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ANALYSIS OF ROLLING RESISTANCE PARAMETERS IN GRAVITY FLOW RACKS FOR HEAVY-DUTY APPLICATIONS

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Abstract: *Flow racks represent a dynamic storage system that utilizes gravitational force to enable controlled movement of unit loads along specially designed, inclined roller lane. Efficient operation of these systems requires a detailed analysis of the resistances encountered during the movement of unit loads. Therefore, the rolling resistance plays a crucial role in determining the speed and stability of the unit loads. This paper investigates the most influential parameters contributing to the total rolling resistance in gravity flow racks. Particular emphasis is placed on the effects of the mass of unit loads, characteristics of rollers, the angle of the inclined roller lane, as well as the condition of the contact surfaces between the rollers and unit loads. The aim of this research is to identify and quantify the impact of relevant parameters in the context of design optimization and system efficiency improvement. The findings contribute to a better understanding of the tribological behavior of gravity flow racks and support improvements in system design, thereby increasing efficiency, reducing downtime and enhancing throughput in modern storage environments.*

Keywords: *flow racks, gravity, rolling resistance, roller*

1. INTRODUCTION

In modern storage systems, the demand for efficient, reliable and energy-sustainable solutions is becoming increasingly prominent due to growing logistical requirements and the rising volume of goods handling. Flow racks represent one solution that meets these demands, particularly in high-throughput systems operating under the First-In-First-Out (FIFO) principle. These racks mostly function without additional driving power, utilizing gravity to move unit loads along smoothly inclined roller lanes. As a result, the need for automatization is reduced, leading to significant savings in energy consumption and space.

Construction of flow racks consists a series of rollers mounted on the supports, spaced evenly on two side frames. The spacing between rollers is determined by size of the unit loads that need to be transported, ensuring that at least two rollers support the unit load at any given time. This paper focuses on the selection and calculation of an unpowered flow rack. In these racks, all rollers are powered by the unit load mass under the action of gravity. However, the efficiency of gravity flow racks largely depends on resistances which are acting during the movement of unit loads. Unfavorable tribological conditions, potentially leading to blockages and product damage, directly compromise the productivity and reliability of storage processes. The analysis of tribological processes is essential for defining material behavior under the influence of rolling resistance. The coefficient of rolling resistance plays a key role in determining the speed and inclination angle, as well as the stability and safety of material flow [1, 2].

By analyzing these parameters, the study seeks to improve the understanding of the mechanisms that affect the speed and stability of motion. That directly contributes to optimize the design and increase the efficiency of the storage system.

Safronov and Nosko [3] addressed determining the safe travel speed of unit loads in flow racks, which pose risks due to gravity racks. Brake rollers and stopping mechanisms are used to mitigate these risks. A method based on Cox's impact theory is used to calculate the allowable pallet speed, which depends on mass of unit load, considering the characteristics of the stopping mechanism, thus enhancing safety in flow racks.

Sharifullin et al. [4] presented a comparative analysis of calculated and experimentally investigated unit load travel speed for gravity flow racks with magnetic brake rollers. This research developed a mathematical model for speed calculation, compared it with experimental results and demonstrated that pallet mass significantly influences travel speed, requiring braking system adaptation to mass of unit load ranges. The study contributes to optimize the design and application of this type of flow rack.

Although this type of rack is expensive, it is considered one of the systems that utilizes storage space most efficiently. A comparison with other rack types is provided in the analysis by Vujanac et al. [5].

This paper focuses on analyzing the parameters that influence rolling resistance in flow racks, with the aim of identifying the most critical factors and providing guidelines for design optimization. This creates an opportunity for the further development of more efficient and durable storage systems that meet the increasingly strict demands of modern logistics.

2. GRAVITY FLOW RACK CHARACTERISTICS

Flow racks represent a combination of selective and drive-through racks, characterized by gravity as the primary driving force for material movement. Unlike static racking systems, flow racks enable so-called dynamic storage of items, typically loaded pallets, along inclined lanes equipped with rollers. This configuration supports FIFO inventory management, which is essential for perishable goods or items with expiration dates. An example of gravity flow rack system is shown in Figure 1.

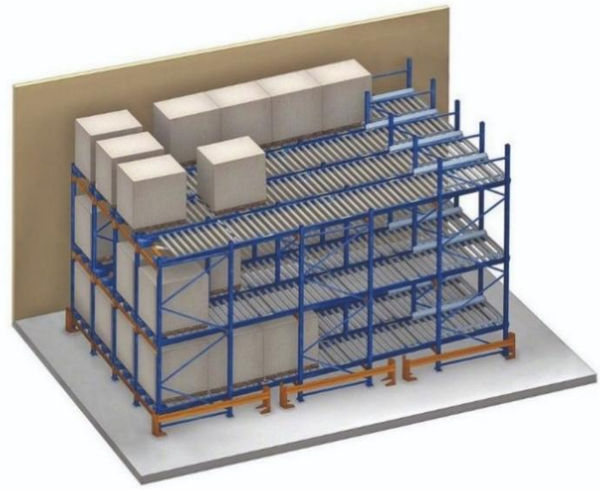

Figure 1. Gravity flow rack [3]

Operating on the FIFO principle requires a separate loading aisle at the rear and a picking aisle at the front of the racking structure. Due to the inclined lanes and the effect of gravity, each unit load is automatically directed toward the picking face, ensuring continuous material flow. The number of parallel lanes directly depends on the available storage space, as single-lane systems are typically not economically viable. Key dynamic structural components, such as inclined lanes, guide rollers, end stops and braking mechanisms, ensure controlled and efficient movement of unit loads within the system [1].

The aim of this paper is to identify and quantify the key parameters that are affecting on rolling resistance in gravity flow racks, with particular focus on:

- the mass of unit load,
- the geometry and material of rollers,
- the incline angle of the roller lane and
- the condition of the contact surfaces between the rollers and unit loads.

Before that, it is important to define the tribological processes that can affect the aforementioned resistances.

3. TRIBOLOGICAL PROCESSES IN GRAVITY FLOW RACKS

In gravity flow racks, as it is shown on Figure 2, unit loads move along inclined rollers under the angle of β, due to their own weight (mg), which causes continuous contact between the rollers and the underside of the unit load. This contact leads to tribological processes, primarily rolling friction, which, although lower than sliding friction, still causes energy losses.

Rolling friction arises due to slight deformations of the roller and the surface it rolls on. These deformations shift the normal force forward, creating a torque that resists rolling, known as rolling resistance.

Low resistance ensures controlled movement, while excessive resistance can lead to irregular motion, increased wear and request for higher maintenance. Therefore, understanding this phenomenon is key for material and bearing selection, as well as for effective lubrication strategy [2, 6].

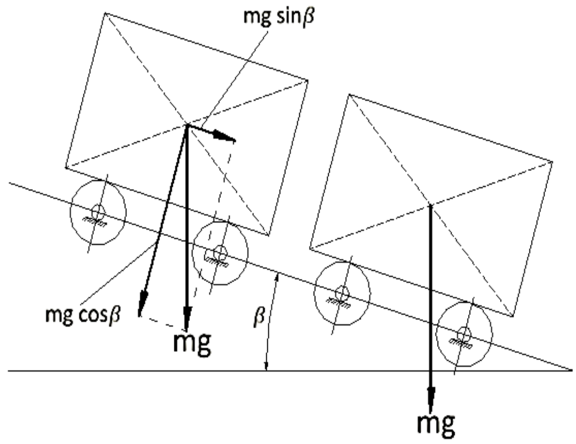

Figure 2. Schematic preview of motion [2]

4. THE IMPACT OF THE MASS OF UNIT LOAD ON TRIBOLOGICAL PROCESSES

The consideration of gravity flow rack components is based on the following initial data of unit load: dimensions $a \times b \times h = 1200 \times 800 \times 1200$ [mm], and variable masses, $m = 500; 850; 1200$ [kg].

The objective is to determine the force required to overcome motion resistance and the influence of the inclination angle. Total resistance of motion consists of:

- resistance caused by the rolling of the unit load on rollers,
- resistance due friction in the roller bearings and
- resistance due to sliding of the unit load on the rollers.

All influencing factors were chosen in order to provide efficient and safe movement of materials in accordance with initial technical demands. The resistance to motion of a single unit load resting on a pair of rollers can be defined as follows [2, 7]:

$$W_1 = \left[m\frac{2f}{D} + (m + m_v \cdot z') \cdot \mu\frac{d}{D}\right] \cdot g + k\frac{m_v \cdot z \cdot v^2}{L} \tag{4.1}$$

As the total length, L, and the unit capacity, z, aren't affecting parameters in this analysis, the equation 4.1 is therefore modified:

$$W_1 = \left[m\frac{2f}{D} + (m + m_v \cdot z') \cdot \mu\frac{d}{D}\right] \cdot g + k\frac{m_v \cdot v^2}{t_v} \tag{4.2}$$

Where are:
f [m] – rolling friction factor,
D [m] – roller diameter,
d [m] – roller journal diameter,
m_v [kg] – roller mass,
z' [–] – number of rollers where a single unit load lies,
μ [–] – roller journal coefficient of friction,
g $\left[\frac{\mathrm{m}}{\mathrm{s}^2}\right]$ – acceleration of gravity,
k [–] – mass distribution coefficient of roller rotating parts,
z [–] – number of rollers,
v $\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$ – motion,
t_v [m] – roller pitch.

The output parameter, which is directly connected with the inclination angle is rolling resistance coefficient, shown with equation:

$$\omega = \frac{W_1}{m \cdot g} \qquad (4.3)$$

5. ANALYSIS OF ROLLING RESISTANCE

For the purpose of evaluating rolling resistance under heavy-duty operating conditions, a steel idle roller with a diameter of 159 mm and a length of 1000 mm was adopted for all cases. Models 312014 and 312024 were selected based on specifications provided in the producer technical catalogue [8]. The load-bearing capacity meets the requirements for transporting palletized unit loads, which were used as representative masses for this analysis.

A cross-section of this type of roller, which is classified as heavy-duty type, is shown on Figure 3, with following positions [8]:
1 – internal protection made of polyamide resin,
2 – roller bearing,
3 – double labyrinth seal made of polyamide resin,
4 – front galvanized steel cartridge,
5 – rear galvanized steel cartridge,
6 – front sealing ring with wear compensation,
7 – rear sealing ring with wear compensation,
8 – integrated axial stop, machined directly on the shaft and
9 – external protection made of elastomer.

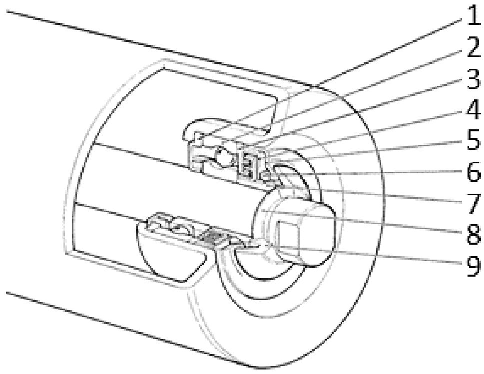

Figure 3. Cross-section of heavy-duty idle roller [8]

Based on equations (4.1) – (4.3), the values obtained in function of mass of unit loads are listed in Table 1.

Table 1. Output parameters in function of mass

Model	m [kg]	m_V [kg]	D [m]	d [m]	v $\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$	W_1 [N]	ω [-]	β [°]
312014	500	20,33	0,159	0,032	0,21	127,269	0,025947	1,4863
312014	850	20,33	0,159	0,032	0,21	211,9189	0,025415	1,4558
312024	1200	20,675	0,159	0,032	0,21	296,6763	0,025202	1,4437

The analysis of the presented results indicates that resistance to motion increases almost linearly with the increasing mass of the transported unit load, which aligns with expected behavior.

The rolling resistance coefficient slightly decreases with increasing mass, suggesting more efficient rolling under higher loads due to more favorable contact of surfaces. Additionally, the inclination angle of the roller lane exhibits a decreasing trend, as it is shown on Figure 4.

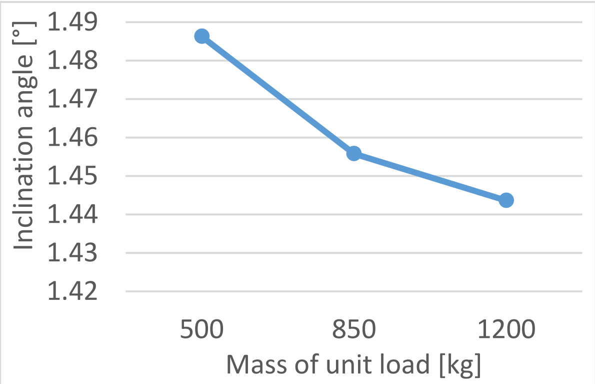

Figure 4. Effect of unit load mass on the required inclination angle

It is implied that lower angles are sufficient for heavier pallets to overcome rolling resistance. This finding may contribute to more compact and efficient flow rack designs in high-load storage applications.

With calculated rolling resistance coefficient and according to the regulations given in [2], it can be confirmed that this analysis is exact and valuable.

6. CONCLUSION

In order to reflect realistic operating conditions in gravity flow racks designed for heavy-duty applications, three characteristic unit load masses are considered. The translational velocity of loads is assumed to be below $0{,}5\ \frac{m}{s}$, in accordance with practical movement speeds observed in these racks.

Understanding tribological phenomena in gravity flow racks is fundamental for assessing operational reliability and efficiency. Rolling friction and wear processes can significantly affect system performance over time. These effects are influenced not only by material pairings and environmental conditions but also by operational parameters, particularly the mass of the unit load and the velocity of its movement.

The observed trends highlight the importance of considering the unit load characteristics and roller lane design in optimizing the performance of gravity flow racks. The decrease in the required inclination angle for heavier unit loads suggests potential savings in vertical space and improvements in storage density. However, the increase in rolling resistance with load mass emphasizes the need for careful balance between slope design and braking or control mechanisms, to ensure safe and consistent material flow, as analyzed in [4]. The slight reduction in the rolling resistance coefficient at higher loads may indicate opportunities for material or structural optimization of rollers used in heavy-duty environments.

This analysis aims to provide a deeper insight into the relationship between load characteristics and tribological performance, ultimately contributing to improved dimensioning, component selection and maintenance strategies in gravity flow racks. Future research may involve experimental validation of the theoretical findings, as well as an investigation into the influence of environmental factors such as temperature and humidity on roller behavior.

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