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Performance Analysis and Cost Effectiveness of Modified Vacuum Systems for Industrial Applications

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Abstract

To meet the pressing need for more cost-effective and efficient technologies across a range of manufacturing and processing sectors, this study investigates the performance and economics of modified vacuum systems designed for industrial usage. We conducted a comparative analysis across multiple industries, including electronics manufacturing, food processing, and pharmaceuticals, to evaluate the improvements in suction performance, energy consumption, and noise levels during operations. This study investigates the impact of vacuum system modifications on production efficiency and cost-effectiveness in an industrial setting, using data collected from Walton Hi-Tech PLC. Three key modifications were implemented: increasing the hose diameter, reducing the hose length, and installing a 1000-liter vacuum vessel. Performance was assessed by comparing data before and after these changes over a two-month period. Results show a significant improvement in production efficiency, with a reduction in the machine cycle time from 90 to 84 seconds per product, leading to an increase in production capacity by 1,133 units per month. Additionally, the modifications resulted in a reduction in damaged products, dropping from 459 to 213 units per month, which contributed to an annual cost savings of 983,200 BDT. This research highlights the operational and financial benefits of optimizing vacuum systems in industrial applications, demonstrating both increased productivity and reduced waste.

Keywords: Industrial vacuum systems, Performance optimization, Cost-effectiveness.

1. Introduction

The vacuum system encompasses various applications and technologies, ranging from high-energy physics to household cleaning devices. This multifaceted concept includes vacuum chambers, pumps, and specialized systems designed for specific functions, such as desalination. Below are key aspects of vacuum systems based on recent research. The High Luminosity Large Hadron Collider (HL-LHC) requires an upgraded vacuum system to enhance beam lifetime and minimize background interference in experiments. This involves improving mechanical robustness and mitigating electron multipathing [1]. A vacuum chamber system is designed with a housing that creates a sealed environment, allowing for controlled pressure conditions. This system includes mechanisms for air withdrawal to maintain vacuum levels [2]. Advanced vacuum pump systems utilize a combination of turbomolecular and Roots pumps arranged in series to achieve efficient air removal and pressure maintenance [3]. A novel vacuum system employing the venturi principle facilitates seawater desalination by reducing boiling points and maintaining low pressure, thus enhancing energy efficiency and simplifying equipment design [4].

The performance analysis and cost-effectiveness of modified vacuum systems in industrial applications reveal significant advancements in efficiency and energy savings. These systems are crucial in various sectors, including oil, gas, and pharmaceuticals, where moisture removal and energy consumption are critical. Modified vacuum drying processes effectively eliminate moisture from piping equipment, preventing issues like hydrate formation and corrosion [5]. Experimental data indicate that optimized vacuum systems can achieve substantial moisture reduction, enhancing operational reliability in industrial heat exchangers [5]. Research shows that energy consumption in vacuum systems can be reduced by 90% to 99%, leading to considerable financial savings [6]. A case study on a 6 MeV industrial LINAC demonstrated a vacuum system that operates at reduced power (0.4 kW) while maintaining performance, resulting in a 40% cost reduction [7]. Vacuum technology is also pivotal in robotic systems, where it enhances the efficiency of gripping mechanisms, particularly in challenging environments. The choice of vacuum generator can impact system performance, but its effect is often minimal

compared to other factors. Custom-designed suction cups can enhance gripping capabilities, especially for complex surfaces, thereby improving overall efficiency [8].
However, a comprehensive understanding of the performance analysis and cost effectiveness of modified vacuum systems for industrial applications remains incomplete. Therefore, this study aims to experimentally analyze the performance and cost effectiveness of modified vacuum systems for industrial applications.

2. Methodology

In this research, we evaluated three potential methods for optimizing pressure and airflow in a vacuum system used for thermoforming. These methods include: (1) increasing the diameter of the hose connecting the vacuum pump to the thermoforming mold, (2) reducing the length of the hose from 10 meters to 5 meters, and (3) installing a vacuum vessel with a capacity of 1000 liters.

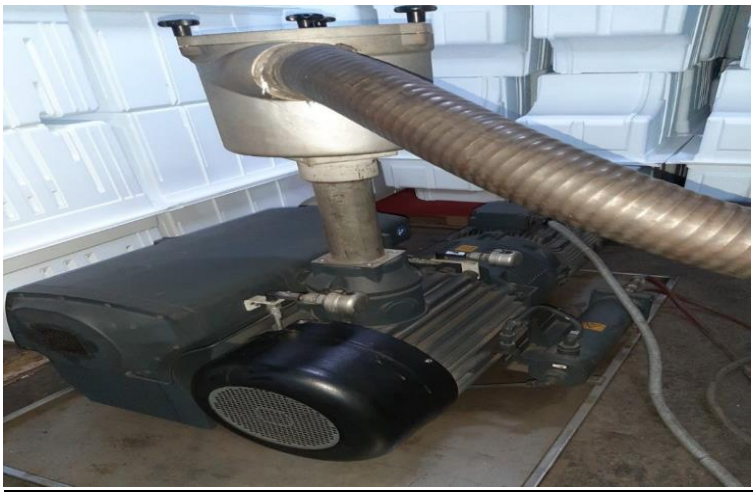


Fig. 1. Piping modification for getting better flow rate.

2.1 Increasing the Diameter of the Hose Pipe

By increasing the diameter of the hose, we can enhance the volumetric flow rate and air velocity within the system. According to the continuity equation, which states that the product of cross-sectional area and flow velocity must remain constant in a steady-flow system, an increase in pipe diameter results in a proportional increase in flow rate. This is because a larger pipe diameter reduces resistance to airflow, allowing for a greater volume of air to pass through with minimal pressure drop.

2.2 Reducing the Hose Length

While the length of the hose plays a role in overall system efficiency, it does not directly impact fluid velocity. However, reducing the length of the hose can minimize pressure losses due to friction and other factors over long distances. Shorter hose lengths reduce these frictional losses, leading to more efficient airflow. Though the continuity equation shows no direct effect on velocity, the overall system performance improves when pressure losses are minimized, which enhances vacuum efficiency.

2.3 Installing a 1000-Liter Vacuum Vessel

The installation of a vacuum vessel with a 1000-liter capacity further improves the system's performance by acting as a buffer for pressure fluctuations. The vessel helps maintain a stable vacuum level by temporarily storing vacuum capacity, ensuring a more consistent pressure and flow rate during operation. This improves response times and maintains optimal vacuum levels, especially in systems that experience periodic variations in demand.
After evaluating these three options, we determined that the most effective solution for optimizing the vacuum system involves a combination of increasing the hose diameter, reducing the hose length between the forming station and the vacuum pump, and installing a vacuum vessel with a 1 m^3 (1000-liter) capacity. This approach maximizes volumetric flow rate, reduces pressure losses, and enhances overall vacuum system performance, contributing to more efficient thermoforming
These methods were chosen because they collectively maximize airflow efficiency, reduce energy losses, and stabilize vacuum performance, directly contributing to increased productivity and cost savings.



Fig. 2. Installation of vacuum vessel with thermoforming machine.

3. Results and Discussion

We obtained data for this study from Walton Hi-Tech PLC, with their permission, to assess the performance of their vacuum system before and after modifications. The data spans two months, one month representing the system's performance prior to modification and the other after the modifications were implemented.

Data Collection

- **Before Modification:** In the initial phase, we recorded the system's operational parameters under standard conditions without any adjustments to the hose diameter, length, or the installation of a vacuum vessel. Key performance indicators such as pressure levels, flow rates, and vacuum efficiency were measured to establish a baseline for comparison.
- **After Modification:** Following the modifications specifically increasing the hose diameter, reducing the hose length, and installing a 1000-liter vacuum vessel we conducted the same measurements. This phase of data collection was crucial for analyzing the impact of these modifications on the vacuum system's performance.

Explanation of Data

The data collected before modification provided insight into the limitations of the existing system, such as reduced volumetric flow rates and fluctuating pressure levels. After the modifications, we observed improvements in these parameters, which can be attributed to enhanced airflow and reduced pressure losses.

By comparing the data from both phases, we were able to quantify the effectiveness of the modifications in improving the system's overall efficiency. This analysis is essential for understanding the practical benefits of the modifications, such as increased production efficiency and reduced energy consumption.

This data serves as a critical component of our research, offering empirical evidence to support the theoretical predictions regarding the benefits of optimizing the vacuum system's design. Table 01 displays data collection before vacuum modification and table 02 represents the data collection after vacuum modification.

Table 01: Data Collection before Vacuum Modification.

Date	Shift	Actual	Damage	Balance
01.03.23-05.03.23	Day	1205	45	1160
	Night	1195	72	1123
06.03.23-10.03.23	Day	1245	41	1204
	Night	1210	40	1170
11.03.23-15.03.23	Day	1100	37	1063
	Night	1190	36	1164
16.03.23-20.3.23	Day	1220	41	1179
	Night	1246	20	1226

21.03.23-25.03.23	Day	1218	30	1188
	Night	1242	12	1230
26.03.23-30.03.23	Day	1248	35	1213
	Night	1195	50	1145
	Total:	**14514**	**459**	**14055**
Production calculation according to the machine specifications				
Machine cycle time / product 90 sec (1.5 min)				
Actual production capacity 60/1.5				**40**
Production /shift (8 hours) 40 x 8				320
Production /day (2 shift) 320 x 2				640
Production /month (24 working days) 640 x 24				**15360**

Table 02: Data collection after Vacuum Modification.

Date	Shift	Actual	Damage	Balance
01.05.23-05.05.23	Day	1005	14	991
	Night	995	11	984
06.05.23-10.05.23	Day	1665	19	1637
	Night	1661	28	1633
11.05.23-15.05.23	Day	1340	15	1325
	Night	1345	12	1333
16.05.23-20.05.23	Day	1325	18	1307
	Night	1332	21	1311
21.05.23-25.05.23	Day	1667	19	1648
	Night	1655	28	1607
26.05.23-30.05.23	Day	998	14	884
	Night	659	14	645
	Total:	**15647**	**213**	**15434**
Production calculation according to the machine specifications				
Machine cycle time / product 84 sec (1.4 min)				
Actual production capacity 60/1.4				42.86
Production /shift (8hours) 42.86x8				342.88
Production /day (2 shift) 342.88x2				685.76
Production /month (24 working days) 685.76x24				**16458.24**

3.1 Cost effectiveness and performance analysis

Table 03: Data for performance analysis.

Sl.	Description	March	May	Result	Remarks
1	Machine production cycle time / product 90 sec (1.5 min)	1.5	1.4	-0.1	Decreased 6 sec per product
2	Machine production capacity	40	42.86	2.86	Increased / hour
3	Production /shift (8 hours)	320	342.88	22.88	Increased / day
4	Production /day (2 shift / 16 hrs.)	640	685.76	45.76	Increased
5	Production /month (24 working days) should be according to the calculation	**15360**	**16458.24**	**1098.24**	Increased / month

6	Production actually done / month (24 working day)	**14514**	**15647**	1133	Increased / month
7	Lack of production done / month	846	811.24	-34.76	Lack of production
8	Damaged / month	459	217	-266	Damaged product reduced
9	Good product / month	**14055**	**15434**	**1379**	Product capacity increased

OBSERVATIONS					
Sl	**Description**	**Calculation**		**Result**	**Remarks**
1	Production before vacuum modification per year	14055	12	168660	
	Production before vacuum modification per year	15434	12	185208	
	Production increased per year			**16548**	Increased
2	Product damage before modification per year	459	12	5508	
	Product damage after modification per year	213	12	2556	
	Damage reduced per year			**2952**	Reduced

COST EFFECTIVENESS					
Sl	**Description**	**Qty**	**Price /HIPS sheet**	**Result**	**Status**
1	Production increased per year	16548			**Efficiency increased**
2	Damage decreased per year	2952	350	1033200	It varies due to dollar rate
3	Cost for the installation a vessel of 1000 liter capacity	1	50000	50000	It varies due to dollar rate
				983200	**Amount saved (BDT)**
	In word: Nine lac, Eighty-three thousand and two hundred BDT.				

Based on the data collected from Walton Hi-Tech PLC, we can assess the impact of the vacuum system modifications on both performance and cost-effectiveness by analyzing production rates, product damage, and financial savings. Table 03 presents the data for performance analysis.

3.1.1 Performance Analysis:

3.1.1.1 Production Cycle Time

Before modification, the machine's production cycle time per product was 90 seconds (1.5 minutes). After the modifications, the cycle time reduced to 84 seconds (1.4 minutes), resulting in a **6-second reduction per product**. This improvement led to higher production capacity.

3.1.1.2 Production Capacity Increase

Before Modification

The production capacity was 40 products per hour, with a total of 320 products per shift (8 hours), and 640 products per day (16 hours in two shifts). Over a month (24 working days), this totaled **15,360 products**.

After Modification

The production capacity increased to 42.86 products per hour, with a total of 342.88 products per shift, and 685.76 products per day. Over a month, this amounted to **16,458.24 products**, marking an increase of **1,098.24 products** per month.

The actual data shows production increased from **14,514** to **15,647 products per month**, leading to an increase of **1,133 products**.

3.1.1.3 Reduction in Damaged Products

Before Modification: The number of damaged products per month was 459.
After Modification: This was reduced to 213 products per month, representing a decrease of **266 damaged products**.

3.1.1.4 Cost Effectiveness Analysis

The reduction in damaged products led to a significant cost saving. Assuming a damage reduction of 2,952 products annually and a price of 350 BDT per HIPS sheet, the total cost saved due to reduced damage amounts to **1,033,200 BDT** annually.

3.1.1.5 Installation Cost

The cost for installing a 1000-liter vacuum vessel was 50,000 BDT. After accounting for the cost of installation, the net savings from the reduced damage totals **983,200 BDT** annually.

The modifications to the vacuum system—namely increasing the hose diameter, reducing the hose length, and installing a 1000-liter vacuum vessel—significantly enhanced production capacity and reduced product damage. The improvements led to an increase in production by **1,133 products per month** and a reduction in damaged products by **266 per month**, translating to a net annual savings of **983,200 BDT**. The performance gains not only improved operational efficiency but also provided substantial cost savings, making the modifications highly cost-effective for Walton Hi-Tech PLC.

Conclusion

This study assessed the performance and cost-effectiveness of vacuum system modifications at Walton Hi-Tech PLC by comparing production data before and after the implementation of key system improvements.
The data indicates a significant reduction in machine cycle time from 90 seconds to 84 seconds per product, which directly contributed to an increase in production capacity. Specifically, the production per month increased from 14,514 units to 15,647 units, representing a gain of 1,133 units. On an annual basis, this translates to an additional 16,548 units produced.
Furthermore, the improvements led to a notable reduction in product damage, with defective items dropping from 459 units to 213 units per month a decrease of 266 units. Over a year, this reduction in damaged products amounts to 2,952 fewer defective items, leading to substantial cost savings.
In terms of cost-effectiveness, the reduction in damaged products, coupled with the increase in production efficiency, resulted in a total annual savings of **983,200 BDT** after accounting for the installation cost of the 1000-liter vacuum vessel. These results highlight the financial viability of the modifications, which not only improved production output but also reduced waste and associated costs.
Overall, the modifications to the vacuum system demonstrated significant operational and economic benefits, reinforcing the importance of optimizing vacuum systems for enhanced industrial performance.

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