are well defined, and the experimental results are easily compared with.

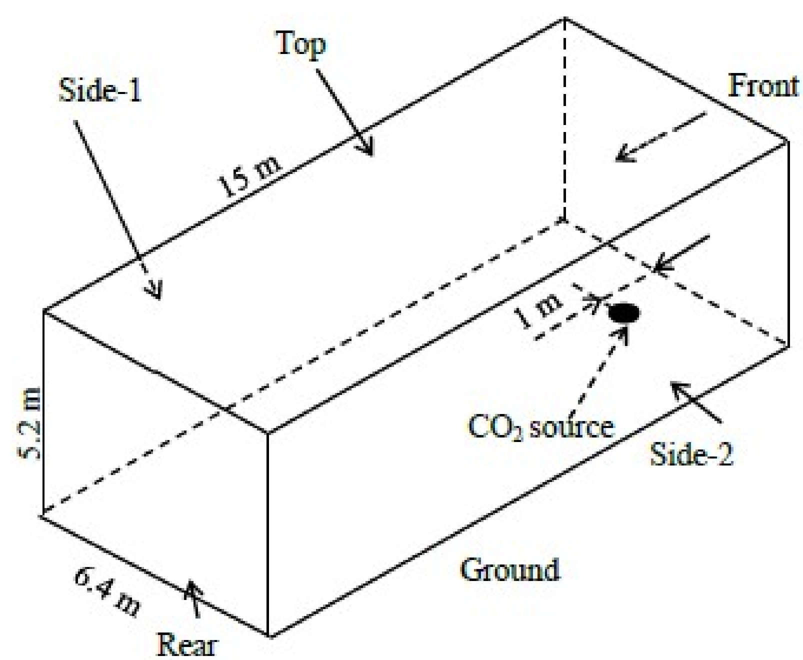
Case I - Computational fluid dynamics simulation of carbon dioxide dispersion in a complex environment (2016). *University of Wollogong Research Online.*

Case II - Experimental and CFD modeling for thermal comfort and CO2 concentration in office building (2017). *IOC Conference Series: Materials Science and Engineering.*

Case III - Thermal comfort conditions and air distribution in educational buildings (2008*). Indoor Air 2008.*

Case I - CO2 Dispersion in Cross-Flow Conditions

Case I represents a single CO2 source entering a flow domain with atmospheric flow conditions. It is essentially a "cross-flow" simulation with a CO2 jet entering a cross-flow air stream.



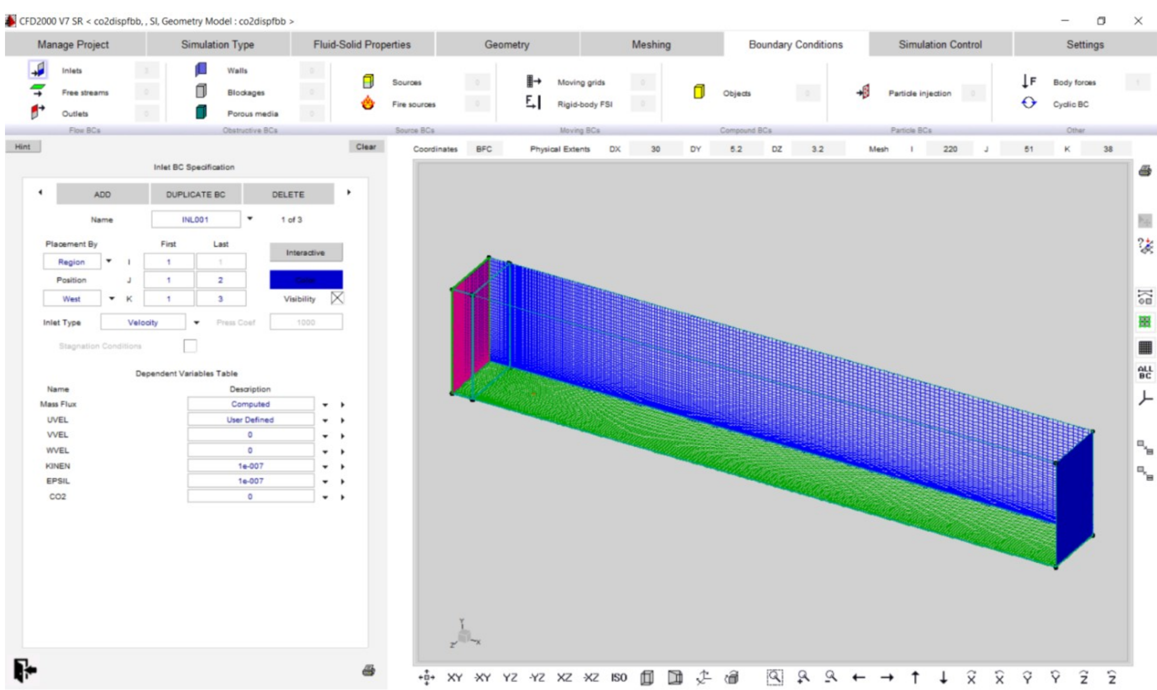
CAESIM Model

The developed CFD model consists of ~425000 computational cells for a "half" model symmetric in the Z-plane. The physical extents were set to the same dimensions as the publication description, except the domain was extended to 30 meters in length to eliminate any influence by the outlet boundary condition.

The CFD solution stabilizes fairly quickly in ~40 transient seconds (for observing the first 10 meters past the CO_2 inlet at the centerline of the box experiment). The k-epsilon Chen-Kim turbulence model was selected as it performs better for dispersion type flows. A customized density function was generated to handle the multi-species transport component of the model, and a buoyancy force boundary condition was also applied.

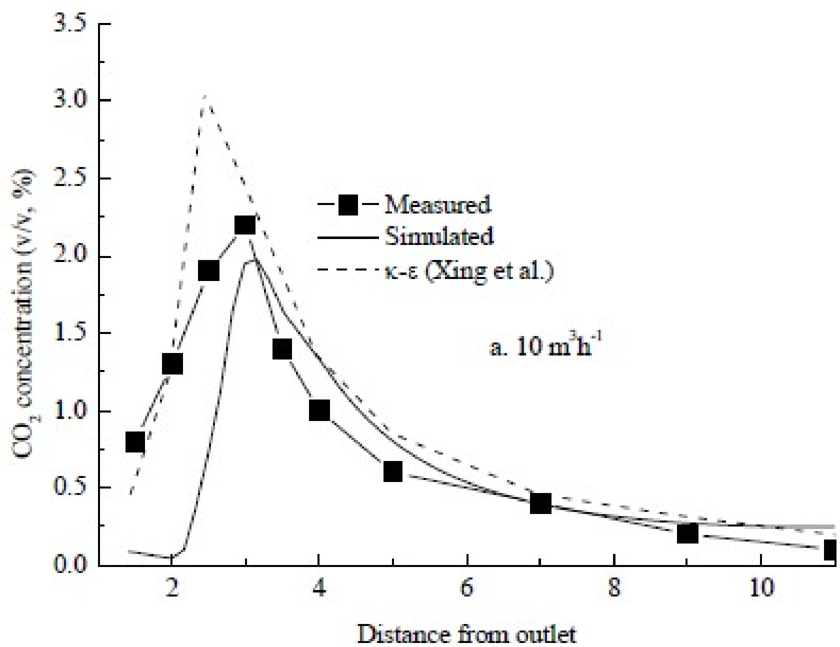
Even though the publication was missing some important information regarding the author's CFD model setup, the developed CAESIM accurately reproduces the centerline results documented in the research publication.

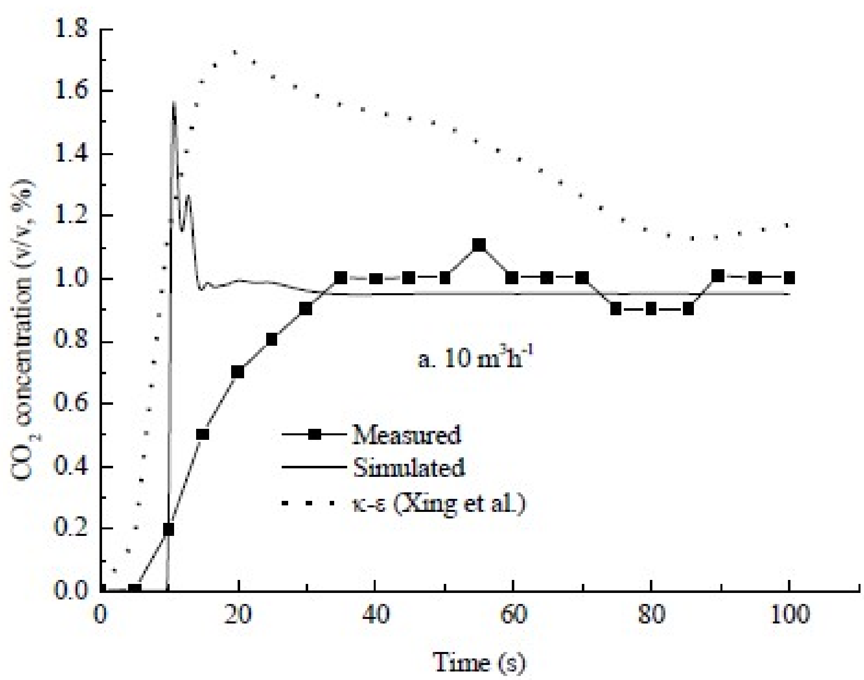
Due to the experimental setup (i.e., using an enclosed box structure), the "actual" CO_2 dispersion is quite complex (and not documented in the publication). See Figure on page 6 for a 3D view of CO_2 plume development at 40 seconds into the simulation. <u>This illustrates the need for additional CO_2 dispersion modeling specifically targeted to indoor plant farming CO_2 enrichment methods.</u>



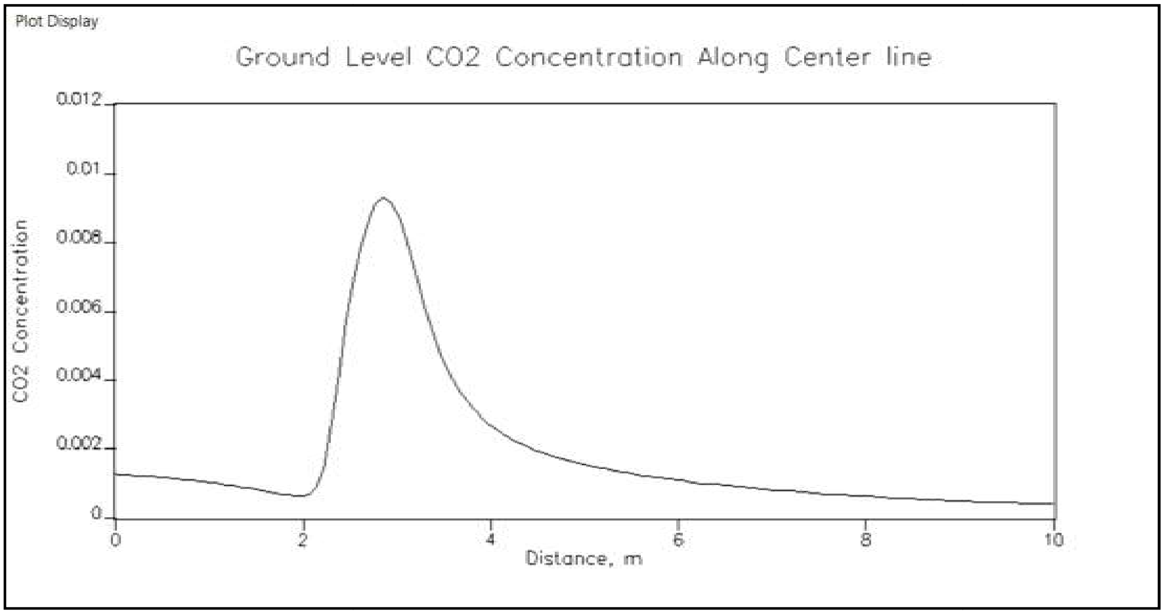
Publication Results

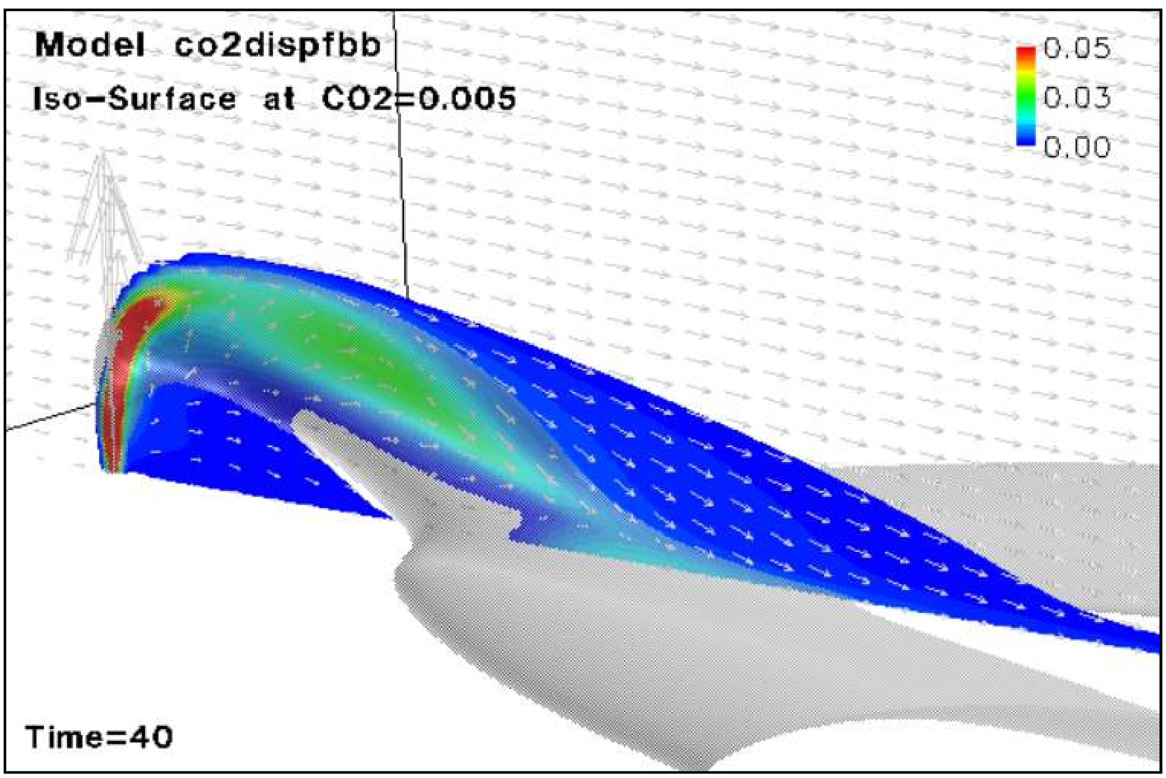
The research publication presents experimental and CFD simulation data for several CO2 flow rates. The lowest flow rate has been selected for comparison (10 m^3/hr). The following two figures show spatial and time-history results for CO2 concentration reported in the publication.





CAESIM Results Comparison





Case II

Case II represents a study that investigates the impact of air change rate in CO2 concentration and to estimate the profile of CO2 concentration in an office setting. The CO2 sources in the office chamber are four human occupants.

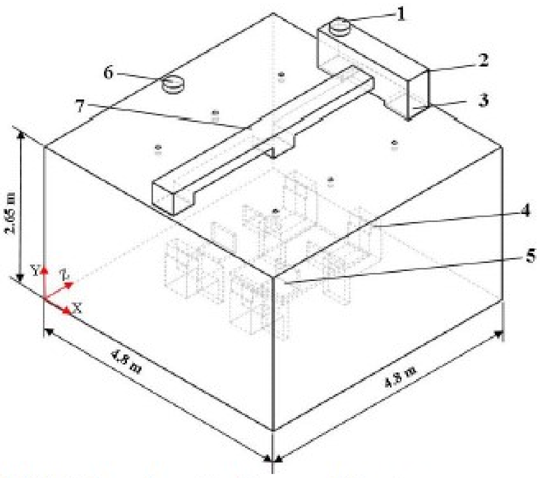


Figure 1 . schematic diagram of chamber
1- Fresh air, 2- Mixing room, 3- Return air, 4- Human body, 5- laptop, 6- Exhaust air, 7- air supply duct

Publication Results

The research publication presents experimental and CFD simulation data for CO2 levels within the office room.

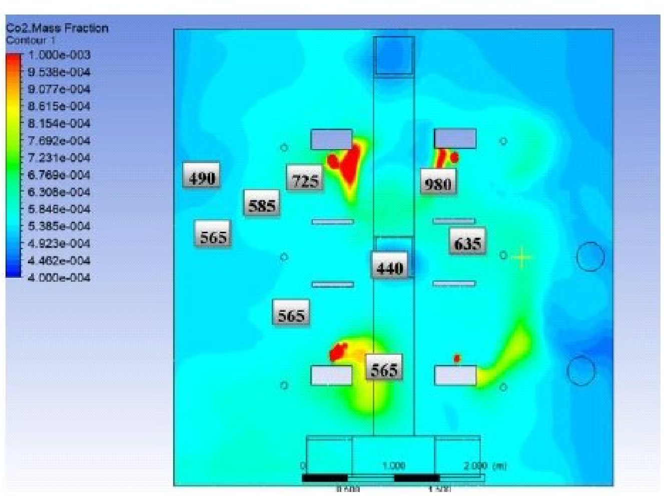
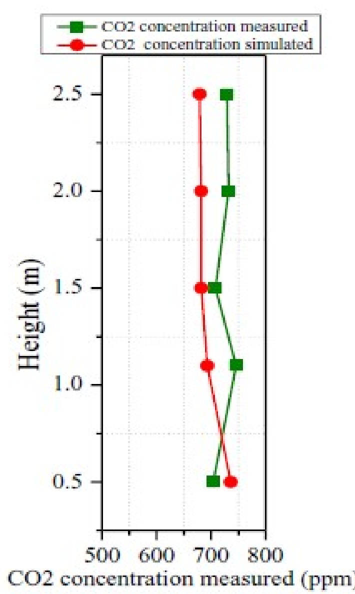


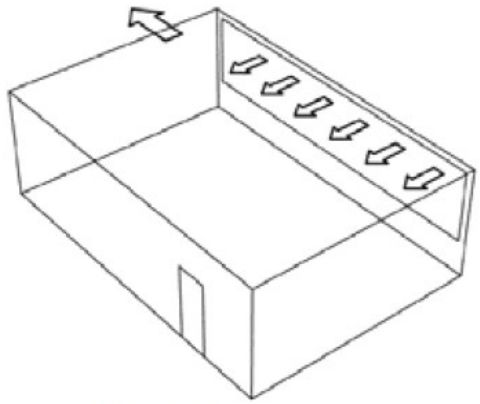
Figure 8. CO_2 concentration top plane (X Z); Y=1.1 m



Line 1(x = 1 m, z = 2.4 m)

Case III

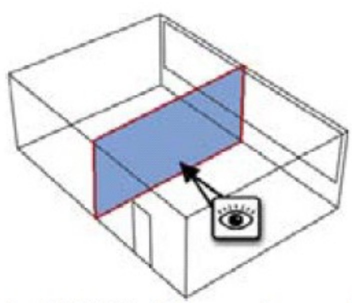
Case III represents a study that investigates thermal comfort conditions and air distribution in educational buildings. The CO_2 sources in the educational room are the students.



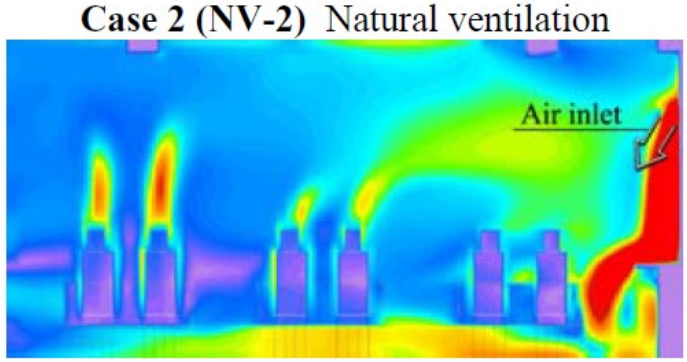
Case 2 (NV-2) Natural ventilation.
Air is supplied through window air inlets. Standard ventilation rate.

Publication Results

The research publication presents CO_2 concentration levels for a variety of room ventilation strategies.



Case 2 (NV-2) Natural ventilation



CO2 Dispersion Related Research Publications

A benchmark for data-based office modeling: challenges related to CO2 dynamics (2015).
International Federation of Automatic Control.

A multi-model approach to monitor emissions of CO2 and CO in an urban-industrial complex (2016).
Atmospheric Chemistry and Physics (Discussions).

Benefits of Atmospheric CO2 Enrichment on Strawberry (2015).
CO2Science and SPPI Original Paper.

Air Quality Impact Assessment: H2S Dispersion Modeling the Sabalan Geothermal Power Plant (2014).
SUNA - Renewable Energy Organization of Iran.

Assessment of CO2 Health Risk in Indoor Air Following a Leakage from a Geological Storage (2017).
Energy Procedia, Elsevier.

Assessment of Urban Area CO2 Concentrations using the Atmospheric Dispersion Model for Micro Areas (2016).
Journal of Environmental Science and Pollution Research.

Atmospheric dispersion of CO2 released from pipeline leakages (2013).
Energy Procedia, Elsevier.

Carbon dioxide enrichment technologies for crop response studies (2006).
Journal of Scientific and Industrial Research.

Response of Basil (Ocimum basilicum) to Increased CO2 Levels.
E&ES359 Global Climate Change, Johan Varekamp.

Computational fluid dynamics simulation of carbon dioxide dispersion in a complex environment (2016).
University of Wollogong Research Online.

Dynamic modeling and control of a pilot plant for post-combustion CO2 capture.
Proceedings of the 234d European Symposium n Computer Aided Process Engineering (2013).

Effects of CO2 enrichment on the photosynthetic light response of sun and shade leaves of canopy seetgum trees in a forest ecosystem.
Tree Physiology (1999).

Elevating Carbon Dioxide in a Commercial Greenhouse Reduced Overall Fuel Carbon Consumption and Production Cost When Used in Combination with Cool Temperatures for Lettuce Production.
Horticulture Technology (2011).

Estimating of CO2 consumption in lettuce according to the leaf area.
Dept of Bio-industrial Machinery Engineering, Gyeongsang National University, Korea.

Evaluation of simplified models for predicting CO2 concentrations in small commercial buildings (2005).
Building and Environment (ELSEVIER).

Experimental and CFD modeling for thermal comfort and CO2 concentration in office building (2017).
IOC Conference Series: Materials Science and Engineering.

Free air carbon dioxide enrichment facility development for crop experiments (2002).
Indian Journal of Radio and Space Physics.

Free-air CO2 enrichment (FACE) using pure CO2 injection: system description (2000).
New Phytologist Research.

Carbon Dioxide Enrichment (Green Coast Hydroponics).

Growing Facilities (DUCTSOX - Textile Air Dispersion Products).

Improvement of the Crop Growth Rate in Plant Factory by Promoting Air Flow inside the Cultivation (2016).
International Journal of Smart Home.

Indoor air quality analysis based on the ventilation effectiveness for CO2 contaminant removal in ventilated cavities (2014).
Revista Mexicana de Fisica Research.

Indoor Environment of a Classroom in a Passive School Building with Displacement Ventilation (2013).
13th Conference of International Building Performance Simulation Association.

Mathematical model for monitoring carbon dioxide concentration in industrial greenhouses (2018).
Agronomy Research.

Modeling and Estimation of Humans' Effect on the CO2 Dynamics Inside a Conference Room (2015).
IEEE Transactions on Control Systems Technology.

Modeling CO2 and water vapor exchange of a temperate broadleaved forest across hourly to decadal time scales (2001).
Ecological Modeling.

Modeling and Management of Fruit Production.
INRA, Avignon.

Modeling Indoor Air Carbon Dioxide (CO2) Concentration using Neural Network (2012).
World Academy of Science, Engineering and Technology.

Numerical Investigation on the Dispersion of Hydrogen Leaking from a Hydrogen Fuel Cell Vehicle in Seaborne Transportation.
Japan Ship Technology Research Association (JSTRA).

Uptake of Carbon Dioxide from Water by Plants (2009).
www.carboschool.org.

Source strength and dispersion of CO2 releases from high-pressure pipelines: CFD model using real gass equation of state (2014).
University of Wollongong - Research Online.

Thermal comfort conditions and air distribution in educational buildings (2008).
Indoor Air 2008.