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Development of a Gas Mixing System for Controlled Atmosphere(CA) Chambers

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Abstract: Based on the viscous flow characteristics of gas through capillary tube, a simple and cheap gas mixing system was developed for controlling gas compositions in CA chambers. The gas flow rate through capillary tube had a linear relationship with pressure, (length) ^{1} and (radius)^{4} of capillary tube, which agreed well with Hagen-Poiseuille's law.

The relationship between flow rate and combined parameters was described as $Q = 0.000209724(\pi r^4 P / \mu L)$ and the coefficient of determination was 0.9984.

The developed system could control gas concentrations in CA chambers within $\pm 0.3\%$ deviation compared to the preset concentrations. It was possible to predict the required time and required gas flow rate for exchanging the gas in CA chamber to a certain concentration of gas by using the mathematical model developed in this study.

Keywords: Gas mixing, Capillary tube, Gas flow, Gas concentration, CA

Introduction

The controlled or modified atmosphere storage, which controls O_2, CO_2 and N_2 concentrations of the air in storage rooms or packages, is used to preserve quality of agricultural products. For practical use of these storage methods, we must find out optimum gas compositions for each commodity through experiments. Most of these experiments require O_2 levels between 1% and 15%, CO_2 levels between 0% and 20%, and the remainder being N_2. Moreover, it needs many storage chambers, different levels of gas concentrations in each storage chamber and continuous flow of test atmosphere. Hence, complex and expensive facilities are required for such experiments.

Studies have been reported on the development of cheap and simple gas mixing system for controlling gas concentrations in CA chambers. Pratt et al.(1960) suggested a method for controlling gas concentrations using flow-through system composed of a Mariotte bottle, capillary tube and flow meter. And the precise control of gas levels was realized. So, many researchers have used similar systems as Pratt's for CA experiments (Marynick and Marynick, 1975; Lee et al., 1991; Choi, 1999). However, these systems have disadvantages: a lot of gas is wasted, evaporation of water in water column have a bad effect to maintain a constant gas flow rate, continuous change of gas flow rate during the time of experiments is troublesome and automatic control of gas flow rate is difficult.

Therefore, this study was carried out to improve the existing gas mixing method that is using water column for controlling gas concentration in CA chambers. For this purpose, a gas mixing system, which is composed of a gas tank, a closed pressure regulating chamber with digital pressure gauge, a needle valve and a capillary tube was developed. Gas flow rate through capillary tube was calibrated according to the gas pressure, length and diameter of capillary tube. The accuracy of the developed system was evaluated and technical suggestions are described for efficient design and proper use of the system.

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Materials and Methods

1. Theory of Fluid Flow in Capillary Tube

The laminar flow (Re < 2,300) through a capillary tube can be described by the Hagen-Poiseuille's law. It is stated that the flow rate is proportional to the pressure difference between the ends of the tube and

the fourth power of its radius (Frank, 1987) as equation (1).

$$Q = \pi r^4 \Delta P / 8 \mu L \quad \cdots\cdots (1)$$

where, Q : gas flow rate(mℓ/s)
ΔP : pressure difference between the ends of tube(Pa)
R : tube radius (mm)
L : tube length (mm)
μ : fluid viscosity (Pa · s)

Therefore, gas flow rate through capillary tube can be changed as pressure difference, length or radius of capillary tube. The developed system in this study was based on this principle for controlling gas flow rate.

2. Calibration of Gas Flow Rate through Capillary Tube

The gas flow rate through capillary tube was calibrated according to the gas pressure, length and diameter of capillary tube. The parameter ranges used in calibration were 490～4,000Pa (pressure), 100～600 mm (length) and 0.3048mm, 0.5588mm and 0.8128mm (diameter). A Teflon-made capillary tube was used (Cole-Parmer Co.), and the gas flow rate was measured by a digital bubble flow meter (Optiflow 570, Humonics Co.).

3. Evaluation of the Accuracy of Developed Gas Mixing System

To verify the precision of the developed system, gas concentration of storage chamber was controlled within the range of 0～4% O_2, 2～10% CO_2, and the remainder being N_2. Required pressure, length and diameter of capillary tube for producing a certain level of gas concentration were taken from calibration result. Measured gas concentration was compared to the preset concentration. Gas concentration was measured by a packaging atmosphere analyzer (Maptest 4000, Hitech Instruments Ltd).

4. Prediction of Required Time for Producing Target Gas Concentration in CA Chamber

It is assumed that gas is supplied with constant flow rate to CA chamber, and the remaining gas in the chamber is discharged to the outside with the same flow rate, simultaneously. In this case, the balance of gas concentration in chamber can be expressed as "Concentration of present gas = Concentration of old gas − Concentration of discharged gas + Concentration of supplied gas". Therefore, the required time for the gas concentration in CA chamber is to become target concentration can be predicted using equation (2). The actual gas concentration in CA chamber(volume : 29,850mℓ) according to elapsed time and gas flow rate (1,000mℓ/min and 571mℓ/min) were measured. And predicted gas concentration and required time were compared to measured data.

$$Cxt = Cxi - \int (Cxi * Q / V)\, dt + \int (Cxs * Q / V) dt \quad \cdots\cdots (2)$$

Where,
Cxt : gas concentration in storage chamber at time t (%)
Cxi : gas concentration in storage chamber at time t-dt(%)
Cxs : supplied gas concentration(%)
Q : flow rate of supplied gas(mℓ/min)
V : volume of storage chamber(mℓ)
dt : time interval(min)

Results and Discussion

1. Development of Gas Mixing System

The schematic diagram of the developed system is shown in Fig. 1. It was composed of gas tanks, pressure-regulating chambers, digital pressure gauges, needle valves, capillary tubes and CA chambers. Each gas tank has a pressure regulator for constant gas flow from gas tank to pressure-regulating chamber although quantity of gas in gas tank was decreased. Pressure in the pressure-regulating chamber was controlled by needle valve and confirmed by the digital pressure gauge, which was installed on the pressure-regulating chamber. The gas passed pressure-regulating chamber was supplied to capillary tubes with constant pressure. Discharged gases from capillary tubes had different flow rates according to length and diameter of capillary tube and applied pressure. Among capillary tubes, three capillaries for O_2, CO_2, and N_2 were selected for each CA chamber according to required gas concentration. Selected three capillaries were united, and so three gas were mixed. Mixed gas at a certain concentration of O_2, CO_2 and N_2 was supplied into the CA chamber and discharged after through CA chamber.

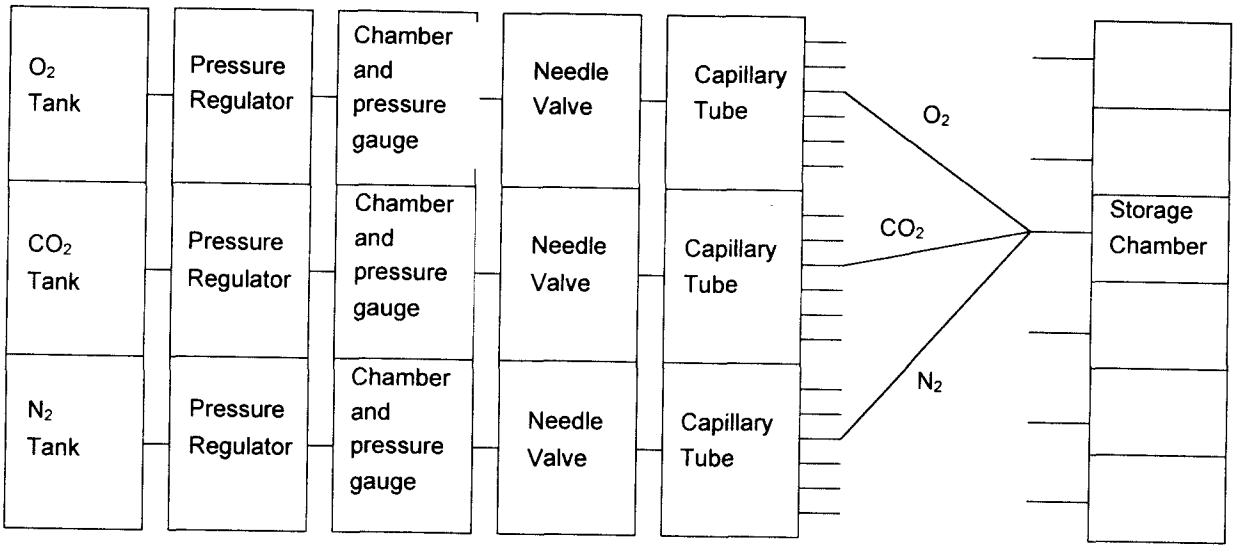

Fig. 1 Schematic diagram of developed system.

2. Calibration of Gas Flow Rate through Capillary Tube

(1) Relationship between flow rate and length of capillary

The relationship between flow rate and length of capillary tube is shown in Fig. 2. When all parameters except length remained constant, the relationship between flow rate and (length) $^{-1}$ was linear, and the resulting graph of the function was a straight line.

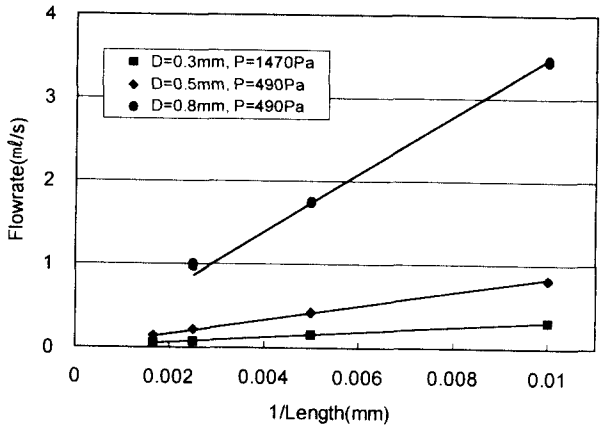

Fig. 2 Relationship between flow rate and length of capillary.

(2) Relationship between flow rate and pressure

The relationship between flow rate and pressure is shown in Fig. 3. When all parameters except pressure remained constant, the relationship between flow rate and pressure was linear and the resulting graph of the function was a straight line.

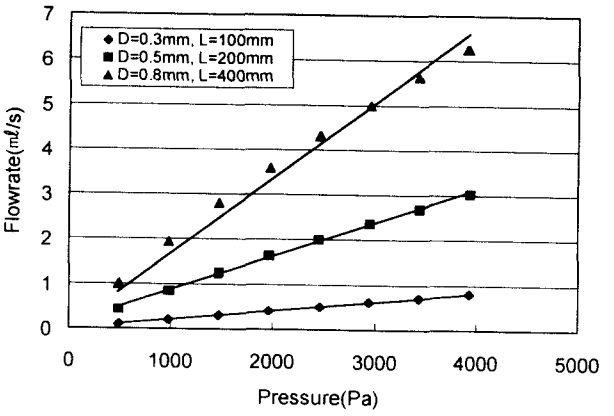

Fig. 3 Relationship between flow rate and pressure.

(3) Relationship between flow rate and radius of capillary

The relationship between flow rate and radius of capillary tube is shown in Fig. 4. When all parameters except radius remained constant, the function between flow rate and (radius)^4 was linear and the resulting graph of the function was a straight line.

(4) Relationship between flow rate and combined parameters

The relationship between flow resistance (R) and combined parameters are presented in Fig. 5. The function between R and $8\mu L/\pi r^4$ is linear and the graph of the function was a straight line. From the regression analysis $R=596.0224(8\mu L/\pi r^4)$ and the coefficient of determination was 0.9984. Since, the flow resistance R is given by $R = P/Q$, therefore, the relationship between flow rate and combined parameter

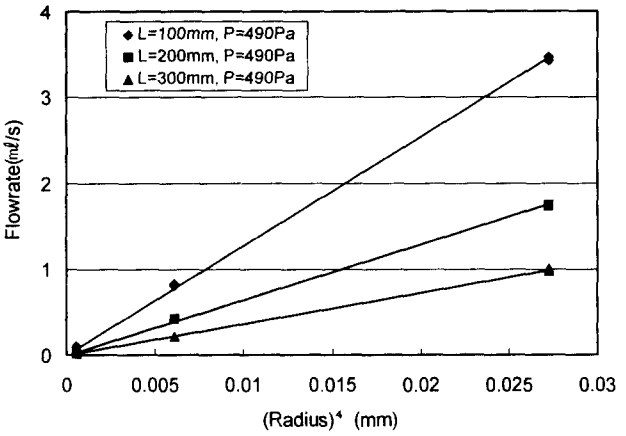

Fig. 4 Relationship between flow rate and radius of capillary.

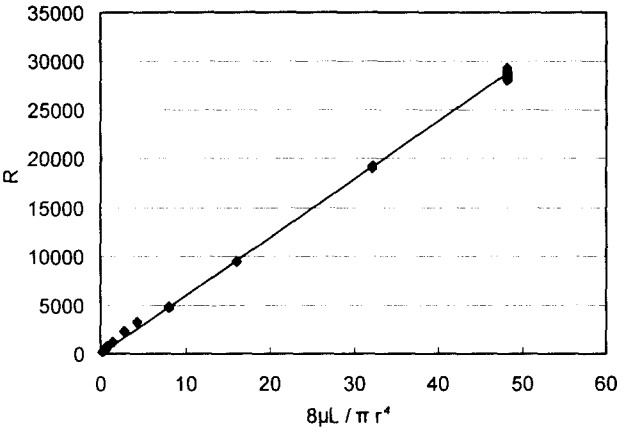

Fig. 5 Relationship between flow resistance and combined parameters.

could be described as equation (3).

$$Q = 0.000209724\ \pi r^4 P / \mu L \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (3)$$

From the equation(3), one can calculate the gas flow rate through capillary tube if diameter and length of tube and pressure of gas are known.

3. The Accuracy of Developed Gas Mixing System

The preset and measured gas concentrations are compared in Table 1. The gas concentration in CA chamber was controlled within ±0.3% deviation compared to the preset concentration. Therefore, it was concluded that the developed system was enough to use for CA experiments.

4. Prediction of Required Time for Producing Target Gas Concentration in CA Chamber

Change of gas concentration in a CA chamber expressed as elapsed time and gas flow rates, is shown in Fig. 6. The predicted and measured concentrations during the time of experiments were not exactly the same. It was caused by gas mixing between remaining gas and supplied gas in chamber. However, the required time for producing the target gas concentration was predicted exactly. Therefore, it was concluded that the developed prediction model could be used to decide required gas flow rate and required time for exchanging the gas in CA chamber to a certain concentration of gas for CA experiments using flow-through system.

In general, when volume of chamber was 29,850mℓ and gas flow rate was 1,000mℓ/min, required time for producing the target concentration is usually calculated as 29,850 ÷ 1,000 = 29.85 min. However, this is not

Table 1 Comparison of preset and measured gas concentration in storage chamber

Preset concentration (A)		Measured concentration (B)						Deviation (|A-B|)					
O_2 (%)	CO_2 (%)	O_2 (%)			CO_2 (%)			O_2 (%)			CO_2 (%)		
		1*	2	3	1	2	3	1	2	3	1	2	3
0.0	6.0	0.18	0.18	0.18	5.9	5.9	5.9	0.18	0.18	0.18	0.1	0.1	0.1
1.0	4.0	0.79	0.75	0.76	4.3	4.5	4.5	0.21	0.25	0.24	0.3	0.5	0.4
1.0	8.0	0.80	0.81	0.79	8.4	8.0	7.9	0.20	0.19	0.21	0.4	0.0	0.1
2.0	2.0	0.69	1.67	1.71	2.4	2.4	2.3	0.31	0.32	0.29	0.4	0.4	0.4
2.0	6.0	2.11	2.05	1.98	6.2	6.4	6.5	0.11	0.05	0.02	0.2	0.4	0.5
2.0	10.0	1.77	1.81	1.81	9.5	9.5	9.9	0.23	0.19	0.19	0.5	0.5	0.1
3.0	4.0	2.71	2.62	2.73	4.4	4.6	4.6	0.29	0.38	0.27	0.4	0.6	0.6
3.0	8.0	2.70	2.56	2.63	7.8	7.8	7.7	0.3	0.44	0.37	0.2	0.2	0.3
4.0	6.0	3.54	3.58	3.60	6.2	6.2	6.2	0.46	0.42	0.40	0.2	0.2	0.2
Average								0.25			0.3		

*: repetition

correct because the required time for the flow-through system is much longer than calculated time as above and the exact required time is about 200min (Fig. 6).

This result is very important for CA experiments using flow-through system. If flow rate is too low, it takes a longer time to reach target gas concentration, and so a large deviation in gas concentrations between inlet and outlet flow occurs. Hence, the steady state is not maintained and this causes serious errors in experimental data. Therefore, it is necessary to make a target gas concentration as quickly as possible by increasing gas flow rate. But, if flow rate is too high, the deviation in gas concentrations between inlet and outlet flow is smaller than experimental error (sampling or measuring error), and so the reliability of experimental condition is lowered. Therefore, it is necessary to use higher gas flow rate during the initial stage of experiment when gas concentration in storage chamber has not reached the target value, and then to use lower flow rate after gas concentration has reached the target value.

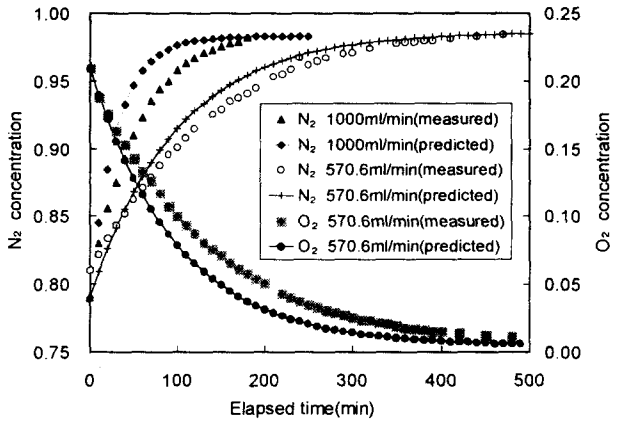

Fig. 6 Change of gas concentrations in CA chambers.

Conclusions

This study was performed to develop a simple and low cost gas mixing system for controlling gas concentration in CA chamber based on the viscous flow characteristics of gas through a capillary tube. For this purpose, a gas mixing system composed of gas tanks, closed pressure regulating chambers with digital pressure gauges, needle valves, and capillary tubes was developed. The gas flow rate through capillary tube was calibrated according to the gas pressure, length and diameter of capillary tube. Also, the accuracy of developed system was evaluated and technical suggestions were described for efficient design and proper use of the developed system.

The obtained results can be summarized and concluded as follows.

1. The flow rate of gas through capillary tube had a linear relationship with pressure, $(\text{length})^{-1}$ and $(\text{radius})^4$ of capillary tube, which agreed well with Hagen- Poseuille's law. The relationship between flow rate and combined parameters was described as $Q = 0.000209724\ (\pi r^4 P / \mu L)$ and the coefficient of determination was 0.9984.

2. The developed system could control the gas concentrations in CA chambers within $\pm 0.3\%$ deviation compared to the preset concentration.

3. It was possible to predict the required time and required gas flow rate for exchanging the gas in CA chamber to a certain concentration of gas by using the mathematical model developed in this study.

4. For CA experiments using continuous flow of gas, it was necessary to use higher gas flow rate during the initial stage of experiment when gas concentration in CA chamber has not reached the target value, and then to use lower flow rate after gas concentration has reached the target value.

5. It was concluded that the developed system was enough to use for CA experiments since it has reliable accuracy for controlling gas concentration. And one could decide on a required flow rate and required time by using the prediction model, also one could control flow rate freely and easily by changing pressure in the pressure-regulating chamber.

References

Cameron, A. C., W. Boylan-Pett and J. Lee. 1989. Design of modified atmosphere- packaging system: modeling oxygen concentrations within sealed packages of tomato fruits. J. Food Sci. (54):1413-1421.

Choi, S. J. 1999. CA storage of 'Fuji' apple fruits by continuous gas flow method and its application to a simple CA system. J. Kor. Soc. Hort. Sci. 40(6): 702-704(In Korean).

Frank, M. White. 1987. Fluid Mechanics. New York. McGraw-Hill Book Co.

Kader, A. A. 1992. Postharvest Technology of Horticultural Crops. University of California.

Kader, A. A. 1997. A summary of CA requirement

and recommendations for fruits other than apples and pears. In: Kader, A.A.(Ed.), Proc. Int. Contr. Atm. Res. Conf., University of California.

Lee, D. S., P. E. Haggar, J. Lee and K. L. Yam. 1991. Model for fresh products respiration in modified atmospheres based on principles of enzyme kinetics. J. Food Sci. (56):1580-1585.

Marynick, D. S. and M. C. Marynick. 1975. A mathematical treatment of rate data obtained in biological flow systems under nonsteady state conditions. Plant Physiol. (56):680-683.

Perry, R. H. and D. Green. 1984. Perry's Chemical Engineers' Handbook. New Tork. McGRAW-HILL Book Co.

Pratt, H. K., M. Workman, F. W. Martin and J. M. Lyons. 1960. Simple method for continuous treatment of plant material with metered traces ethylene or other gases. Plant Physiology. (35):609-611.

White, F. M. 1986. Fluid Mechanics. McGRAW-HILL BOOK Co. 732 pp.