Numerical Simulation of Thermal Flow Characteristics in Plasma Reactor for Rotten Citrus Fruits Drying

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ABSTRACT

Rotten citrus fruits, which spread odor gas during shipping season, pose a severe problem in Jeju Island, Republic of Korea. The existing methods for food waste management such as composting using electro-drying and microorganisms have a high electricity cost and require a precise temperature control, respectively. Herein, we conducted a basic numerical study on a plasma reactor using microwave plasma and liquefied petroleum gas as a combined heat source for drying and composting rotten citrus fruits. To determine the design and operating conditions of the plasma reactor, the thermal flow characteristics inside the reactor were analyzed using a computational fluid dynamics code in ANSYS-fluent. In particular, the temperature distribution in the plasma reactor was simulated at different air flow rates of the centrifugal fan. The numerical simulation accuracy was evaluated by comparing the numerical results and actual experimental data. The temperature of the reactor decreased with the increase in the air flow rate of the centrifugal fan. Above 10 m/s, the temperature of the drying chamber and the exhaust gas remained almost constant at 507 K. In the present work, the calculated temperature shows a difference 1.13 % from the measured temperature at the combustion chamber.

Keywords: Microwave plasma, Rotten citrus fruits, Numerical simulation, Thermal flow, Computational fluid dynamics

1. Introduction

Jeju Island accounts for more than 90 % of domestic citrus production. Owing to the large output, there is an excess of decaying citrus fruits at the beginning of the year during which citrus are distributed and shipped. However, there is an absence of an appropriate measure that can deal with rotting citrus fruits. Landfilling was used initially. However, it was found that the Sackdal landfill site, where rotten citrus fruits were landfilled on Jeju Island has a remaining landfill capacity of approximately 4 % based on a report published in 2019. As a result, handling non-combustible waste is restricted owing to the saturation problem at the landfill on Jeju Island. This makes it impossible to discard rotten citrus fruits in the landfill site. The saturation of the landfill has resulted in various problems within its vicinity such as odor, leachate contamination, corruption, and complaints from farm households, owing to the inability to dispose waste [1]. Therefore, an appropriate solution for the problem is required immediately. Currently, Jeju is conducting a project not only for landfilling, but also for installing microbial composting facilities. However, the disadvantage regarding this method is that a specific temperature should be maintained to allow the survival of microorganisms for a long time. Therefore, a new method is required.

In this study, to solve the problems related to rotting citrus fruits, a method of drying using a plasma reactor is proposed. The thermal flow of the plasma reactor was simulated. Microwave plasma was used

in the plasma reactor [2–4]. Microwave plasma has the advantage that its durability is robust owing to electrodeless discharge, and it is possible to develop various gas discharges and processes. As a heat source, a liquefied petroleum gas (LPG) was combined with the microwave plasma torch. A high temperature air plasma jet ejected from the torch promotes the complete combustion of the LPG. Furthermore, it has the flexibility of generating plasma suitable for commercialization purposes. Through the numerical simulations in this study, the design and operating conditions of the reactor will be presented.

2. Microwave plasma reactor and numerical method

2.1. Microwave plasma reactor for rotten citrus fruits treatment

The plasma reactor consists of a combustion chamber and a drying chamber as shown in Fig. 1. In addition, the grid system with major boundaries used in the present work is depicted in Fig. 2. Two plasma torches and a centrifugal fan with a diameter of 100 mm are connected to the combustion chamber. The drying chamber has four inlets to allow the entry of the hot air from the combustion chamber and one outlet for the exit of hot air. In the actual process, rotten citrus fruits are placed in the drying chamber of the plasma reactor and dried.

Figure 1. Microwave plasma reactor for rotten citrus fruits treatment.

Figure 2. Grid system and major boundaries of the plasma reactor.

2.2. Numerical simulation method and boundary condition

A commercial computational fluid dynamics (CFD) code, ANSYS-fluent (version R.19), was used to analyze the thermal flow characteristics of the plasma [5–10]. For turbulence modeling, standard $k-\epsilon$ turbulence modeling was applied. The temperature distribution when LPG fuel was used together with the plasma torch was calculated. The calculated values of the complete combustion reaction of LPG fuel and the air flow rate required for plasma discharge were applied. The hybrid heat generation of plasma jet and LPG combustion takes place in the combustion chamber. Finally, it reaches the drying chamber to dry the decaying citrus. However, in this simulation, it was assumed that there were no decaying citrus fruits, and the thermal flow when the plasma reactor is operated was simulated.

For the boundary condition, the outer wall of the plasma reactor was considered to be isothermal at 350 K. The wall of the drying chamber inside the reactor was set as the coupled condition with the thermal flow around. In the simulation, air velocities of the centrifugal fan were controlled at 0, 5, 10, and 15 m/s. The plasma torch was used by calculating the profiles of the temperature and velocity values when

Figure 3. (a) Velocity and (b) temperature profiles for the plasma torch inlet.

the LPG supplied at 2.2 kg/h and the air flow rate was 500 L/min, respectively. The temperature profile was calculated using the results obtained in previous studies [11, 12]. After determining the temperature at the center of the torch using reported data, the temperature profiles of the plasma and LPG flame were calculated by the interpolation method. The velocity profile for the plasma inlet was calculated and used with the initially obtained temperature profile and flow rate value, as shown in Fig. 3.

3. Results and discussion

3.1. Simulation results according to the air velocity of the centrifugal fan

The heat flow of the plasma reactor was simulated according to the air velocity at the centrifugal fan. The centrifugal fan affects the temperature distribution through stable torrefaction of rotten citrus fruits in the plasma reactor and the cooling effect during drying.

Observing Fig. 4, which shows the thermal flow in the plasma reactor with LPG fuel, the thermal flow changes according to the flow velocity of the air entering through the inlet of the centrifugal fan. In addition, the flow rate of air increases with an increase in the flow velocity of air, and as the air cools the plasma reactor, the temperatures of the combustion chamber and the drying chamber decrease. Simulated temperatures graph at the combustion chamber according to the air velocity at the centrifugal fan are presented in Fig. 5.

Simulated temperatures at each location according to the air velocity at the centrifugal fan are presented in Table I. From Table I, the temperature is maintained in the drying room for the velocity of the centrifugal fan is higher than 10 m/s.

Table I. Simulated temperatures at each location according to the air velocity at the centrifugal fan.

	Air velocity at the centrifugal fan inlet			
	0 m/s	5 m/s	10 m/s	15 m/s
Exhaust gas	670 K	507 K	507 K	507 K
Drying chamber	776 K	561 K	507 K	507 K
Combustion chamber	1421 K	883 K	668 K	615 K

Figure 4. Numerically simulated temperature distribution in the microwave plasma reactor according to the air velocity at the centrifugal fan (a) 0, (b) 5, (c) 10, and (d) 15 m/s.

3.2. Temperature comparison between simulation and measured values.

As explained, Figure 1 shows the actual plasma reactor, and the rotten citrus fruits enter the drying chamber through the pipe on the upper left. After the operation of the reactor is completed, the device connected to the drying chamber opens to remove the dried rotten citrus fruits.

Numerical simulation of the thermal flow in the reactor was performed with the same condition used for the actual plasma reactor operation. The air flow rate for the microwave plasma discharge and LPG combustion was 500 L/min. The actual air flow rate of 2,500 L/min at the centrifugal fan is corresponding to 5 m/s for the air velocity. In this condition, simulated temperature distribution is presented in Fig. 6.

Experimentally measured temperatures in different positions were compared with numerically calculated values in Table II. According to the comparison in the thermal flow temperature distribution of the measured value and the simulation value, the differences in the combustion chamber, drying chamber, and exhaust gas are 1.13, 15.7, and 16.7 %, respectively. The numerically predict temperature in the com-

Table II. Temperature comparison between measured and simulation values

	Combustion chamber	Drying chamber	Exhaust gas
Measured value	873 K	473 K	423 K
Simulation value	883 K	561 K	507 K

Figure 5. Temperature profile for the plasma reactor combustion chamber.

Figure 6. Simulated temperature distribution in the plasma reactor at the same operating condition in the actual process for rotten citrus fruits drying.

bustion chamber is quite correct, while the temperature differences in the drying chamber and the exhaust gas are large. It is because that the existence of rotten citrus fruits in the drying chamber was ignored during numerical simulations. In the consideration of evaporation of the water in the citrus fruits, it is ensured the the validity of the numerical analysis results.

4. Conclusions

In this study, the temperature distribution characteristics of the microwave plasma reactor were analyzed through thermal flow simulation, and the design and operating conditions of the reactor were considered. As a result of examining the heat flow according to the change in the air flow rate of the centrifugal fan, it was found that in the actual plasma reactor, an air velocity of 5 m/s was required to obtain an appropriate temperature for drying rotten citrus fruits. The temperature difference in the combustion chamber was 1.13 % between the simulation and experiment. Relatively large temperature differences from the actual experiment in the drying chamber and exhaust gas

were caused by the latent heat of water vaporization. The numerical simulation, however, show the correct prediction in the combustion chamber where the heat is supplied and provides reasonable trend of the temperature distribution according to the fresh air supply in the centrifugal fan. Using the simulation results of this study, the operating condition of the plasma reactor as a treatment facility for rotten citrus fruits in Jeju Island are derived and it can be used as basic data for research on food waste disposal facilities.

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