Design and Optimization of Strength type Negative Pressure Suction Force Pluck Port based on Tesla Valve

Zijie Niu (✉ niuzijie@nwsuaf.edu.cn)

Northwest A&F University: Northwest Agriculture and Forestry University <https://orcid.org/0000-0002-0769-9235>

XU Shengming

Northwest A&F University: Northwest Agriculture and Forestry University

JIANG jiangang

Northwest A&F University: Northwest Agriculture and Forestry University

ZHANG Jun

Northwest A&F University: Northwest Agriculture and Forestry University

Original Article

Keywords: Tesla valve, Negative pressure suction force pluck, Fluent, Curve air passageway

Posted Date: February 19th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-213596/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Design and optimization of strength type negative pressure suction force pluck port based on Tesla valve

NIU Zijie^{*1}, XU Shenming¹, Jiang Jiangang², Zhang Jun¹

1、College of Mechanical and Electronic Engineering (Northwest Agriculture and Forestry University), Xian 712100, Shanxi Province, China

2、College of Science (Northwest Agriculture and Forestry University), Xian 712100, Shanxi Province, China

Abstract: An apple pluck port based on negative pressure suction force can realize contactless apple plucking and also reduce possible damage to the apple. Accordingly, in this study, a strength type pneumatic pluck port was designed on the basis of a Tesla valve. First, a low air pressure block for mechanization of the Tesla valve structure at the intersection between the main and curved air passageway was theoretically modelled and analyzed. Then, the air pressure and the flow speed distribution were analyzed for three different types of structure parameters under various distances of the Tesla pluck port from the apple; on the basis of a fluent simulation, the maximum pressure difference at both sides of the apple was also simulated. Finally, the structure parameters under an optimal negative pressure field according to the simulation analysis were proposed, and a manufactured experimental test was conducted to compare the results with the simulation. The simulation and experimental data prove that when the included angle between the main and curved air passageway of the Tesla pluck port is lower than 45°, the low air pressure block at the intersection between the main and curved air passageway of the Tesla valve affects the flow of the pluck port and extends the length of the low air pressure block. The Tesla pluck port guarantees a flow in the pipe when the pipe port diameter is 10–15 mm larger than the apple diameter, ensuring the negative strengthening effect of the Tesla pluck port. The experiment proves that the Tesla pluck port designed in this study exhibits a better negative pressure strengthening effect than that achieved via previously existing methods, which can strengthen the plucking effect.

Keyword: Tesla valve; Negative pressure suction force pluck; Fluent; Curve air passageway

0 Introduction

Significant manpower is required for fruit plucking; in the context of apple plucking, several domestic and overseas specialists and scholars have proposed methods to improve the plucking process. German enterprises have adopted the vibration pluck method, for which an umbrella is used for fruit collection (Lu et al.2018). Applying this method enables rapid apple plucking from the trees; however, standardized planting is required for this method to be effective. Most importantly, owing to the longer maturation periods of apple breeds in China, apple plucking needs to be divided into three lots, where the pluck time of each lot is 7 days, with an interval of approximately 10 days between each lot. The vibration pluck method cannot distinguish unripe fruits, which cannot be sold out, leading to economic loss. Xindong Ni proposed a cutting pluck device which can determine the degree of apple ripeness and

is also suitable for other spherical fruits; .However, its revolving blades cause mechanical damage to the apple surface during plucking, also leading to economic loss(Ni et al.2018). Wang Heng designed a computer simulated moving mechanical arm.However, the direct contact plucking causes mechanical damage to the apple surface(Wang et al.2018). Yang Zhang designed a rear carrying apple plucking and collecting integral machine, which improved the plucking and collection efficiency of fruits; however, the pluck head shields the visibility of the pluck workers, further increasing the possibility of mechanical damage (Zhang et al.2020). In addition, further studies regarding apple plucking were conducted from the standpoint of discrimination of the fruits (André Klostermann 2019 ; Li et al.2016). However, these have not solved the problem of mechanical damage being caused to the fruit during the process. Aiming to resolve the aforementioned issue, which requires the consideration of plucking apples in batches and the

relative mechanical damage, we consider the advantages of a negative pressure suction force for contactless plucking and achieving an even load.

Through negative pressure suction force, different suction forces can be generated accordingly. The suction force exhibits a fluid motion, which applies an even force load on the object surface in the fluid field and is suitable for plucking of fruits such as apples. Through the negative pressure suction force, a negative pressure field should be created at the pluck port, which is impacted by factors such as the intensity of pressure and fluid speed, among others, based on the mechanical shape of the pluck port; therefore, a suitable strength-type negative pressure suction force pluck port is needed. Jiashou Yang designed a fan/pressurize level that can achieve multiple levels of pressure and improves the working stable margin of fans; however, this design is applied in a situation involving a high altitude and low Reynolds number (Yang et al. 2020). Senthil Kumar Raman analyzed a reentry empty body with a flap, which affects the pneumatic dynamics; we can consider using the flap to create a negative pressure field which favors the aim of negative plucking (Senthil Kumar Raman et al. 2020). Nazanin Ansarifard utilized the computational fluid dynamics (CFD) method, modified the turbine design, and achieved an optimal steady state efficiency; this CFD method and experiment can be used in this study (Nazanin Ansarifard et al. 2020). Matinpour Hadis used experimental and simulation methods to study the secondary circulation within a mixing box, and determined the influence of the secondary circulation on the turbulence (Matinpour Hadis et al. 2020); Atsuhide Kitagawa determined the flow condition of the superhydrophobic grooves under the condition of Reynolds number, Re , ($2000 \leq Re \leq 5000$) through experimental research (Kitagawa Atsuhide et al. 2020); Allison Lee explored the kinetic energy density of waves generated by oscillatory terrain in nonlinear stratification through numerical simulation (Lee Allison et al. 2020). These studies provide ideas for the study of this paper, and use CFD and experimental analysis. The Tesla valve is a

one-way resistance valve without active parts. Both ends of the valve can generate a large pressure drops under a certain condition, which is mainly affected by the structure of the valve. Domestic and overseas specialists and scholars have analyzed and exploited these characteristics of the Tesla valve. Professor Zhijiang Jin utilized a Tesla valve to process a high-pressure hydrogen pressure drop in new energy vehicles and analyzed the structural parameters of the Tesla valve, such as the hydraulic power diameter, valve body angle, and how the radius in the return passageway affects the pressure drop of the Tesla valve. Finally, it was determined that a smaller hydraulic power diameter and radius of the return passageway, as well as a larger valve body angle, creates a greater pressure drop under a low flow speed (flow speed lower than 100 m/s and Reynolds coefficient ranging between 2000 and 27700), and can generate a low air pressure area at the intersection of the Tesla valve under a certain condition (Jin et al. 2018). Yamabe et al. and Gerland et al. analyzed the air pressure reduction method under a high pressure and in the nanometre scale; however, the results were unsuitable for the negative pressure condition (Yamabe et al. 2020; Gerland et al. 2016). In addition, scholars have utilized the limit volume method to analyze the pressure distribution of Tesla valve which use water as the fluid; however, the Reynolds coefficient of water is larger than that of air under the same conditions (de Vries et al. 2017; Zhang et al. 2007; Truong et al. 2003). Jin-yuan Qian analyzed the pressure drop effect and optimized the actions of multiple levels of the Tesla valve at the backset status; however, the reverse pressure drop effect of Tesla valve and multiple levels of the valve were used to process the pressure drop (Qian et al. 2019). Jin-yuan Qian used numerical simulations and analyzed the inlet/outlet pressure ratio and temperature gradient of multiple levels of the Tesla valve under a reverse flow. In another study (Qian et al. 2019), Jin-yuan Qian also analyzed the flow distribution of nanometer-level multiple phase flows in the Tesla valve (Qian et al. 2018). Haiyang Liu researched the flow difference in the positive and negative directions of the Tesla

valve and used CFD to process the simulation and experimental comparison(Liu et al.2020). Because the curved shape of the wall and air load of the Tesla valve are similar to those of the wing, the towing theory can be referenced; the air flow is divided into two directions at the intersection between the main and curved air passageways when presenting the outlet-inlet flow direction. Fluid continues to flow partially along the main air passageway, and another portion of the fluid, which is close to the wall surface, flows along the curved air passageway and is finally collected; this flow method is similar to the air flow method based on the wing theory, which has also been applied to the flow speed of the wing in consideration of the hydrodynamics by Guoxiang Hou(Hou et al.2015). Yu, Meili analyzed the non-fixed normal flow of the wing, the density of pressure, and the flow speed of fluid according to the flow of the Tesla valve that is presented in this study(Yu et al.2013). In addition, the hydrodynamics of the wing was previously analyzed, and the fluid dynamics were determined to be similar to those obtained in our study(Mohammed et al.2018 ;Orlov et al.2015).

Considering the aforementioned problems, the intensity of pressure and flow speed distribution of the inlet and outlet of the Tesla pluck port, the low air pressure block of the negative pressure peak value, and the position of the Tesla pluck port need to be analyzed to optimize the position for collection of apples by strengthening the suction force of the negative pressure pluck port. In this study, a method that uses the Fluent software is adopted to process the hydrodynamics simulation, which is combined with an actual experience, to develop a fluid field for the Tesla valve under a negative pressure suction force to obtain an improved Tesla valve structure and optimized apple space condition, and to determine an optimal collecting position for the negative pressure suction force plucking system.

1 Theoretical model of Tesla valve negative pressure pluck port

1.1 Basic structure and characteristics of Tesla valve

The Tesla valve shown in Fig. 1 was used in this study, which consists of the following: an inlet on the left, outlet on the right a main air passageway directly from the inlet to the outlet, and a curved air passageway at both sides of the main air passageway.

Fig.1 Basic Tesla valve topology

h indicates the distance from the center of an apple to the pipe port of the Tesla valve pluck port, α indicates the angle between the curved and main air passageways, and $D1$ is the diameter of the inlet. The topology structural parameters are presented in Table 1.

Table 1 Fixed size and design dimension of Tesla picking

mouth			
Parameter type		Initial dimensions	Design size
Fixed parameters	D2/mm	180	180
	D3/mm	180	180
	d/mm	40	40
Condition parameter	D1/mm	180	110, 140
	$\alpha / ^\circ$	45	30, 45

In this study, a fixed flow speed negative pressure source was added at the inlet of the Tesla valve pluck port, and the generated intensity of pressure and the flow speed distributed at the outlet of the Tesla valve structure was analyzed, along with the minimum value, size and distribution of the negative pressure of the low air pressure block at the intersection between the main and curved air passageways.

1.2 Numerical model of Tesla valve

An equation that presents the motion can be deduced through the equation of the mass conservation and momentum conservation law (Wang et al.2004). The equation of mass conservation can be expressed as follows:

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho V) = 0, \quad (1)$$

where ρ is the density of the fluid, V is the resultant velocity vector, consisting of u , v , and w in the x , y , and z directions, respectively, and div is the calculated divergence; for a given vector α ,

$$\text{div}(\alpha) = \frac{\partial \alpha_x}{\partial x} + \frac{\partial \alpha_y}{\partial y} + \frac{\partial \alpha_z}{\partial z} \quad \text{The momentum}$$

conservation law can be obtained in the x , y , and z directions according to momentum theorem as follows:

$$\frac{\partial(\rho u)}{\partial t} + \text{div}(\rho u V) = \text{div}(\mu \text{grad} u) - \frac{\partial p}{\partial x} + F_x \quad (2)$$

$$\frac{\partial(\rho v)}{\partial t} + \text{div}(\rho v V) = \text{div}(\mu \text{grad} v) - \frac{\partial p}{\partial y} + F_y \quad (3)$$

$$\frac{\partial(\rho w)}{\partial t} + \text{div}(\rho w V) = \text{div}(\mu \text{grad} w) - \frac{\partial p}{\partial z} + F_z \quad (4)$$

where, $\text{grad}()$ is the calculated gradient; for a given

scalar α , $\text{grad}(\alpha) = \frac{\partial \alpha}{\partial x} * i + \frac{\partial \alpha}{\partial y} * j + \frac{\partial \alpha}{\partial z} * k$ μ is

the dynamic viscosity, p is the pressure on the fluid micro block, and F_x , F_y , and F_z are the mass forces acting on the fluid micro block. For facilitating a comparison, equations (1)–(4) can all be expressed in the following common form:

$$\frac{\partial(\rho \phi)}{\partial t} + \text{div}(\rho V \phi) = \text{div}(\Gamma \text{grad} \phi) + S, \quad (5)$$

where ϕ is a common variable, which indicates u , v , w , and other solvable variables, Γ is the generalized diffusion coefficient, and S is the generalized source item. In consideration of solving the numeric common equation (5), a suitable given expression and boundary condition of Γ and S are needed to solve for various ϕ .

2 Simulation analysis of Tesla valve negative pressure pluck port

2.1 Grid model of Tesla valve negative pressure pluck port

In this study, the ICEM CFD software was used to divide the grids of the Tesla valve at $\alpha=45^\circ$ with

$D1=110$ mm, as shown in Fig. 2.

Fig.2 Mesh generation of Tesla valve

Because a turbulent flow exists at the intersection between the main and curved air passageways, the non-grids were divided at the intersection of the air passageways to reduce the tail flow influence. The model is a center revolving body; cutting the center plane of the model reduces the grid quantity, and air passing through the generated grid can then ensure that the required grid independence performance condition is met. To obtain different h and valve body structure parameters that affect the intensity of the pressure and flow speed of the system, we processed three types of the Tesla valve topology structures, as shown in Table 1.

2.2 Simulation contrast between Tesla valve negative pressure pluck port and common pluck ports

The reduced diameter of the common pluck port raised the intensity of pressure, whereby a peak value of $-1.56\text{e}+03$ was achieved at the pluck port, and the occurrence of a wall surface turbulent flow was enabled. Fig 3(a) presents the intensity of the low air pressure block, which was between $-2.74\text{e}+03$ and $-2.80\text{e}+03$; a higher flow speed existed at the center of the pluck port, which was affected by the reduced diameter, and a peak value of $6.18\text{e}+01$ was achieved at the inlet of the pluck port.

The distribution of the intensity of pressure at the Tesla valve pluck port did not change in the main air passageway and was concentrated between $-1.28\text{e}+03$ and $-1.57\text{e}+03$. A larger pressure intensity range was observed in the curved air passageway, ranging from $-3.90\text{e}+02$ to $-3.05\text{e}+03$. The peak value of the low air pressure block at the intersection between the main

and curved air passageways was -6.01×10^3 . Considering the flow speed distribution, the flow speed of the main air passageway ranged between 4.25×10^1 and 4.96×10^1 , whereas the curved air passageway involved a lower flow speed. The flow speed distribution at the blocks ranged from 0 to 3.19×10^1 , and the curved air passageway at the

intersection involved a high flow speed between the main and curved air passageways. Owing to the effect of the curved air passageway fluid, a peak value of 7.09×10^1 was observed for a larger low flow speed area. At the intersection of the main air passageway, the size ranged from 4.61×10^1 to 4.96×10^1 .

(a) Distribution of pressure, velocity, and velocity vector in the general closure

(b) Distribution of pressure, velocity, and velocity vector at the end of Tesla valve

Fig.3 Distribution of pressure, velocity and velocity vector of the common closing and Tesla valve closing

Considering the intensity of pressure at the common pluck port, in contrast to the scenario shown in Fig. 3(a) and (b), there was no apparent low-pressure area at the port and no apparent flow speed distribution loss; the intensity of pressure and flow speed according to the Bernoulli equation and the intensity of the pressure changes at the inlet / outlet were related to the diameter of the pluck port. The common pluck pipe diameter reduced and generated the return flow; however, the low-pressure part of the return flow at the interior of the pluck port had no influence on the collection. The low air pressure area in the Tesla pluck port was at the intersection between the main and curved air passageways. Furthermore, as shown in the speed figure, a lower center flow speed occurred in the low air pressure block and was located at the pipe port; a larger difference existed with the external atmosphere, favoring the negative pressure pluck.

3 Simulation analysis of Tesla valve negative pressure pluck port with target apples

3.1 Grid division of Tesla valve negative pressure pluck port with target apple and external air pressure field

This study was divided according to the national apple grade, grade A apples (maximum diameter larger than 80 mm^[27]). The intensity of the pressure and flow speed of the Tesla negative pressure pluck port was analyzed for h values of 30 mm, 10 mm, 0 mm, and -10 mm. The grid division in the ICEM CFD, indicated in article 2 above, adopted a non-structure grid division. The apple diameter was set to 97 mm, using an external 0 type grid, which was then deleted, and the external atmosphere field was drawn with a length of 287 mm and width of 100 mm, following which the structure grid was divided. The process grid

was concentrated at the outlet of the apple and pluck port, with a maximum grid diameter of 0.1, and the internal boundary at the pluck port ensured that the air flow direction was vertical to the grid and that the tail flow effect was reduced. The detailed grid division is shown in Fig. 4.

Fig.4 Mesh generation of negative pressure collecting port of Tesla valve with target Apple and external pressure field

3.2 Simulation contrast at different Tesla valve negative pressure pluck port

Finite element analysis was processed for three types of topology structures considering the Tesla valve pluck port for the apples and an external air field. The intensity of the pressure simulation result when $h=0$ mm is shown in Fig.5.

Fig.5 Pressure distribution of the distance between the apple center and Tesla collector with three structural parameters of 0 mm

Considering the Tesla valve pluck port under the condition that h was 0 mm, the intensity of pressure distribution of the pluck port at $\alpha=45^\circ$ and $D1=110$ mm is shown in section 3.3. For the pluck port at $\alpha=30^\circ$ and $D1=110$ mm, the intensity of the pressure distribution of the main and curved air passageways were approximately the same, which is $-9.81e+04$ to $-1.21e+05$; for the apples affected by streaming, the main and curved air passageway intersection, the rear side has a smaller area with a pressure intensity of $-6.04e+04$ to $-1.13e+05$. For the pluck port at $\alpha=30^\circ$ and $D1=140$ mm, the intensity of pressure distribution for the main and curved air passageways were approximately the same, which is $-1.44e+04$ to $-1.70e+04$; for the apples affected by streaming, the main and curved air passageway intersection, the rear side had a smaller area with a pressure intensity of $-9.18e+03$ to $-1.57e+04$. Streaming affected the area

behind the apples, both sides of the apples had a low air pressure block because it was affected by the throttle formed by the apples and pipe port; the intensity of pressure was $-1.70e+04$ to $-2.62e+04$.

Considering the three Tesla valve pluck ports under the conditions of h being -10 mm, 10 mm, 20 mm, and 30 mm, the intensity of the pressure distribution of the pluck port at $\alpha=45^\circ$ is shown in section 1.3.2; and the intensity of the pressure distributions of the pluck port at $\alpha=30^\circ$ and $D1=110$ mm, as well as $D1=140$ mm, are listed in Table 2.

Table 2 Pressure distribution at Tesla collection port

h	Picking	Pressure region	Data space (Pa)
	port		
	serial number		
-10	D1=110	Global pressure	$[-1.18e+05, -1.36e+05]$

mm	mm	Lateral back pressure	[-8.17e+04, -1.81e+05]
		Global pressure	[-1.60e+04, -1.89e+04]
	D1=140	Flow around pressure	[-1.02e+04, -1.31e+04]
	mm	Low pressure cluster pressure	[-1.75e+04, -2.91e+04]
	D1=110	Global pressure	[-4.85e+06, -5.25e+06]
	mm	Lateral back pressure	[-3.38e+04, -9.64e+04]
10		Global pressure	[-1.19e+04, -1.41e+04]
mm	D1=140	Flow around pressure	[-6.50e+03, -1.30e+04]
	mm	Low pressure cluster pressure	[-1.30e+04, -2.17e+04]
	D1=110	Global pressure	[-1.53e+04, -1.86e+04]
	mm	Lateral back pressure	[-5.46e+03, -2.18e+04]
30		Global pressure	[-6.83e+03, -7.81e+03]
mm	D1=140	Flow around pressure	[-2.93e+03, -6.83e+03]
	mm	Low pressure group pressure	[-6.83e+03, -9.76e+03]

As h increased, the intensity of the pressure in the Tesla valve pluck port at $\alpha=45^\circ$ and D1=110 mm reduced, having a smaller drop inline ratio. The intensity of the pressure in the Tesla valve pluck port at $\alpha=30^\circ$ and D1=110 mm first increased and then reduced; extreme values were observed at $h=10$ mm in

the simulation data. The intensity of pressure in the Tesla valve pluck port at $\alpha=30^\circ$ and D1=140 mm reduced, having a larger drop inline ratio. Compared to the Tesla valve pluck port at $\alpha=45^\circ$ and D1=110 mm, the pluck port curved air passageway at $\alpha=30^\circ$ and D1=110 mm had a greater affect on the low intensity of the pressure area; the low pressure occurred when $h=0$ mm and it started collecting at the main air passageway; however, the pluck port at $\alpha=45^\circ$ and D1=110 mm still did not collect at $h=30$ mm. The inlet diameter of the Tesla valve pluck port at $\alpha=30^\circ$ and D1=140 mm increased, the curved air passageway affected the low intensity of the pressure area, which did not fill the main air passageway when $h=0$ mm, but started to fill the main air passageway when $h=30$ mm.

Compared to the pluck port at $\alpha=45^\circ$, the α of the pluck port curved air passageway at $\alpha=30^\circ$ is smaller, which increases the flow of the curved air passageway; the proportion of total flow increases along with the influence of the low air pressure area. However, when D1=140 mm, the inlet diameter of the pluck port increases, more fluid flows into the main air passageway, and the ratio of the main air passageway in the total flow increases, restraining the performance of the curved air passageway, and reducing the low air pressure area.

When $h=0$ mm, the flow simulation drawing of the three-type Tesla valve topology structure is shown in Fig. 6.

Fig.6 Velocity distribution with the distance of 0 mm between Apple center and Tesla collector with three structural parameters

For the three types of Tesla valves under the condition that h is 0 mm, the flow speed distribution

of the pluck port at $\alpha=45^\circ$ and $D1=110$ m is shown in section 3.3. For the pluck port at $\alpha=30^\circ$ and $D1=110$ mm, the flow speed of the main and curved air passageways are approximately the same, which is $0\text{--}8.61\text{e}+01$; it has high a speed area at $8.61\text{e}+01\text{--}4.31\text{e}+02$ because the rear side of the apple is affected by streaming, and the intersection between the main air passageway and the curved air passageway. For the pluck port at $\alpha=30^\circ$ and $D1=140$ mm, the flow speed of the main air passageway is different from the curved air passageway; the main air passageway is affected by the throttle and the curved air passageway, leading to a higher flow speed, which is $0\text{--}4.53\text{e}+01$. There is an area with a speed of $0\text{--}1.18\text{e}+02$ owing to the streaming at the back of the apples; a high flow speed area of $5.44\text{e}+01\text{--}1.81\text{e}+02$ exists at both sides of the apples because it is affected by the apples and the pipe port from the throttle. The flow speed distribution of the pluck port at $\alpha=45^\circ$ and $D1=110$ m for the three Tesla valve pluck ports when h equals -10 mm, 10 mm, and 30 mm, are presented in section 1.3.2. The flow speed distribution of the pluck port at $\alpha=30^\circ$ and $D1=110$ m, and for $\alpha=30^\circ$ and $D1=140$ mm, are listed in Table 3.

Table 3 Velocity distribution of Tesla collection port

h	Pickin g port serial numbe r	Velocity region	Data Space (m/s)
-10mm	D1=11	Overall flow	[0, 1.12e+02]
		rate	
		Side Rear	[1.12e+01, 4.49e+02]
		Flow Rate	
		Main airway	[4.80e+01, 1.25e+02]
		flow rate	
	D1=14	Curved airway	[0, 5.77e+01]
		flow rate	
		Bypass flow	[0, 9.61e+01]
		rate	
		Orifice flow	[4.80e+01, 1.92e+02]
		rate	
10mm	D1=11	Overall flow	[0, 1.07e+02]

0mm	D1=14	rate	[8.93e+01, 3.57e+02]
		Side Rear	
		Flow Rate	[4.09e+01, 1.23e+02]
		Main airway	
		flow rate	[0, 5.73e+01]
		Curved airway	
	0mm	Bypass flow	[0, 9.01e+01]
		rate	
		Orifice flow	[4.09e+01, 1.64e+02]
		rate	
		Overall flow	[0, 8.39e+01]
		rate	
30mm	D1=11	Side Rear	[0, 9.23e+01]
		Flow Rate	
		Side Rear	[4.20e+01, 1.68e+02]
		Flow Rate	
		Main airway	[2.77e+01, 9.96e+01]
		flow rate	
	D1=14	Curved airway	[0, 4.98e+01]
		flow rate	
		Bypass flow	[0, 5.53e+01]
		rate	
		Orifice flow	[2.77e+01, 1.11e+02]
		rate	

As h increases, the high-speed streaming of the three types of the Tesla pluck port increase in the main passageway. The distribution of high-speed streaming at $\alpha=45^\circ$ and $D1=110$ mm differs from the other two types of structures. The high-speed streaming incline is distributed at the back side of the apples in the Tesla pluck port at $\alpha=45^\circ$, and $D1=110$ mm. Compared to the pluck port at $\alpha=45^\circ$ and $D1=110$ mm, the high-speed streaming of the Tesla pluck port at $\alpha=30^\circ$ and $D1=110$ mm is smaller, and rapidly collects after passing through the apples. Comparing the port at $\alpha=30^\circ$ and $D1=110$ mm, the high-speed streaming of the Tesla pluck port at $\alpha=30^\circ$ and $D1=140$ mm increased, and rapidly collected after passing through the apples.

Compared to the pluck port at $\alpha=45^\circ$, the flow speed direction in the curved air passageway of the Tesla valve pluck port at $\alpha=30^\circ$ is more parallel to the

axis, and better affects the fluid in the main air passageway. The high-speed streaming rapidly collects at the axis of the pluck port after bypassing the apples and acted on by the fluid that flows along the curved air passageway. The flow in the pluck port after h increased, did not completely reduce the speed of the curved air passageway to high-speed streaming, and the area increased. The flow increased when $D_1=140$ mm; the high-speed streaming flow also increased, and did not completely reduce the speed in the curved air passageway; the area of high-speed streaming increased.

Considering the aforementioned simulation analysis, the angle of the curved air passageway reduces the performance of the Tesla valve pluck port, and an increase in the pluck port inlet diameter will restrain the performance of the Tesla valve curved air passageway. Therefore, the topology structure at $\alpha=30^\circ$ is better than the structure at $\alpha=45^\circ$; an optimal curved air passageway should be smaller. The inlet diameter of the pluck port should not be significantly large, and should be 10 – 15mm larger than the target fruits being collected.

3.3 Simulation contract using same type of Tesla valve negative pressure pluck port but a different apple distance

Fig.7 Pressure distribution of an apple with the distance from the center to the Tesla valve collecting port h of -10

mm, 0 mm, 10 mm, and 30 mm

Fig 7 presents the cloudy pressure for h values of -10 mm, 0 mm, 10 mm and 30 mm. The intensity of pressure in the main and curved air passageways were approximately the same when h was 0 mm, namely $-1.06e+05$ to $-1.13e+05$. Streaming occurred in the main air passageway because it was affected by the apples; the intensity of pressure at the streaming area was $-1.06e+05$ to $-1.36e+05$. The outlet port position was mutually acted on by the intersection of apples. A low air pressure block occurred in the main and curved air passageways, with a peak value of $-1.51e+05$. Approximately the same amount of distribution occurred when h was -10 mm, 10 mm, and 30 mm, as shown in Table 4

Table4 Pressure distribution of the first Tesla collection

Distance between Apple center and nozzle H (mm)	port	
	Pressure region	Data space (Pa)
-10	Main curve airway pressure	$[-1.27e+05, -1.36e+05]$
	Flow around pressure	$[-1.36e+05, -1.72e+05]$
	Peak value of low pressure cluster	$[-1.81e+05]$
10	Main curve airway pressure	$[-6.75e+04, -7.23e+04]$
	Flow around pressure	$[-6.27e+04, -7.23e+04]$
	Peak value of low pressure cluster	$[-9.64e+04]$
30	Main curve airway pressure	$[-1.64e+04, -1.75e+04]$
	Flow around pressure	$[-1.53e+04, -1.75e+04]$
	Peak value of low pressure cluster	$[-2.18e+04]$

The throttle port formed by the apple and pipe port increased when h increased, the intensity of pressure in the pluck port reduced, the low intensity of the pressure area increased, and a difference in the intensity of the pressure in the curved and main air passageways occurred. When $h = -10$ mm, the intensity of pressure in the curved and main air passageways were approximately the same; a higher air pressure block occurred behind the apples because of the streaming. When $h=30$ mm, the difference in the intensity of pressure in the curved and main air passageways was greater; the low intensity pressure

nearly filled the entire main air passageway in the middle section of the Tesla valve, as shown in Fig 5 (d).

The reason for this appearance is the low pressure area of the Tesla valve generated by the influence of the curved air passageway. Although a smaller flow port, higher flow speed, and lower intensity of pressure existed when $h=-10$ mm, an overall smaller flow of the entire Tesla valve existed; the curved air passageway affected the main air passageway owing to the small flow and small low-pressure area of the Tesla valve. When $h=30$ mm, the flow in the Tesla valve increased, the performance of the curved air passageway increased, and the low pressure area increased.

Fig.8 Velocity distribution with the distance between the apple center and Tesla collecting port h of -10 mm, 0 mm, 10 mm, and 30 mm

Fig 8 presents the flow speed cloudy figure when h was -10 mm, 0 mm, 10 mm, and 30 mm. When h was 0 mm, the flow speed of the main air passageway was $2.15\text{e}+01$ – $2.58\text{e}+02$ and the flow speed of the curved air passageway was $4.31\text{e}+01$ – $8.68\text{e}+01$. Because the apple and pipe port form the throttle port, streaming occurred at the intersection of the main and curved air passageways, with a peak value of $4.31\text{e}+02$. A similar distribution occurred when h was -10 mm, 10 mm, and 30 mm, as shown in Table 4.

Table 4 Velocity distribution of the first Tesla collection port

Distance between Apple center and nozzle H (mm)	Velocity region	Data space (m/s)
-10	Main curve airway velocity	[$2.25\text{e}+01$, $1.80\text{e}+02$]
	Curvilinear airway velocity	[$6.74\text{e}+01$, $1.12\text{e}+02$]
	Peak value of intersection	[$4.49\text{e}+02$]
10	Main curve airway velocity	[$1.79\text{e}+01$, $1.79\text{e}+02$]
	Curvilinear airway velocity	[$1.79\text{e}+01$, $1.25\text{e}+02$]
	Peak value of intersection	[$3.57\text{e}+02$]
30	Main curve airway velocity	[$8.39\text{e}+00$, $9.23\text{e}+01$]
	Curvilinear airway velocity	[$1.68\text{e}+01$, $5.87\text{e}+01$]
	Peak value of intersection	[$1.68\text{e}+02$]

The flow speed of the Tesla valve gradually decreased as h increased, and the high-speed streaming at both sides of the apples extended to the outlet. When $h=-10$ mm, the high speed streaming at both sides of the apple started from the inlet of the Tesla valve and extended to the internal pipe. When $h=30$ mm, the high speed streaming started from the external Tesla valve pipe port, and the flow speed was not reduced after passing through both sides of an apple. It collected behind the apples, and occupied the middle of the main air passageway; the fluid was collected at the Tesla valve close to the outlet and in the curved air passageway, reducing the flow speed.

Considering why this appearance was generated when $h=-10$ mm, a smaller throttle and low flow, as well as an increased diameter of the fluid after it entered the main air passageway through the throttle, reduces the flow speed when the fluid was in the curved air passageway. The flow in the Tesla valve increased when $h=30$ mm; the fluid diameter increased, and the curve air passageway did not reduce the streaming high-speed flow to the Tesla outlet.

For the Tesla valve pluck port at $\alpha=45^\circ$ and $D1=110$ mm, the process for an apple with a diameter of 97 mm was analyzed at various h values, considering

how the size of the throttle affects the flow at the Tesla pluck port and the curved air passageway; a small flow in the curved air passageway weakened the effect of the fluid and had a small low pressure area. An apparent effect of the curved air passageway was observed under a high flow; however, an overall increased intensity of pressure and low flow speed of the Tesla valve was observed when the flow speed is high, having a wide range of the low pressure area but a higher intensity of pressure value.

4 The negative pressure pluck port experiment of Tesla valve with target apples

4.1 Experiment of common pluck port and three type Tesla valve pluck port

In this study, an experimental pluck platform was built, in which a culvert motor was used as the power source. The Tesla valve pluck port was experimentally tested with three different topology structures. The built pluck system is shown in Fig. 9.

Fig.9 Negative pressure suction picking system

A JP120 mm metal culvert motor which independently utilizes a 6S battery supply power was used for the power source. It can achieve and stabilize the flow speed of the pluck port base at 20 m/s. Using a 3D printer, the Tesla valve pluck port was printed, as shown in Fig. 11.

The culvert motor was started during the system experimental process, and a flow speed meter

measured a 20 m/s speed at the base port under the condition of no pluck port. After installation of the pluck port, the common pluck port without the apples was measured in addition to the pipe port flow speed at the three types of the Tesla valve pluck ports, as shown in Fig. 10. A Smart 100836 air speed meter with a resolution ratio of 0.001 m/s and a range of 0.3.45 m/s was used in this study.

Fig.10 Measure of the flow rate at the collecting port

After hanging of an apple with a diameter of 97 mm on a spring hook balance with a precision of 0.1 kg, the amount of suction force and speed of air flow on the top of the three-type Tesla valve pluck port was measured under four various h values, including 30 mm, 20 mm, 10 mm, 0 mm, and -10 mm. Fig. 11 presents an apple at $h=30$ mm.

Fig.11 The state of apples in different positions

4.2 Experimental analysis when apples at different position of Tesla valve pluck port

The experimental results were contrasted and analyzed because the flow speed can be more directly measured when contrasted.

Considering the Tesla valve negative pressure pluck port with different topology structures indicated in section 1.3.2, the tendency of the simulation and experimental data of the Tesla valve pluck port at $\alpha=45^\circ$ and $D1=110$ mm are similar, as shown in Fig. 12; they are the highest when h is 10 mm.

Fig.12 The first Tesla valve negative pressure collection port at different h simulation flow rate data and experimental flow rate data line chart

The flow speed was the highest at the 10 mm position according to the simulation data; however, the experimental data presents that it remains leveled at the 10 mm position. Upon analyzing the Tesla valve negative pressure pluck port at $\alpha=45^\circ$ and $D1=110$ mm, a large flow speed exists at the 10–20 mm position. Furthermore, upon analyzing the experimental data of the apple load suction force (Fig 13) at varying distances from the Tesla valve pluck port at $\alpha=45^\circ$, the apple load suction force is maximum when the largest experimental flow speed exists at the 10 mm position. Therefore, an optimal working distance for this type of Tesla valve pluck port is determined to be 10–20 mm.

Fig.13 Broken line chart of experimental data on suction force of three types of Tesla valve negative pressure collection port at different h values

For the Tesla valve pluck port at $\alpha=30^\circ$ and $D1=110$ mm owing to the smaller pipe port diameter, the size of the throttle formed by the collecting pipe port and apples has a greater influence on the size of the flow. Considering the flow speed of the Tesla valve at $\alpha=30^\circ$ and $D1=110$ mm, the figure indicates that the size of the simulation and experimental flow speed continues to decrease while h decreases. A larger slope is observed when h is 0–30 mm; when h is smaller than 0 mm, the slope of the experimental flow speed apparently decreases.

Fig.14 The second type of Tesla valve negative pressure collection port at varying h simulation flow rate data and experimental flow rate data line chart

As shown in Fig.12, the suction force is maximum when $h=0$ because a smaller flow caused the Tesla valve pluck port to be reduced, thereby reducing the suction force when h was smaller than 0 mm. The optimal working distance for this type of Tesla valve pluck port is determined to be 0–10 mm.

For the Tesla valve pluck port at $\alpha=30^\circ$ and $D1=140$ mm, owing to the smaller pipe port diameter, a flow remains in the pluck port under a smaller h . At the

same time, the intersection between the main air passageway and the curved air passageway draws back, and restrains the effect of the Tesla valve structure, as shown in Fig. 15. The experimental and simulated flow speed does not increase when h ranges between 10–30 mm; a larger slope is observed if h is smaller than 10 mm.

Fig.15 Third type of Tesla valve negative pressure collection port at different h simulation flow rate data and experimental flow rate data line chart

At the same time, as shown in Fig. 13, considering the suction force of the Tesla valve pluck port at $D1=140$ mm, the apple loading suction force does not significantly change when h ranges between 10–30 mm because the throttle reduces after h is smaller than 10 mm, causing the curved air passageway and suction force to increase. The optimal working distance of this type of Tesla valve pluck port is determined to be smaller than -10 mm.

4.3 Results and Discussion

Considering the flow speed experiment of the Tesla pluck port having three various topology structures, the flow speed of the Tesla valve pluck port at $\alpha=45^\circ$ and $D1=110$ mm obtained a peak value at the 10–20 mm position; the flow speed decreases when h is reduced. However, the slope decreases when $h=0$ mm. The flow speed of the pluck port at $D1=140$ mm decreases, and a lower slope is obtained when h is larger; the slope increases when h is reduced. Considering the transverse three-type Tesla valve pluck port, the pluck port at $D1=140$ mm can generate a higher negative intensity of pressure but a smaller performance range, still not achieving the peak value when $h=-10$ mm. This increased the difficulty of

control for the pluck system. The peak value range of the pluck port at $\alpha=45^\circ$ is 10–20 mm, which presents a larger performance range but not an apparent effect. The Tesla valve pluck port at $\alpha=30^\circ$ and $D1=110$ mm presents a more suitable range of performance in the experiment, a better negative pressure generation effect, and an improved Tesla valve topology structure.

Considering the three types of Tesla pluck ports simulated in this study, the following can be obtained:

1) For the Tesla pluck port at $\alpha=45^\circ$ and $D1=110$ mm, the pressure drop effect of the Tesla valve structure does not increase at a larger distance, it has a smaller negative pressure influence at the pluck port, and there are no apparent effects at the Tesla valve structure. The included angle between the main air passageway and curved air passageway of the Tesla pluck port should be set to a smaller value.

2) For the Tesla pluck port at $\alpha=30^\circ$ and $D1=110$ mm, the outlet diameter of the pluck port is smaller, closer to the apple diameter, and a significantly small flow exists in the pluck port when the apple is closer to the pipe port. Considering the small impact of the curved air passageway of the Tesla valve, and a larger intensity of pressure difference at both sides of the apples, the pipe port diameter of the Tesla pluck port should be set to 10–15 mm larger than the apple diameter.

3) For the Tesla pluck port at $\alpha=30^\circ$ and $D1=140$ mm, the outlet diameter of the pluck port is larger, the curve air passageway has a larger flow when collecting grade A fruits and a larger low air pressure area of the pipe port of the pluck port, but the effect was lower than that of the Tesla valve pluck port at $D1=110$ mm.

5 Conclusions

Aiming to create the negative pressure required for apple plucking, this study proposes a method that creates a larger intensity pressure difference at both sides of apples by the low air pressure block which affects the area of the Tesla valve. Achieving a larger

suction force and determined that the pipe port diameter of the Tesla pluck port should be set to 10–15 mm larger than the apple diameter, including the angle between the main air passageway and the curve air passageway which should be smaller than 45°, a larger negative pressure suction force effect can then be obtained.

1) A negative pressure field with an intensity of negative pressure 3 times that of the common pluck port can be obtained when adopting the Tesla pluck port to process the negative pressure pluck.

2) Reducing the curved air passageway angle α effects the strength of the Tesla valve, but increasing the pluck port pipe diameter restrains the effect. In conclusion, the pipe port diameter of the Tesla pluck port should be 10~15 mm larger than the apple diameter, which includes that the angle between the main air passageway and curved air passageway should be smaller than 45°.

3) The Tesla pluck port at $\alpha=30^\circ$ and $D_1=110$ mm has a better structure, with a 10–20 mm range in which the apple center distant to the pipe port h is the best action range.

This study contrasts the size of the negative pressure field between the common pluck port and the Tesla pluck port through CFD and experimental tests, and obtained a better topology structure for the Tesla pluck port. However, this study does not consider pluck grade B fruits. Because the apple leaves and branches were left out of the pipe port, we did not process the simulation at the intensity of pressure and the flow speed distribution of an actual apple entering the pipe, which will be processed in a future study.

Availability of data and materials: The datasets used or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests: The authors declare that they have no competing financial interests

Funding: National Key Research and Development Project (2019YFD1002400).

Authors' contributions: Niu Zijie is responsible for theoretical analysis, data processing and thesis writing. Xu Shenming is responsible for the experiment and data recording. Jiang Jiang is responsible for data recording. Zhang Jun is in charge of chart drawing

Acknowledgements: This work was carried out with National Key Research and Development Project (2019YFD1002400).

References

- Lu YB, Zhou Z, Zhang ZB, et al. Agricultural mechanization development and institutional change in 40 years of reform and opening up [J]. Journal of northwest agricultural and Forestry University of science and Technology (SOCIAL SCIENCE EDITION), 2018, 18 (06): 24-31
- Ni XD, Wang X, Wang SM, et al. Structure Design and Image Recognition Research of A Picking Device on the Apple Picking Robot[J]. IFAC Papers OnLine, 2018, 51(17): 112-118.
- Wang H, Cameron J. Hohimer, Santosh Bhusal, et al. Simulation As A Tool In Designing And Evaluating A Robotic Apple Harvesting System.[J]. IFAC Papers OnLine, 2018, 51(17): 142-150.
- Zhang Y, Huang JH, Shi FL, et al. Design and test of the integrated harvester for carrying Apple [J]. Manufacturing automation, 2020, 42 (02): 102-106
- André Klostermann. Picking an apple from a tree: Response-selection demands, inhibition requirements, and the functionality of the Quiet Eye in a far-aiming task. 2019, 72(5):1233-1241.
- Li J, Manoj Karkee, Zhang Q, et al. Characterizing apple picking patterns for robotic harvesting[J]. Computers and Electronics in Agriculture, 2016, 12(7):153-162.
- Yang JS, Ji GF. Aerodynamic design of high altitude low Reynolds number fan / booster stage [J / OL]. Propulsion technology: 1-7 [2020-03-30].

- Senthil Kumar Raman, Wu K X, Tae Ho Kim, et al. Effects of flap on the reentry aerodynamics of a blunt cone in the supersonic flow[J]. *International Journal of Mechanical Sciences*, 2020, 176.
- Nazanin Ansarifard, S.S. Kianejad, Alan Fleming, et al. Design optimization of a purely radial turbine for operation in the inhalation mode of an oscillating water column[J]. *Renewable Energy*, 2020, 152.
- Matinpour Hadis, Atkinson Joseph, Bennett Sean. Secondary circulation within a mixing box and its effect on turbulence. 2020, 61(11):2231-2239
- Kitagawa Atsuhide, Shiomi Yuriko, Murai Yuichi, et al. Transient velocity profiles and drag reduction due to air-filled superhydrophobic grooves. 2020, 61(11)
- Lee Allison, Hakes Kyle, Liu Y X, et al. Evanescent to propagating internal waves in experiments, simulations, and linear theory. 2020, 61(12):1424-1432
- Jin Z J, Gao Z X, Chen M R, et al. Parametric study on Tesla valve with reverse flow for hydrogen decompression[J]. *International Journal of Hydrogen Energy*, 2018, 35(12):1131-1141.
- Junichiro Yamabe, Takashi Matsumoto, Shin Nishimura. Application of acoustic emission method to detection of internal fracture of sealing rubber material by high-pressure hydrogen decompression[J]. 30(1):76-85.
- Junichiro Yamabe, Shin Nishimura. Nanoscale fracture analysis by atomic force microscopy of EPDM rubber due to high-pressure hydrogen decompression[J]. 46(7):2300-2307.
- Gerland, Michel, Boyer, Séverine A.E, et al. Early stages of cavitation in a stretched and decompressed poly(vinylidene fluoride) exposed to diffusive hydrogen, observed by Transmission Electronic Microscopy at the nanoscale. 2016, 41(3):1766-1774.
- S.F. de Vries, D. Florea, F.G.A. Homburg, et al. Design and operation of a Tesla-type valve for pulsating heat pipes. 2017, 105:1-11.
- Zhang S, Winoto S H, Low H T. Performance Simulations of Tesla Microfluidic Valves[C]// 2007 First International Conference on Integration and Commercialization of Micro and Nanosystems. 2007.
- Truong T Q, Nguyen N T. Simulation and optimization of tesla valves. *Nanotechnology* 2003, 1:178-181.
- Qian J Y, Chen M R, Gao Z X, et al. Mach number and energy loss analysis inside multi-stage Tesla valves for hydrogen decompression[J]. *Energy*, 2019, 179.
- Qian J Y, Wu J Y, Gao Z X, et al. Hydrogen decompression analysis by multi-stage Tesla valves for hydrogen fuel cell[J]. *International Journal of Hydrogen Energy*, 2019, 44(26):235-243.
- Qian J Y, Chen M R, Liu X L, et al. A numerical investigation of the flow of nanofluids through a micro Tesla valve[J]. *Journal of Zhejiang University Science A Applied Physics & Engineering*, 2018.
- Liu H Y, Ma J, Wang S, et al. Study on one-way conductivity of Tesla valve [J / OL]. *Physics and Engineering*: 1-5 [2020-03-28].
- Edited by Hou G X; reviewed by Xu H Z, fluid mechanics, mechanical industry press, December 2015
- Yu M, Wang Z J, Hu H. High fidelity numerical simulation of airfoil thickness and kinematics effects on flapping airfoil propulsion[J]. *Journal of Fluids & Structures*, 2013, 42:166-186.
- Mohammed A, Waqar A, Erwin S, et al. Aerodynamics of porous airfoils and wings[J]. *Acta Mechanica*, 2018.
- Orlov Y F, Khimich S A. Wing motion above the interface between fluids with different densities behind a dipole disk[J]. *Fluid Dynamics*, 2015, 50(2):263-271.
- Wang F J. Principle and application of CFD software for CFD analysis [M]. Beijing: Tsinghua University Press, 2004

Figures

Figure 1

Basic Tesla valve topology

Figure 2

Mesh generation of Tesla valve

(a) Distribution of pressure, velocity, and velocity vector in the general closure

(b) Distribution of pressure, velocity, and velocity vector at the end of Tesla valve

Figure 3

Distribution of pressure, velocity and velocity vector of the common closing and Tesla valve closing

Figure 4

Mesh generation of negative pressure collecting port of Tesla valve with target Apple and external pressure field

Figure 5

Pressure distribution of the distance between the apple center and Tesla collector with three structural parameters of 0 mm

Figure 6

Velocity distribution with the distance of 0 mm between Apple center and Tesla collector with three structural parameters

**(a) Pressure distribution
with $H = -10$ mm**

**(b) Pressure distribution
with $H = 0$ mm**

**(c) Pressure distribution
with $H = 10$ mm**

**(d) Pressure distribution
with $H = 30$ mm**

Figure 7

Pressure distribution of an apple with the distance from the center to the Tesla valve collecting port h of -10 mm, 0 mm, 10 mm, and 30 mm

**(a) Velocity distribution
with $H = -10$ mm**

**(b) Velocity distribution
with $H = 0$ mm**

**(c) Velocity distribution
with $H = 10$ mm**

**(d) Velocity distribution
with $H = 30$ mm**

Figure 8

Velocity distribution with the distance between the apple center and Tesla collecting port h of -10 mm, 0 mm, 10 mm, and 30 mm

Figure 9

Negative pressure suction picking system

Figure 10

Measure of the flow rate at the collecting port

Figure 11

The state of apples in different positions

Figure 12

The first Tesla valve negative pressure collection port at different h simulation flow rate data and experimental flow rate data line chart

Figure 13

Broken line chart of experimental data on suction force of three types of Tesla valve negative pressure collection port at different h values

Figure 14

The second type of Tesla valve negative pressure collection port at varying h simulation flow rate data and experimental flow rate data line chart

Figure 15

Third type of Tesla valve negative pressure collection port at different h simulation flow rate data and experimental flow rate data line chart

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [GraphicalAbstract.pdf](#)