Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Note

Design and construction of a flexible laboratory-scale mixing apparatus for continuous ethylene supplementation of fresh produce

Robert S. Amoah, Sandra Landahl, Leon A. Terry *

Plant Science Laboratory, Cranfield University, Bedfordshire, MK43 0AL, UK

ARTICLE INFO

Article history:
Received 8 November 2016
Received in revised form
9 February 2017
Accepted 27 February 2017

Keywords:
Ethylene blending
Controlled atmosphere
Mass flow controller
Fresh produce
Storage

The design and construction of a laboratory-scale apparatus for generating variable concentrations and flow rates of exogenous ethylene for fresh produce supplementation during storage trials is described. A stock of compressed ethylene in nitrogen (5000 μl l^{-1}) was blended into a continuous flow stream of air and diluted to the desired concentrations. The ethylene and air flow rates were controlled with calibrated mass flow control valves. An empirical mathematical model was derived for real-time variation of both the mixed concentration and flow rate during continuous flow. Validation of the model was performed using fresh sweet potato as a case study where a steady continuous ethylene concentration of 10 μl l^{-1} was achieved for three months. The bespoke system offers easy-to-manage ethylene supplementation for research.

1. Introduction

Postharvest research often requires controlling the atmospheric composition of the storage environment. Monitoring and regulating the proportion of respiratory gases is critical and finds practical applications in controlled atmosphere (CA) storage and modified atmosphere packaging (MAP) techniques. CA storage and MAP are primarily concerned with the balance between oxygen, carbon dioxide and nitrogen in a headspace (Kader, 2002). However, many systems are not flexible enough for continuous ethylene to be exogenously applied into the atmosphere mix.

Besides the familiar role ethylene plays in promoting the ripening of climacteric fresh produce, ethylene supplementation has been shown to inhibit sprouting in many bulbs, tubers and roots (Amoah, Landahl, & Terry, 2016; Cools, Chope, Hammond, Thompson, & Terry, 2011; Foukaraki, Cools, Chope, & Terry, 2016). Exogenous ethylene, however, elicits variable, and sometimes contrasting, responses in plant tissues depending on a matrix of crop factors and the application regime employed. In particular, the ethylene concentration and timing of exposure have been shown to have distinctive effects (Amoah et al., 2016; Cools et al., 2011; Foukaraki, Chope, & Terry, 2014). Therefore, it is desirable to optimise reliable ethylene supplementation

* *Corresponding author.*
E-mail address: l.a.terry@cranfield.ac.uk (L.A. Terry).
http://dx.doi.org/10.1016/j.biosystemseng.2017.02.010

Nomenclature

CA	Controlled atmosphere
MAP	Modified atmosphere packaging
MFC	Mass flow controller
MFC-4	Four-channel mass flow control unit (Sable Systems)
Ve	Ethylene flow control valve
Va	Air flow control valve
SLPM	Standard litres per minute
FS	Calibrated full-scale mass flow rate of ethylene control valve (SLPM)
EE	Continuous ethylene-flushed boxes
EA	Ethylene, then air-flushed boxes
AA	Continuous air-flushed boxes
AE	Air, then ethylene-flushed boxes
Me	Ethylene gas distribution manifold
Ma	Air distribution manifold
A	Hydrovane air compressor
C	Ethylene cylinder
OD	Outside diameter of tubing (mm)
ID	Inside diameter of tubing (mm)
RH	Relative humidity
HWD	Hot wire detector
FID	Flame ionisation detector
CO_2	Carbon dioxide
C1	Stock concentration of ethylene in nitrogen (5000 $\mu l\ l^{-1}$)
C2	Target concentration of ethylene in air ($\mu l\ l^{-1}$)
M1	Total mass flow rate of compressed air and ethylene stock ($ml\ l^{-1}$)
M2	Target mass flow rate of ethylene in air ($ml\ l^{-1}$)
E	Any given stock ethylene concentration ($\mu l\ l^{-1}$)
F_e	Any given calibrated full-scale flow through the ethylene valve (SLPM)
F_a	Any given calibrated full-scale flow through the air valve (SLPM)
x	Percentage of the calibrated full-scale flow through the ethylene valve (%)
y	Percentage of the calibrated full-scale flow through the air valve (%)
z	Percentage of the calibrated full-scale flow through the control (pure air) valve (%)
Q1	Total gas flow rate through the ethylene/air mix tubing ($ml\ l^{-1}$)
Q2	Gas flow rate through the pure air tubing ($ml\ l^{-1}$)
χ^2	Chi-square
R^2	Correlation coefficient
RMSE	Root mean square error
df	Degrees of freedom
Kpred	Model-predicted ethylene concentration
Kexpt	Experimentally obtained ethylene concentration

regimes to uniquely suit individual crops and storage conditions.

Postharvest applications of ethylene are predominantly in the gaseous phase and come from the catalytic decomposition of ethanol in ethylene generators or from cylinders of the compressed gas which are diluted with air to the required concentrations (Blankenship & Sisler, 1991). The latter application method is more suited to laboratory studies. With many laboratory-based designs for storage trials, however, only fixed concentrations and flow rates are possible. Facilities and techniques to flexibly manipulate the gas flow parameters such as the concentration, flow rate and timing of exposure to the crops poses a major challenge.

Gas mixing systems are employed for analytical research to blend two or more different gases in precise proportions to achieve target concentrations delivered at specified flow rates. In static mixing systems, the individual gases, measured gravimetrically, volumetrically or manometrically are combined whilst in dynamic gas mixing techniques, streams of gases with known flow rates are mixed (Degn & Lundsgaard, 1980). The individual flow rates of the mixing gases are adjusted by integrated mass flow controllers (MFCs). Achieving the target concentration and flow rate, however, may require iterative settings of the MFCs, followed by sampling for validation in a suitable instrument such as the gas chromatograph. This process can be time consuming and inconvenient especially, in experiments which require rapid stabilisation of the target concentration. Innovative designs that allow for automatic adjustment of the gas mixture to achieve precise concentrations and flow rates are commercially available (Dansensor Co., 2014) but they are industrial in scale and require significant pressures (above 5 Nm^{-2}) and flows (1500 $l\ min^{-1}$) which are too great for down-scaled laboratory applications. This research note describes a modular laboratory design which permits the simultaneous flushing of multi-storage chambers with adjustable ethylene levels at any time during prolonged storage.

2. Materials and methods

Controlled ethylene supplementation was accomplished using a custom-built continuous flow-through apparatus (Fig. 1). The flow rates of the mixing gases were regulated by connecting mass flow control valves (Sierra, The Netherlands: models 840-L-2-OV1-SV1-D-V1-S1 and 840-L-2-OV1-SV1-E-V1-S1) in line with the ethylene (Ve) and air streams (Va_1), respectively. A third mass flow control valve (Va_2) was connected in a parallel air stream for direct flushing of the control samples with pure air. The mass flow control valves were factory calibrated to deliver 0.03 and 13.5 standard litres per minute (SLPM) maximum flow rates of ethylene and air, respectively. All the valves were connected to a digital multi-channel MFC-4 control unit (Sable Systems, NV, USA) to regulate the flows. Certified ethylene (BOC, Surrey, UK) made inert with nitrogen against explosion and compressed (200 Nm^{-2}) into a 50 l capacity cylinder (C) was diluted with air from a Hydrovane Air Compressor (A) (HVO2, Bedfordshire, UK) at room temperature from the stock concentration 5000 $\mu l\ l^{-1}$ to the target concentrations (10 $\mu l\ l^{-1}$ in the test experiment). At each setting of the MFC-4, a regulated amount of ethylene from the cylinder was blended into a corresponding amount of air stream at a T-junction without a mixing chamber. The blended gases were supplied directly