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Research Paper

Simulation and experimental test of waterless washing nozzles for fresh apricot

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To design a nozzle for washing fresh apricot with compressed air, four types of nozzles were studied by simulation and test methods. The working section for waterless washing was determined through the analysis of the air jet flow characteristics of the nozzles. In this working section, the best nozzle of the four tested was found through a comparison analysis of their flow characteristics by computational fluid dynamics (CFD) simulation and pressure-sensing test. The results showed that the trends of the simulation velocity and the test stress were consistent. A machine vision test was also conducted to assess the cleaning effect of the four nozzles. The results showed that the best nozzle was the column cone nozzle, and its average waterless washing efficiency was up to 99.07%. This study indicated that the combination of a simulation and an experimental test can be used to analyse and design waterless washing nozzles for fresh apricots.

1. Introduction

Apricot is rich in nutrition and medicinal value, and it is popular around the world (Ellis & Salt, 2003; Ogawa & Southwick, 1995, pp. 5–6; Zhebentyayeva, Ledbetter, Burgos, & Llácer, 2012, pp. 415–458). Xinjiang, China, is an important apricot planting area of the world. More than 125 kha were planted here in 2015, and the amount of exports was up to 1.20 Mt (Statistics Bureau of Xinjiang Uygur Autonomous Region, 2015). However, the surface of fresh apricot can be easily covered by dust or sand during harvesting because of the unique arid climate. Because water cleaning can easily damage the waxy cuticles, fresh apricots are usually packed in the field after harvest and sold at market directly. The dust seriously affects the external quality of fresh apricots. The fresh apricots must be cleaned and currently, the common cleaning method of fresh fruits is high-pressure water washing (Hansen, Heidt, Neven, Mielke & Bai, 2006; O'Donoghue, Somerfield, McLachlan, Olsson, & Woolf, 2013). However, fresh apricots are easily destroyed after washing using high-pressure water because of their thin wax layer (Domínguez, Cuartero, & Heredia, 2011; Jetter, Kunst, & Samuels, 2008; Schönherr, 2000). The wax layer has the function of resisting bacterial invasion and preventing water loss. It is a natural barrier formed during the growth of fresh apricot. Its destruction usually results in a substantial economic loss because the fruit quality can deteriorate during transportation or storage (Long, Kuan, Li, & Zuo, 2010).

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Nomenclature

CFD	Computational fluid dynamics
CN	Column nozzle
CCN	Column cone nozzle
FN	Fan nozzle
CFN	Column fan nozzle
Re	Reynolds number
ρ	Air density, kg m^{-3}
v	Average velocity, m s^{-1}
d	Internal diameter of the nozzle, m
μ	Viscosity coefficient of air, Pa s
V_m	Velocity of the axis point, m s^{-1}
V_0	Beginning velocity of the nozzle inlet, m s^{-1}
σ	Standard deviation
R	Jet radius, m
r_0	Nozzle radius, m
λ	Coefficient of the outflow section
a	Coefficient of turbulence
s	Jet range, m
FPGA	Field programmable gate array
P	Air pressure, kN m^{-2}
r	Air weight ratio, kN m^{-3}
g	Acceleration of gravity, m s^{-2}
D	washing efficiency, %
N	Number of white pixels on the image of the black rubber ball before washing
n	Number of white pixels on the image of the black rubber ball after washing

To avoid these disadvantages, waterless cleaning methods for washing fruits and vegetables have been studied. Davies, Fahy, and Rau (2014, pp. 135–146) noted that a series of waterless washing techniques and equipment had been developed to reduce the dependence on water-based washing. Brogden (1935) invented a waterless washing device to clean fresh oranges. The device depends on a brush roller with a special cleaning agent. In addition, it uses high-temperature drying to sterilise. Bichel (1992) also designed a waterless washing machine with a rotary-type brush roller. Some dust and foreign matter on the surfaces of fruit can be removed under the action of centrifugal force. Because fresh apricots are vulnerable, they are unsuitable for washing using these two methods. Huang (2015) proposed a method for the waterless washing of raisins. This method can achieve cleaning, sterilisation and disinfestation simultaneously, based on high-density carbon dioxide with an ultrasonic treatment. But the reactor should be washed with hydrogen peroxide firstly. And the condition of waterless washing required a processing time of more than 3 min, a temperature greater than 20 °C, pressure greater than 5.8 MPa and ultrasonic frequency of more than 10 kHz. The strict requirements on the condition and the long processing period make this method unsuitable for cleaning fresh apricots.

Nozzle structure greatly affects waterless washing performance. The shell nosing angle is an important parameter of nozzle structure. Hou and Hou (2007)found the washing effect of nozzle was closely related to the flow field parameters of the working section. Erfan, Chitsaz, and Ziabasharhagh (2015) have studied the jet characteristics of the nozzle. The turbulent jet is generally divided into three stages, named the beginning stage, the basic stage and the dissipated stage (Dong, 2005, pp. 11–16). The beginning stage is usually used to crush (Voitsekhovskii, Isotomin, & Mitrofanov, 1990) and cut (Ayed, Germain, Ammar, & Furet, 2015). The basic stage is usually used to clean (Liu, Dong, Zhang, & Zhang, 2014) and remove impurities (Qian, Chen, Jiao, Shen, & Yan, 2012) because it has a larger effective jet width and larger effective velocity. The dissipation stage is usually used to cool (Agarwal, Kumar, Gupta, & Chatterjee, 2014; Liu, Li, Feng, & Simon, 2015) and remove dust (Ellenbecker & Leith, 1983). In these analyses of nozzle structure and flow field, numerical simulation has been applied by many. Aravind, Reddy, and Baserkoed (2014) simulated the effect of different operational conditions and geometric shapes on the working efficiency of steam nozzles. The result indicated that the entrainment rates of foam fog decreased with increasing steam temperature and saturation temperature of the boiler. Cai and He (2013) used Computational fluid dynamics (CFD) to simulate supersonic steam nozzles. The study showed that the entrainment ratio increased with increasing superheat of the steam. Peng and Song (2013) found that, among four bilateral nozzles, the cone column nozzle was the most suitable for polishing. Compared with traditional design methods, numerical simulation has many advantages, such as low cost, rapidity and wide applicability. Numerical simulation technology has been widely used to make decisions about structure and working parameters (Zhu, Lin, & Xie, 2015, pp. 79–90). These studies were mostly aimed at industrial design tasks, but some focused on using the technique for waterless washing of fruit.

The overall objective of this paper was to propose a waterless washing plan for fresh apricots, in which high-pressure air was sprayed through the waterless washing nozzle to clean apricot. Four different structures of nozzles were analysed to determine the better nozzle structure through simulation and experimental testing. The specific objectives of this study were as follows:

- To select and evaluate the best nozzle structure for apricot waterless washing by combining simulation analysis, experimental tests, and machine vision technique.
- To compare and analyse the airflow velocity distribution characteristics of the four nozzle types, to determine the working section of fresh apricot cleaning.
- To build a test platform based on sensing pressure film in order to conduct pressure tests for the four nozzles.
- To collect images of fresh apricots before and after waterless washing with each nozzle and to calculate the washing efficiency of each type using MATLAB software.

2. Materials and methods

2.1. Simulation analysis

2.1.1. Study on fresh apricot

In this study, two varieties of apricots were selected, small-sized Xiaobai apricots and large-size Dahong apricots,