การวิเคราะห์การขนส่งท่อเหล็กด้วยกลไก Star Wheel เพื่อการใช้พลังงานอย่างมีประสิทธิภาพ

Analysis of Steel Pipe Conveyance using Star Wheel Mechanism for Energy Efficiency

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Abstract

Efficient material handling systems are vital for minimizing energy consumption and enhancing operational efficiency. This study addresses the gap in optimizing Star Wheel mechanisms for steel pipe conveyance, focusing on energy-efficient operations. Specifically, it evaluates the effects of hopper angles (30°, 45°, 60°) and Star Wheel rotational speeds (6 - 18 rpm) on the efficiency of transporting 1-inch diameter, 0.7-meter-long steel pipes. Results reveal that a 30° hopper angle facilitates smooth loading, while rotational speeds of 6, 9, and 12 rpm provide optimal performance, achieving a transport rate of 2,880 pipes per hour and reducing energy consumption to 0.079 watt-hours per pipe. These insights contribute to improved industrial conveyance systems with enhanced energy efficiency.

Keywords: Star Wheel, Conveyance, Energy consumption

1. Introduction

In today's industrial landscape, production efficiency and effective management are paramount for maintaining competitiveness and sustainability. One critical challenge is achieving energy-efficient material handling systems that can minimize operational costs while maximizing throughput. Steel pipe transportation, a vital process in manufacturing and construction industries, requires innovative solutions to address energy consumption and handling inefficiencies.

Among various mechanisms, the "Star Wheel" has gained significant attention due to its capability to precisely control material movement, integrating gears with the Geneva mechanism to provide enhanced flexibility and precision (Hughes, 2019). However, despite its advantages, research on optimizing Star Wheel mechanisms for steel pipe conveyance remains limited. Specifically, the relationship between hopper angles, rotational speeds, and their combined impact on energy efficiency and throughput has not been thoroughly investigated. Prior studies have primarily focused on general conveyor mechanisms, leaving a gap in understanding the optimal configurations for specific materials such as steel pipes.

Notably, the Star Wheel is commonly incorporated into conveyor systems, where it offers distinct advantages over traditional conveyor methods. Specifically, it enables control over both the angle at which materials enter the system and the rotational speed of the wheel, allowing fine-tuned management of the conveyance process. As Chen et al. (2021) demonstrated, adjusting the entry angle of materials enhances the flow rate within the system. Moreover, modifying the rotational speed can further improve transportation efficiency, which not only boosts overall process performance but also reduces potential material damage a critical factor in high-efficiency operations (Crompton, 2012; Emblem, 2012).

In this study, we applied the Star Wheel to a material handling system focused on transporting steel pipes with a diameter of 1 inch and a length of 0.7 meters. These pipes were processed within VRP Engineering & Trading Company Limited, an Original Equipment Manufacturer (OEM) in Thailand. To determine optimal settings, we examined three different angles 30°, 45° and 60° and evaluated the effects of varying rotational speeds and distances between the Star Wheel and the steel pipes. By analyzing these factors, this research aims to identify strategies for improving material handling efficiency and accuracy. Li et al. (2023) and Chen et al. (2020) provided foundational insights into similar configurations, while Gatade et al (2020). and Shi et al (2018) offered valuable frameworks for optimizing material handling and conveyance performance.

2. Objectives

2.1 To identify the optimal hopper angle and rotational speed for efficient steel pipe conveyance using the Star Wheel mechanism.

2.2 To evaluate the energy efficiency of different configurations and provide recommendations for industrial applications.

3. Research methodology

3.1 Mathematical Formulation for Loading with Star Wheels

The efficiency of conveying a steel pipe with a diameter of 1 inch and a wall thickness of 1.20 mm is derived by calculating the conveying area for each arm rotation. Specifically, the conveyed mass per single arm is calculated and then multiplied by both the rotational speed and the number of arms on the Star Wheel to determine the total conveying area and the amount of steel pipe transported per revolution, as shown in Equations (1) – (3) (Li et al., 2023).

$$A = \pi\left(\frac{D}{2} - \frac{d}{2}\right)^2 - Za \qquad (1)$$

Where

A is the conveying area for one revolution of rotation.

D is outer diameter of the Star Wheel (m)

d is inner diameter of the Star Wheel (m)

Z is the amount of arms

a is the surface area of arm (m^2)

$$Q_1 = A \times \rho \times h \times \varphi \qquad (2)$$

Where

Q_1 is mass of steel pipe conveyed per revolution (kg)

h is height of Star Wheel (m)

φ is loading factor, 0.68, ρ is density of steel pipe (kg/m^3)

The conveying efficiency of Star Wheel per second is shown as

$$Q = \frac{1}{60} \times Q_1 \times z \times n \qquad (3)$$

Where

Q_1 is mass of steel pipe that can be conveyed per second

Z is the amount of arms

n is the rotational speed of Star Wheel (rpm)

Calculating the energy consumption of the Star Wheel relies on understanding the torque involved in sweeping and conveying the steel pipes. This analysis considers energy losses during the rotation of the Star Wheel, particularly frictional losses. The torque acting on the arm of the Star Wheel can be calculated using the torque value on the shaft, accounting for the moment of inertia. This is expressed by Equation 4, as outlined by Chen et al. (2020).

$$G_s = Z \times Q_1 \times g \tag{4}$$

The frictional force encountered when the Star Wheel and the steel pipe slide over the feeder's surface is represented by Equation 5. This frictional force must be overcome to maintain smooth operation of the conveyance system. According to studies conducted by Shi et al (2018), the torque generated by the friction between the steel pipe and the feeder is given in Equation 6.

$$f = G_s \times \mu \tag{5}$$

$$\tau = f\frac{D}{2} \tag{6}$$

Where

f is the friction force between the Star Wheel and the sliding steel pipe. (N)

G_s is the gravitational force acting on the steel pipe loaded per revolution of the Star Wheel (N)

g is the acceleration of free fall, Gravity (N)

μ is the coefficient of friction between the steel pipe and the Star Wheel.

In the design phase, the inclined angle of the fed pipe during conveyance is generally not considered. To thoroughly analyze the forces acting on the Star Wheel and to calculate the torsional force experienced during steel pipe conveyance, Equation 7 is applied, as

$$F_{gn} = \frac{mn^2\pi^2 r}{900} \tag{7}$$

Where

F_{gn} is the torsional force acting during the conveyance (N)

m is the mass of steel pipe at the end of Star Wheel (kg)

n is speed of revolution (rpm)

r is radius of Star Wheel (m)

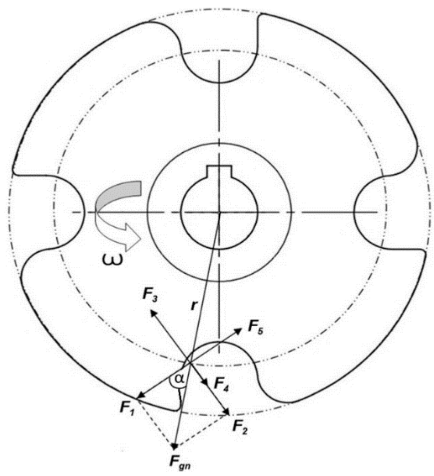


Figure 1 Free body diagram of Star Wheel

As shown in Figure 1, the torque moment relative to the center of gravity, which is inclined to the surface of the Star Wheel, is calculated using Equations (8) and (9).

$$F_1 = \frac{mn^2\pi^2 r}{900}\cos(\alpha) \tag{8}$$

$$F_2 = \frac{mn^2\pi^2 r}{900}\sin(\alpha) \tag{9}$$

The frictional force acting between the steel pipe and the Star Wheel can be determined by Equation (10). The normal force exerted between the surface areas can be represented by Equation (11). This normal force ensures that the steel pipe can fully enter the conveyor system. The centrifugal force acting between the Star Wheel, the pipe, and the frictional force from the steel pipe aligns with the rotational speed calculations used for the conveyor system. The rotational speed, which allows for a balance between applied forces and rotational motion, can be determined using Equation (12).

$$F_3 = mg\mu \tag{10}$$

$$F_4 = F_3 - F_2 = mg\mu - \frac{mn^2\pi^2 r}{900}\sin(\alpha) \tag{11}$$

Where

r is radius of Star Wheel (m.)

α is the angle between the centrifugal force tangent to the steel pipe (°)

$$n \geq \frac{30\mu}{\pi}\sqrt{\frac{g}{\mu r \sin(\alpha)}} \tag{12}$$

Equation (12) specifically calculates the rotational speed of the Star Wheel when it is in equilibrium. At the maximum balanced rotational speed, the speed remains constant, and the centrifugal force on the steel pipe, as well as the force exerted by the arm of the Star Wheel, corresponds directly to the radius of the Star Wheel. The relationship between the angle of inclination and the rotational speed forms part of the model used in the quality conveyance of steel pipes, as calculated in Equation (13).

$$\alpha \geq \arcsin\frac{900\mu g}{\pi^2 n^2 r} \tag{13}$$

3.2 Design of the Star Wheel and preparation of experiment with conveyer

In this study, we examine a conveyor system designed for transporting steel pipes with a diameter of 1 inch and a length of 0.7 meters. The system utilizes a Star Wheel constructed from superlene (nylon), a material commonly used in industrial conveyor systems due to its durability and versatility. Details of the Star Wheel are shown in Figure 2, illustrating that each rotation can transfer up to four pipes at a time. The hopper angles were selected to simulate common industrial configurations, balancing gravitational feeding efficiency and material handling reliability. Angles below 30° were avoided due to insufficient gravitational force, while angles above 60° were excluded to prevent clogging caused by increased friction. Similarly, the range of rotational speeds (6-18 rpm) was chosen to reflect practical operational limits in industrial Star Wheel systems.

In this experiment, the Star Wheel is fed pipes from a hopper, utilizing gravitational acceleration. The hopper's angle can be adjusted to 30°, 45° or 60°, enabling flexible feeding angles for optimal loading conditions. It can hold up to 80 pipes with a 1-inch diameter, which are then arranged independently, as depicted in Figure 3.

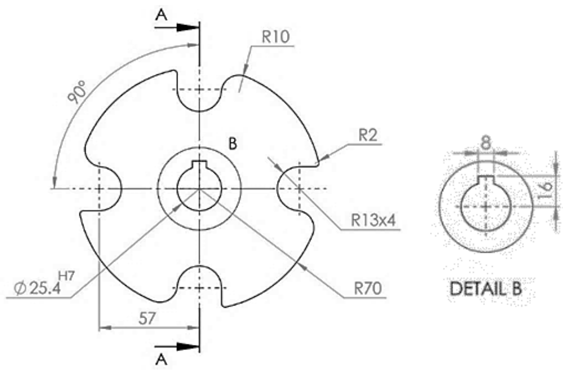


Figure 2 Details of the Star Wheel in experiment

The Star Wheel is continuously rotated, with its speed controlled by an inverter to evaluate the effect of various speeds on the system's performance. The rotational speed settings tested include 6, 9, 12, 15 and 18 rotations per minute, allowing us to identify the most effective speed for the conveyor system.

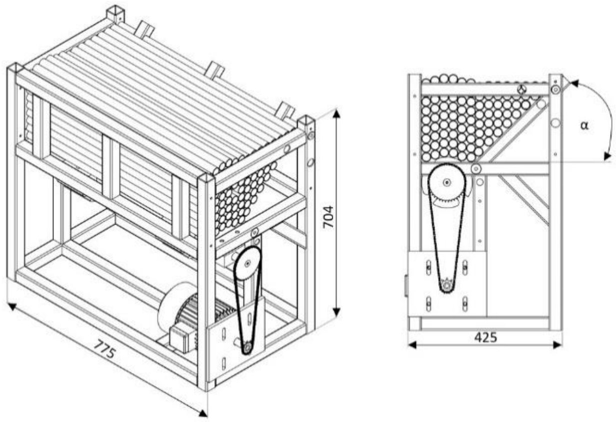


Figure 3 Characteristics of the experimental for transporting 1-inch steel pipes with adjustable angle of steel pipe feeder

The setup includes two Star Wheels mounted on a central axis, with their positions adjusted to three different lengths along the axis. The first position is set at half the axis length, centered between the two Star Wheels; the second is two-thirds of the axis length; and the final position spans the entire length, with a Star Wheel at each end, as shown in Figure 4. The coefficient of friction between the steel pipe and the Star Wheel is 0.4, illustrating the frictional relationship within the system.

(A)

(B)

(C)

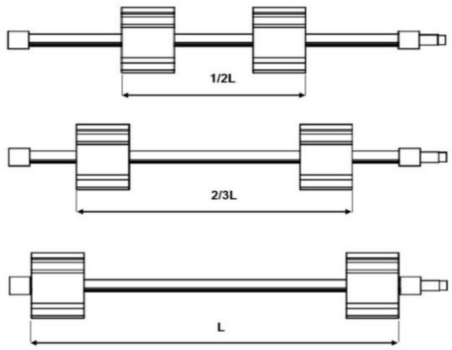


Figure 4 Placement of Star Wheel

(A) Star Wheel spacing arrangement with 1/2L

(B) Star Wheel spacing arrangement with 2/3L

(C) Star Wheel spacing arrangement with L

Therefore, this experiment investigates the effects of three main factors on the conveyor system: (1) the hopper angle, (2) the rotational speed of the Star Wheels, and (3) the distance between each Star Wheel along the axis.

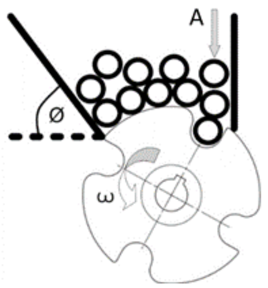
4. Results and Discussion

Results of conveyor system with steel pipe of 1-inch diameter with the length 0.7 meters, with “Superlene” as the Star Wheel’s material has shown that one rotation can convey 4 steel pipes. This experiment was separated into three parts: The first study was to find the effects of adjusting the angle of the conveyer feeder at 30, 45 and 60 degrees. The second study was to find effects of comparing the Star Wheel’s rotational speed. The third study to observe the effects of the Star Wheel’s spacing arrangement. The experiment’s results of testing the conveyor system are as followed:

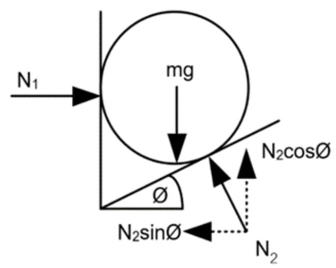
The experiment started by first adjusting with one of the angles (30, 45 and 60 degrees), which is followed by the steel pipes being loaded onto the feeder until full and the Star Wheel spins at 6 rounds-per-minutes. With this setting, each of the three angles would be trial for 3 times to see which angle would be compatible. Observations were shown that the angle which was perfectly suitable for conveying was 30 degrees. This was further evident with the fact that the steel pipes would slide in the Star Wheel’s conveyor without disturbance. The higher angles (45 and 60 degrees) would cause the steel pipes to rub against each other and would not flow into the conveyor system, due to the angle θ having a higher value. This causes the steel pipes to have higher forces acting on each other, as shown in Figure 5 (A and B).

When the angle θ increases, the N_1 value increase. the N_1 value of each angle is equal to $\tan\theta = \frac{N_1}{mg}$

The study of the impact from adjusting the rotational speed of the Star Wheel and the study of the impact from adjusting the spacing of the Star Wheel was conducted by adjusting the angle as specified, which was 30 degrees, before adding the steel pipes into the feeder. (45 & 60 degrees would cause the steel pipes to be stuck and thus unable to perform the experiments) The experiment was carried out by adjusting the Star Wheel spacing the ratio lengths of 1/2L, 2/3L and L respectively, while being coupled along with continuously rotating Star Wheels at speeds of 6, 9, 12, 15 and 18 rpm. respectively. Observations has found that the Star Wheel speeds of 6, 9, 12 and 15 rpm. were able to transport steel pipes continuously in all length ratios. However, the Star Wheel speed of 18 rpm was unable to convey due to its speed being too fast for the system. All results are shown in Table 1.



(A) Falling position of the steel pipe



(B) Analysis of forces applied to steel pipes when waiting to be conveyed

Figure 5 Analysis of forces applied to steel pipes

However, the Star Wheel's speed of 15 rpm for the steel conveying was found to have a relatively fast rotation characteristics and is not suitable for conveying. Due to the high rotational speed resulting in angular velocity (ω) and the linear speed of the object is higher, operators and machines may be in risk of danger. As for the length ratio of 1/2L, 2/3L and L, observations has found that the steel pipe and the Star Wheel's length ratio did not affect the conveying. The designer may choose any ratio found to be appropriate. However, key way should be specified for use with the machine Keys for the Star Wheel and drive shaft to reduce the tolerances between each Star Wheel.

Therefore, from the experiment's results, the angle of the container waiting be conveyed will be obtained at 30 degrees. The rotational speed of the Star Wheel suitable for conveying steel pipes were at speeds of 6, 9 and 12 rpm, with the ratio of the Star Wheel's length to steel pipe lengths 1/2L, 2/3L and L for 1-inch steel pipes with the length of 0.7 meters.

In addition to studying the conveying process, this research also measured the energy consumption of a 1-inch steel pipe conveyor system with a length of 0.7 meters. To achieve accurate measurements, a digital power meter was connected to the inverter controlling the Star Wheel. The device recorded the total energy consumed during each trial, and the values were normalized to calculate the energy usage per pipe. Furthermore, the relationship between the rotational speed of the Star Wheel and the energy used to transport the steel pipe was examined. It was discovered that as the rotational speed increased, the energy consumption increased consistently. For rotational speeds of 6, 9, 12 and 15 rpm, the energy consumption values were 248, 260, 273 and 285 watts-hours respectively, as depicted in Figure 6.

Table 1 Experimental results

RPM	Feeder angled at 30°			Feeder angled at 45°			Feeder angled at 60°		
	Length ratio			Length ratio			Length ratio		
	1/2L	2/3L	L	1/2L	2/3L	L	1/2L	2/3L	L
6	✓	✓	✓	×	×	×	×	×	×
9	✓	✓	✓	×	×	×	×	×	×
12	✓	✓	✓	×	×	×	×	×	×
15	✓	✓	✓	×	×	×	×	×	×
18	×	×	×	×	×	×	×	×	×

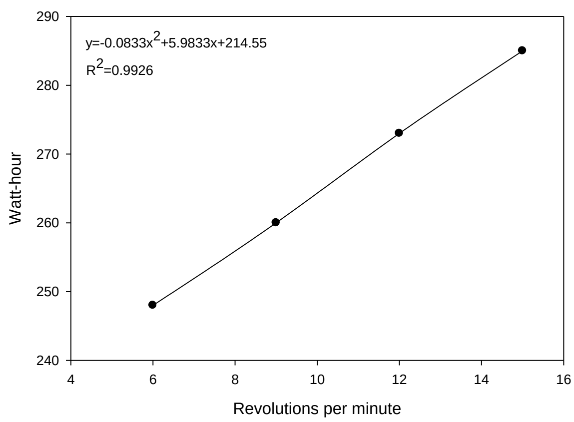


Figure 6 Relationship between the rotational speed of the Star Wheel and the energy used to transport the steel pipe.

From Figure 6, the analysis of energy consumption (y) as a function of rotational speed (x) reveals the following quadratic regression model This model y^2=-0.0833x^2+5933x+214.55 demonstrates high accuracy (R^2=0.9926). The graph indicates that as rotational speed increases, energy consumption follows a curved pattern. Within the tested range of 6–15 RPM, energy consumption increases consistently, highlighting a strong positive relationship between rotational speed and energy usage within this interval. While higher rotational speeds lead to increased energy consumption, they also allow the conveying system to transport more efficiently. At rotational speeds of 6, 9, 12 and 15 rpm, steel pipes can be transported at rates of 1,440, 2,160, 2,800 and 3,600 steel pipes per hour respectively. When considering the energy consumption index of "Watts-hour per piece," it was observed that as the rotational speed increased, the energy consumption index decreased significantly. For rotational speeds of 6, 9, 12 and 15 rpm, the energy consumption index values per piece were 0.172, 0.120, 0.095 and 0.079 watts-hour per piece respectively, as shown in Figure 7.

From Figure 7, The relationship between energy consumption per piece (y) and rotational speed (x) is described by the quadratic regression model y=0.001x^2−0.0311x+0.3219 With a high level of accuracy (R^2 = 0.9967), the model indicates that energy consumption per piece decreases substantially as rotational speed increases, reaching its minimum value at approximately 15.55 RPM. Beyond this point, the rate of decrease slows, and energy consumption stabilizes. Within the tested range of 6–15 RPM, the findings highlight that adjusting rotational speed can significantly improve energy efficiency per piece.

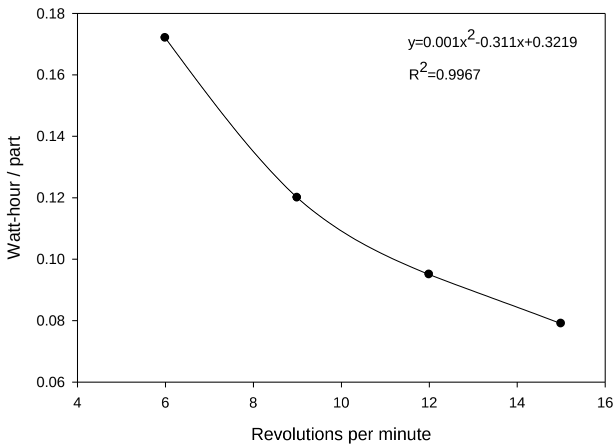


Figure 7 Relationship between the rotational speed of the Star Wheel and the energy consumption index for conveying steel pipes.

5. Conclusions

This study developed and tested a conveying system prototype for steel pipes with a diameter of 1 inch and a length of 0.7 meters. The prototype, measuring 0.425 × 0.775 × 0.704 meters with a capacity for 80 pipes, features a Star Wheel constructed from Superlene, capable of transporting steel pipes in four segments per revolution. Key parameters tested included loading angles (30°, 45°, 60°), rotational speeds (6, 9, 12, 15, and 18 rpm), and Star Wheel arm spacing ratios (1/2L, 2/3L, L).

The results showed that a 30° loading angle and rotational speeds of 6, 9, and 12 rpm provided optimal performance, ensuring smooth pipe conveyance and minimizing risks of damage. Rotational speeds above 12 rpm were not recommended due to potential safety and mechanical concerns. The spacing ratio of the Star Wheel arms had no significant impact on performance, offering flexibility in design.

Energy consumption remained a critical consideration, with transport rates of 1,440, 2,160, 2,880, and 3,600 pipes per hour achieved at 6, 9, 12, and 15 rpm, respectively. The energy efficiency improved with increased speeds, achieving energy indices of 0.172, 0.120, 0.095, and 0.079 watt-hours per pipe at these speeds. This study highlights the importance of balancing operational speed and energy efficiency for optimal system performance.

Future studies could expand the scope of research by experimenting with hopper angles outside the tested range, such as below 45°, to evaluate their impact on material flow and efficiency.

6. Acknowledgements

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