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A systematic method for identifying energy-efficient and sustainable solutions in the Flexographic printing process

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Abstract

The growing demand for printing on packaging products from end-users increases energy demand, raw materials consumption, and direct emissions in the flexible packaging print and conversion industries. Innovative and energy-efficient solutions must be implemented in the flexographic printing process for long-term energy savings and reducing the environmental impact. However, the existing studies on flexographic printing processes in industries lack a detailed, in-depth analysis of the energy, material, and emissions study at a process sub-unit level. Moreover, a systematic method is needed to investigate the influence of process parameters, waste heat potential, and auxiliary units in the flexographic printing processes to explore future research possibilities. Therefore, a Life cycle-oriented in-depth approach is presented for the use phase of flexographic printing machine at a process sub-unit level. A detailed measurement test plan is presented to identify the unknown flows through the machine for in-depth Life cycle analysis. The paper concludes with possible recommendations for energy savings and sustainability solutions for flexographic processes in the future.

***Keywords**: Energy efficiency, sustainability, flexographic printing, life cycle analysis, waste heat recovery.*

1. Introduction

The global energy demand is increasing due to the increasing population and rapid industrialisation. The manufacturing sector of industries not only consumes energy and resources but also generates significant levels of emissions and waste into the atmosphere. Industries account for 37% of global energy use and are directly responsible for a quarter of the global CO2 emissions, which lead to serious environmental issues such as global warming and climate change [1]. To mitigate these impacts, industries have started implementing energy efficiency measures by adopting sustainable and innovative solutions in manufacturing processes. Government policies and measures that aim to improve energy efficiency in industries also help reduce emissions and environmental impact to a great extent. Energy optimisation in the industrial sector not only improves sustainability performance but also reduces manufacturing costs.

Flexographic printing is widely used for producing high-quality prints in the packaging and labelling industry due to its faster production speed, extremely versatile print process, and in-line converting flexibility. The growth of the flexographic printing market has been driven by the rising demand for high-quality printed packaging products, especially in the food, beverages, pharmaceuticals, and cosmetics sectors. According to recent reports, the market size was valued at approximately USD 8.5 billion in 2022 and is expected to grow at a compound annual growth rate (CAGR) of over 14% from 2023 to 2029 [2]. However, this growth creates several challenges, particularly concerning the environmental impact of the flexographic printing process due to higher energy demand, resource consumption, and direct emissions. To address this issue, the Printing and Packaging Industries have also started adopting the concepts of sustainability and energy efficiency principles in flexographic printing. The main driving forces behind implementing energy-efficient, sustainable, and innovative solutions in industries include stringent government policies, environmental concerns, and the long-term economic benefits achievable in the manufacturing of flexographic printed products.

1.1 Flexographic printing technology

Flexographic printing technology uses a flexible printing plate, usually a polymer or rubber, mounted on a cylinder to transfer ink to a substrate (web). A wide variety of substrates can be used in flexographic printing, such as paper, plastic, and aluminium. The plate cylinder holds the ink graphics plate (flexo plate) to be printed on the substrate. At first, the ink is transported from the ink tray to the anilox roller, which is then transferred to the graphics of the flexible plate. The doctor blade removes the excess ink from the anilox roller before it transfers ink to the flexible plate. This ensures the precise amount of ink transfer and improves the print quality. The substrate passes between the plate cylinder and the impression cylinder to transfer the print, and sufficient pressure for printing the web is provided by the impression cylinder (**Fig. 1.**)

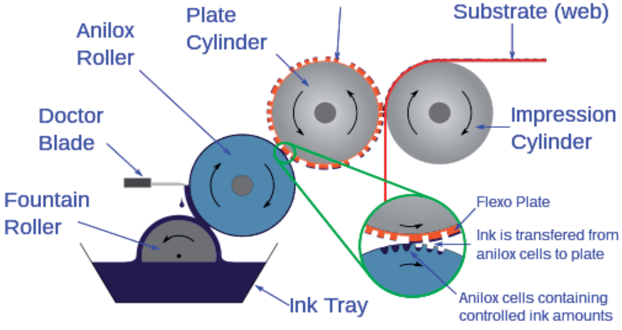


Fig. 1. Flexographic printing technology [3]

1.2 Processes involved in flexographic printing.

The main processes involved in manufacturing a flexographic printed substrate are shown in **Fig.2**. At first, the loaded substrate on the machine is unwound and then fed into the main printing unit. Inks of distinct colours needed for printing are pumped into the main printing unit. Once the ink is transferred from the plate roller to the substrate by flexographic printing, wet ink on the substrate needs to be converted from liquid to solid phase. The curing of inks is done by the drying process, which generally consumes a lot of energy and produces significant emissions into the atmosphere. Depending on the final product requirements and ink type, several types of drying technologies can be used. The hot printed substrate coming out from the drying section undergoes a cooling process; usually, chilled rollers are used to reduce the substrate temperature by absorbing the excess heat present in it. Finally, the final product of the flexographic printed substrate is re-winded and ready for the customers. The operator checks the quality of the printed substrate, and if needed, the process parameters are adjusted for the required print quality. Depending on the requirements of users, post-printing processes such as coating and laminating can be done on the final product, if needed.

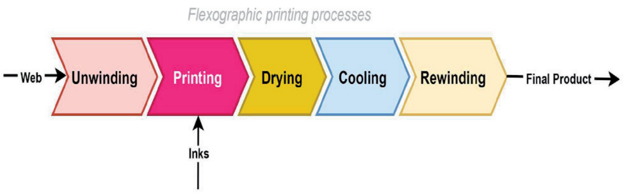


Fig.2. Main Process in Flexographic Printing

1.3 Drying process

The drying process in flexographic printing is the main source of direct emissions with significant energy consumption. The product quality of the printed substrate depends not only on the visual aspect but also on the drying quality. The presence of residual solvents in the printed substrate must be strictly avoided especially when printing food packaging and pharmaceutical products. The drying quality in the flexographic process depends on many factors, such as the ink type, ink viscosity, substrate material, production speed, and the kind of drying mechanism used. The primary focus will be optimising the drying process to ensure energy efficiency and sustainability in flexographic printing. **Fig.3** shows the common types of drying processes used in flexographic printing.

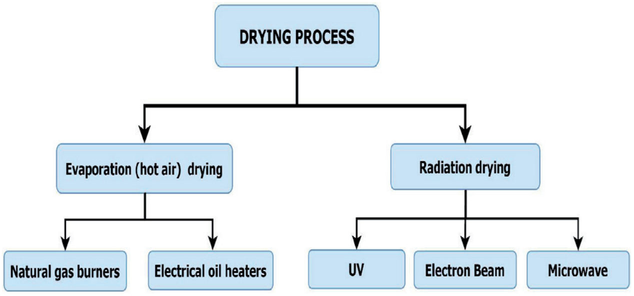


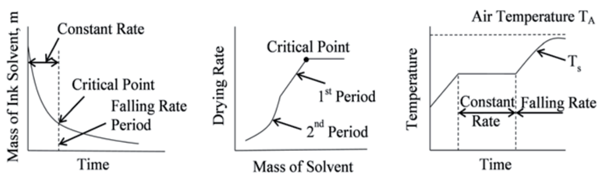
Fig. 3. Main types of Drying in Flexographic printing

Evaporation drying

Evaporation drying is the most commonly used drying method in the flexographic printing process for water- or solvent-based inks, but it consumes a significant amount of thermal and electrical energy. Using ventilation fans, hot air is blown into the printed substrate over both sides with nozzles in the drying tunnel. The solvents or water present in the ink evaporates quickly, and the remaining ink components create a dry film on the printed substrate. Natural gas burners and electrical oil heaters are generally used to heat the air to the required temperature needed for the drying process. The temperature and speed of hot air are the main process parameters that affect the drying rate in hot air drying. The higher the temperature and speed of air, the higher the drying rate, but it also increases thermal and electrical energy consumption [4]. Therefore, an optimum value of hot air temperature and fan speed must be set for proper drying quality as well as for energy savings. The choice of a suitable nozzle is also a key factor for optimising the drying process.

The experimental research conducted by Hardisty used the infra-red technique to identify the drying curves of inks. [5]. The drying curves consist of a constant rate period and a falling rate period separated by a critical point (**Fig. 4.**) [6]. Around 80% of the solvents in the printed web get evaporated in the early stages of drying at a constant rate. In the final stages of drying, more time is required to remove even smaller quantities of solvents from the web, and the trend of falling rate period is experienced. These insights show that during the falling rate period, air temperature and speed have less influence on the drying rate and thus provide a future research scope for energy savings in the drying process.

A study conducted by Burak et al. [7] investigated the heat and mass transfer coefficients in the evaporative drying of ink films with impinging air jets. The comparison of the theoretical results for the falling rate and constant rate period obtained in the study with other experimental and theoretical data showed a satisfactory result, especially for drying time.



a)Drying Curve b)Rate of Drying Curve c)Ink Temperature

Fig. 4. Drying curve characteristics of inks [6,7]

The solvent-based inks evaporate at lower temperatures and require less energy for ink curing than water-based inks. Water-based inks generally limit printing production speed due to their lower drying rate. Higher air temperature and flow rate are needed for the proper drying of water-based inks. Special attention must be paid while printing with water-based inks because the substrate could also lose material properties due to overheating. Due to higher humidity content in the exhaust air leaving the drying chamber, direct recirculation of the exhaust air into the drying process is limited in the case of water-based inks.

On the other hand, a part of the exhaust air is always recirculated into the drying process in the case of solvent-based inks, and the remaining inlet air is always compensated with fresh air or ventilation air. This reduces the thermal energy demand of the drying process when printing with solvent-based inks. However, using solvent-based inks instead of water-based inks is not the best solution when considering the environmental impact.

The solvent-based inks contain Volatile organic compounds (VOC) such as ethanol, ethyl acetate, and isopropyl alcohol, which are the main sources of direct emissions in the flexographic printing process. The drying process of solvent-based ink contributes around 75% of the total VOC emissions in the printing industry. Due to their highly volatile nature, some of the solvents evaporate directly from the ink tank at room temperature. The exhaust air leaving the drying section containing VOC must undergo a treatment process before expelling air into the atmosphere [8].

A material and energy flow study conducted by Irina et al. [9] in a flexible printing and packaging plant adopted the Integrated pollution prevention and control (IPPC) methods such as replacing solvent-based with water-based inks, upgrading the ventilation system, and improving the lighting system. The results showed a decrease in VOC emissions of 92.5% and a reduction in energy consumption by 21.5% in the industry.

Radiation drying

Radiation drying is used in flexographic printing industries to accelerate production speed by reducing the drying time needed to cure the inks. Moreover, the environmental impact of radiation drying is less when compared to the hot-air drying process. The main types of radiation drying are UV, LED- UV, Electron beam and microwave drying.

The UV dryers consist of a beam source and reflector. The UV light transforms the liquid ink present in the printed substrate into a solid form through a photo-polymerization process. For UV drying, the inks must be of a special type that reacts to UV radiation. The ink curing can be completed within a fraction of a second with UV drying, thereby helping achieve high production speed. Since there is no evaporation of solvents in UV curing inks, it is a better solution for environmentally friendly drying without VOC emissions to the atmosphere. In addition, the print quality and print stability of UV drying are high. However, high energy consumption, ozone emissions, and huge capital investment are the drawbacks of conventional UV drying. LED-UV drying is an innovative system that uses diodes to convert electrical energy to light, and the UV radiation then converts the liquid ink film to solid by polymerisation. Compared to conventional UV systems, LED-UV consumes less energy and has a lower rate of emissions, which helps achieve sustainable goals [10].

Electron beam drying is also an alternative to the traditional drying process. In electron beam drying, the high-energy electrons are accelerated towards the printed substrate to cure the inks. The chances of overheating the substrate are comparatively low, thereby saving energy for the cooling process.

A study conducted on the printing and publishing industries by Margolis et al. [11] suggests that by replacing natural gas hot air drying with UV and Electron beam drying, energy consumption can be reduced by 50%. Higher capital costs and the need for special types of inks in UV and Electron beam drying are the main factors that limit their application in flexographic industries.

Microwave drying is a non-ionizing radiation drying process where the molecule in the heated medium becomes polarised with positive and negative charges by a microwave electromagnetic field. Several tests were conducted by Marios et al. [12] to identify the drying rate and energy consumption of different types of radiation drying and evaporative drying on flexographic water-based inks. Results showed that microwave drying consumes less energy and drying time compared to other drying processes, such as infrared and hot-air drying.

Implementing energy-efficient and low-emission drying technologies in the flexographic printing process is essential. It ensures both economic and environmental sustainability. Future research should focus on optimising drying parameters and exploring sustainable ink formulations to further enhance the efficiency and sustainability of flexographic printing processes.

1.4 Lean techniques in flexographic printing

Manufacturing processes use lean methodologies to improve energy efficiency and productivity. These methods also help eliminate waste and reduce the overall cost of production. The value stream mapping, 5 why analysis, SMED, and Kaizen methods can be combined as a lean approach to enhance energy and process efficiency. The first step in the lean method is the proper identification of problematic areas where improvements are needed. After that, the root cause of this problem can be investigated with a 5-why analysis. Later, improvements can be developed to achieve better overall equipment effectiveness using the Kaizen approach. Finally, the proposed idea is implemented in the existing process for better efficiency.

A study conducted by Zahoor et al. [13] improved the overall equipment efficiency of a flexographic machine by reducing the breakdown time with the help of total productive maintenance measures. 5-whys analysis techniques were implemented to analyse the root cause of the breakdown time and thereby improved the overall efficiency from 34% to 40.2%. Similar to the work of [13], the Overall Equipment Effectiveness of a flexographic printing machine is improved by 24% with the implementation of visual stream mapping, 5- why root cause analysis and kaizen lean approach [14].

In the manufacturing of flexographic printed substrates, the idle time needed for job setting, job changeover, job waiting, and optimisation of process parameters is normally very high. Even though the machine does not produce any printed material during idle time, it consumes a considerable amount of energy. This is because the pumps, motors, and other mechanical and electrical devices are still working and consume energy during idle time. A study was conducted by Ivander et al. [15] to increase production efficiency by reducing the setup time in a flexographic machine with the Single Minute Exchange of Dies (SMED) and the Internet of Things method. The result shows that the implementation of the SMED method reduced the set-up time by 9.7 minutes. The study also proposes implementing the Internet of Things in the machine to reduce setup time in the future. Another study conducted by Zaher et al. [16] on flexographic printing machines to improve energy efficiency by applying Lean principles such as 5 why analysis and kaizen approach during production job. The study found that by reducing the idle time of Miraflex and F&K flexographic machines by 30%, energy savings of 34.198% and 38.635% can be achieved respectively per meter.

1.5 Artificial intelligence and machine learning

Artificial intelligence and machine learning techniques are used in industries that optimise energy consumption. A regression model using Python was developed by Zaher et al. [16] to predict the energy consumption of flexographic machines for optimising the scheduling of jobs. The input parameters used in the model were machine speed, substrate density, total run time of the machine, working time, idle time, and produced meter. A limitation of the work is that the main process parameters that influence the energy demand, such as air speed and temperature for the drying process, were not considered in the energy prediction model. Menezes et al. [17] developed a linear programming mathematical model for printing industries to optimise energy consumption. The main goals of the work were to reduce the electrical energy consumption of the machine and to minimise the machine's production time by implementing optimisation techniques to assist with production planning, scheduling, and control in the printing industry.

1.6 Limitations of the existing works

The main limitation of the existing research works is the lack of a well-defined systematic method to identify the possible scope of energy savings opportunities and sustainable solutions in flexographic printing machines at a sub-unit process level. **Fig.5.** shows the less explored areas in flexographic printing that need to be investigated in detail. Even though flexographic printing machine uses many energy-consuming devices such as motor drives, dryer units, pumps, and ventilation fans and releases direct emissions, heat, and wastes into the atmosphere, the lack of a detailed energy breakdown analysis on the flexographic printing machine and their corresponding processes is still a research problem to solve. Moreover, less research was carried out on the auxiliary units that support the manufacturing of the flexographic printing process.

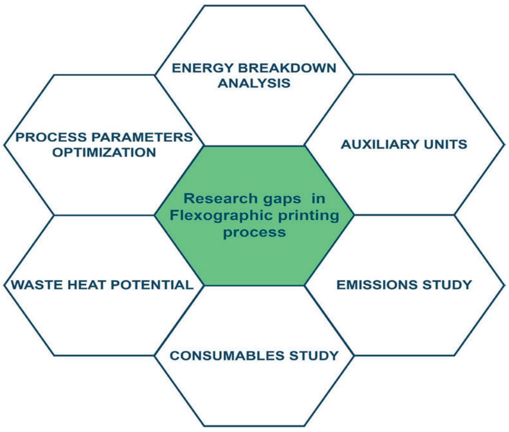


Fig. 5. Research gaps in the flexographic printing process.

Compressed air is generally used for a variety of purposes, and industrial chillers are used in flexographic printing. However, no investigations were carried out to quantify the energy demand of chiller and compressed air units to explore the possible scope of energy savings. Since flexographic printing can be applied to a wide range of applications and different types of jobs, optimising the main process parameters for different job types for energy savings is still an unanswered research question.

The know-how energy efficiency solutions in other industrial processes can also be integrated into flexographic printing. Still, there is a knowledge gap in identifying the right processes or areas to implement innovative solutions for energy savings. Therefore, an in-depth analysis of the flexographic printing machine at a single process sub-unit level, which includes the auxiliary support units, is needed to identify the main energy and resource-consuming hot spots and their corresponding emissions for implementing innovative and sustainable solutions in the relevant sections.

2. Materials and Methods

To address the research gap, a flexographic printing machine, Onyx Race, which has a maximum printing speed of 600 m/min and uses natural gas burners for hot air drying, is analysed in the case study. The machine has a Central impression printing unit consisting of eight colour stations. It is capable of printing on a wide variety of substrates, such as plastics, paper, and aluminium, with the flexibility to use water-based and solvent-based inks.

A detailed data collection was conducted to gather information on relevant sub-units, including auxiliary units in the machine. Semi-structured interviews were conducted with product innovation engineers, technicians, and machine operators in the manufacturing industry to identify the various processes involved in the flexographic machine at different phases of production.

The web passes from the unwinder undergoes a corona treatment (infeed unit) before passing to the printing unit to improve the surface energy of the substrate if the material to be printed is plastic. The corona treatment unit releases ozone gas, which is removed from the machine with an exhaust fan. Apart from the main drying tunnel, the machine has separate drying boxes for each colour unit in the flexographic printing group section, except for the last colour unit. Two separate gas burners with ventilation fan units are used for hot air drying in the printing group section and drying tunnel. An air-cooled chiller is used in the machine with an on-off control for the compressor. In addition to cooling the web passes through the outfeed roller, chilled water is also used to cool the motors. The Central impression drum is also maintained at a particular set point temperature with the thermoregulation unit in the chillers. When the printing job needs to be changed, the washing and cleaning of the anilox, cliché, and entire printing units are done with either solvents or water, depending on the type of ink used. The washing and cleaning process is the main source of liquid emissions in flexographic printing. The compressed air is used in the machine to pump inks and solvents, anilox and cliché change, nip pump, etc.

A life cycle-oriented in-depth approach is proposed for the use phase (operating stage) of the flexographic printing machine, which includes an energy, consumables, and emissions study at a sub-unit process level. [18]. The study excludes the rest of the life cycle phases of the machine, such as material processing, production, and disposal. Also, the post-treatment process involved in removing the VOC solvent content in exhaust air, leaving the drying sections is excluded from the scope of this study. The main goal of the Life cycle-oriented analysis in a flexographic printing machine is to identify the environmental impact and emissions released from each process as well as the energy and resource-consuming sub-units in the manufacturing of flexographic printed substrates.

The input consumables and the corresponding emissions from the machine during each process were identified. The system boundaries of the machine were defined with the input and output flows [19]. An understanding of the main process parameters that influence the energy consumption of the machine was identified with a preliminary test campaign. To identify the unknown flows in each process of the LCA, a detailed measurement test plan is proposed for the flexographic machine through a careful examination of the machine and its sub-units.

In the main test campaign, different varieties of substrate materials can be printed at various production speeds with different print widths, ink types, and ink coverage to explore the variations in energy demand and corresponding emissions in each case. The results obtained from the measurements campaign can be analysed more deeply to implement innovative solutions that minimise the energy demand and environmental impact of flexographic printing. A flow diagram illustrating the systematic approach used in this study is shown in Fig. 6.

3. Results and Discussion

The system boundaries have been defined, and the input and output flows of the main relevant processes and subunits in the flexographic machine are shown in **Fig.7**. The functional unit selected in the analysis is the production of printed substrate per tonne. The main process parameters that influence the power demand are hot-air temperature, ventilation fan speed, machine production speed, and material tension.

3.1 Energy Breakdown Analysis

A detailed measurement test plan is presented in this section to identify the electrical and thermal energy demand, both as a whole and at a sub-unit level, for different production phases of the machine. Since energy demand is calculated by multiplying power consumption with operational time, a power and time study is being conducted to perform the energy analysis.

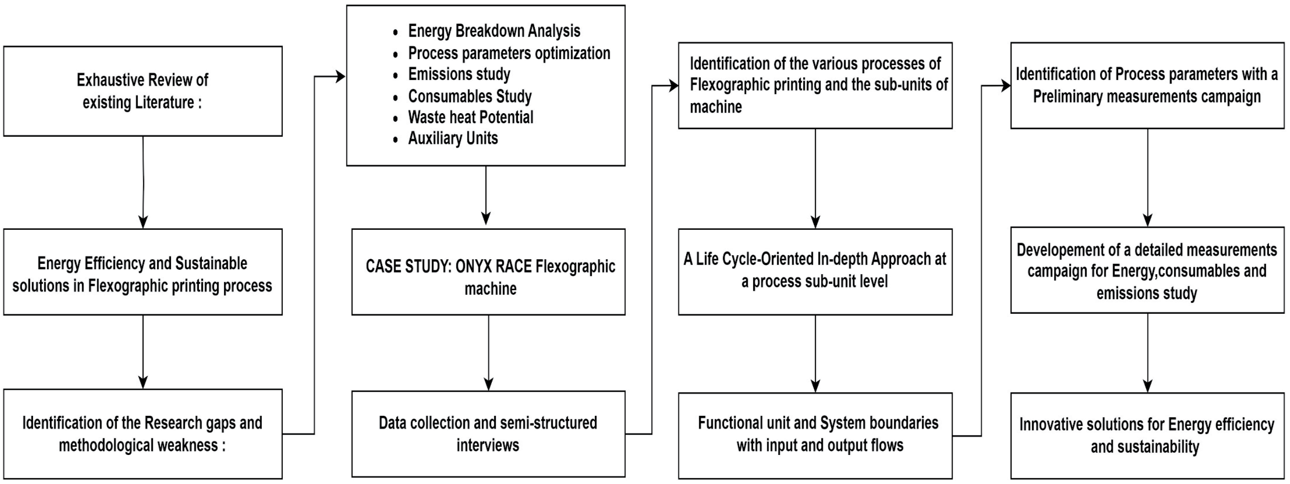


Fig.6. Flow diagram of a systematic approach used to identify the energy savings and sustainable solutions in the flexographic process

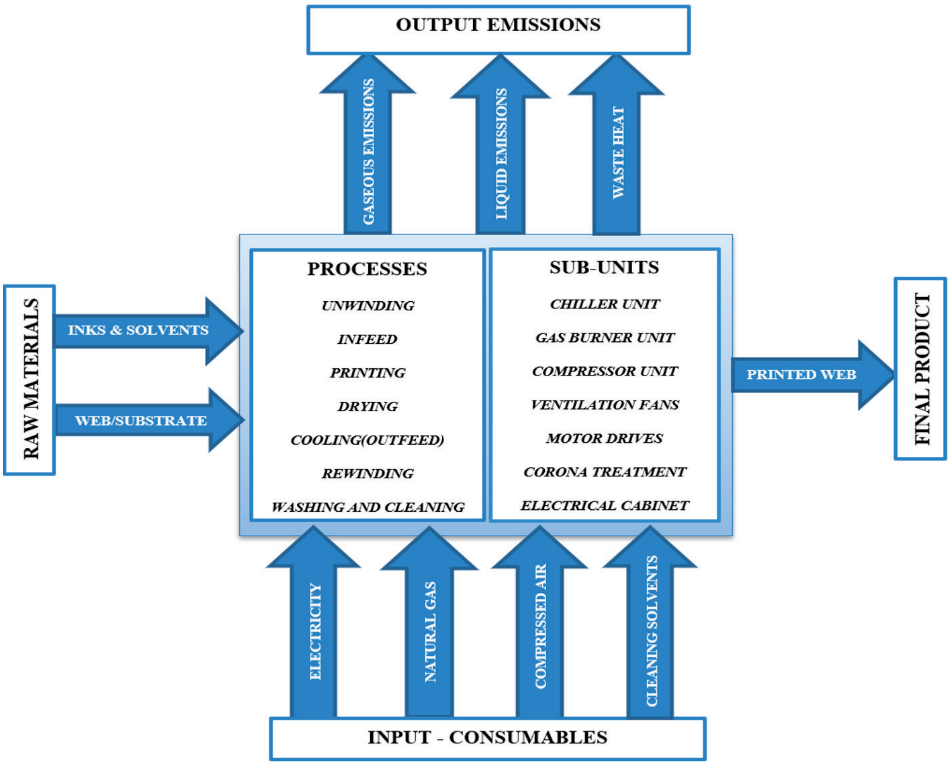


Fig. 7. LCA: System boundaries for the flexographic printing machine with input and output flows

Power and time study

The total electrical power consumption of the Onyx Race flexographic machine, along with the power demand of relevant sub-units, such as chiller, motor drives, and ventilation fans, was measured simultaneously using power analysers during production. The electrical power consumption of the ventilation fan motors used in the inlet and outlet sections of drying units was measured separately. The thermal power demand of the two gas burners in the machine for the drying process is also being monitored and analysed in detail.

The measurements of the chiller unit include not only the total electrical power demand of the chiller but also the compressor power, heater power, pump power, and heat load (measurements by flow rate and temperature sensors) removed by cooling processes and thermoregulation unit.

The influence of the main process parameters on the total power demand of the machine, such as drying air temperature, ventilation fans speed, and material tension, is being investigated for several types of jobs (different ink coverage, ink type, substrate material, print width) at various production speeds.

The different production phases of the machine, such as the start-up mode, job setting mode, productive mode, job-changeover mode, and shutdown mode, and their corresponding time, were investigated in the time study. Thus, the energy demand needed for each production phase of the flexographic machine as a total and at the subunit level can be identified with the power and time study. Once the complete measurements are done, special focus can be given to the main consuming processes and sub-units of the machine for the possible scope of energy savings with innovative solutions.

3.2 Consumables study.

In the consumables study, the consumption of raw materials used in the flexographic printing process such as compressed air, natural gas, substrate material, inks, and solvents are being measured during production. The natural gas consumed by the gas burners, which heat the inlet air to the required drying temperature, is being measured using gas flow meters compensated to standard temperature and pressure.

The compressed air consumption in the machine for various purposes, such as pumping of inks and solvents, anilox and sleeve change, etc., is being measured (flow rate and pressure) at a sub-unit level with flow meters. The consumption of solvents or water used for the washing and cleaning process in the machine is also being monitored with flowmeters.

3.3 Emission study

The waste heat, liquid and gaseous emissions rejected from the machine during the production phases of the printed substrate are being mainly investigated as the main parameters in the emissions study. Since the exhaust air leaving the drying section of the machine releases waste heat and direct emissions, such as VOC and CO2, to the atmosphere, special attention must be given to this section.

The main unknowns in the energy and mass flow balance equations in the relevant sections of the drying unit are being determined by experimental measurements.

The waste heat lost from the drying units through exhaust air can be calculated by the equation:

$$Q = V \times \rho \times C \times (T_2 - T_1) \tag{1}$$

Where Q is the heat energy losses, V is the volumetric flow rate, ρ is the density of air, C is the specific heat capacity of air, T_2 is the temperature of exhaust air, and T_1 is the temperature of inlet fresh air.

The waste heat rejected from the chiller unit ($Q_{chiller}$) can be calculated by measuring the heat removed by cooling processes (Q_{load}) and the electrical power consumption of the compressor ($W_{compressor}$).

$$Q_{chiller} = Q_{load} + W_{compressor} \tag{2}$$

Additionally, the sensible heat transferred to the substrate material from the drying process is being monitored using infrared sensors.

Finally, the ozone gases removed from the corona treatment unit can also be quantified in the study.

3.4 *Future scope of energy savings in Flexographic printing*

Based on the observations from a preliminary analysis of the machine, the main areas for energy efficiency improvements identified are waste heat rejected from the machine, process parameters optimisation, implementation of AI and machine learning techniques, energy efficiency measures for chiller, compressed air, ventilation fans, and motor drives unit. Innovative solutions can be implemented for each of the sections for long-term energy savings and sustainability. Among the different areas for improvisations, the thermal energy demand for the drying process and waste heat lost from the subunits of the machine are expected to be the main hot spots where efficient solutions can be implemented with a top priority.

The waste heat lost from the drying process through exhaust air could be recovered by heat recovery techniques to preheat the inlet air for energy savings [20]. It reduces the thermal energy demand and natural gas consumption of the drying process with a considerable reduction in direct emissions. Moreover, the sensible heat lost from the drying section to the printed material due to overheating (dry-out point) can be monitored with infrared sensors, thereby optimising the process parameters in the drying unit for further energy savings. At higher production speed, the time needed for drying (ink curing) the printed substrate is a challenge in flexographic printing and drying quality must be guaranteed with the corresponding production speed to ensure product quality.

With in-line measurement devices, the drying quality of the substrate at higher production speeds can be determined quickly, and the process optimisation could be done by quick feedback and a faster response system that reduces downtime.

The main process parameters could also be optimised for energy savings based on different types of job conditions, such as substrate material, ink coverage, print width, and production speed, by implementing AI and machine learning techniques. The possible scope of recovering the waste heat lost from the condenser of an air-cooled chiller to use it for other processes could be investigated in the study. The scope of integrating the free cooling option for the chiller unit during colder months of the year could also be a possibility for energy savings. The on-off control of the compressor increases energy demand by causing frequent cycling between on and off states, which leads to inefficient energy use. During startup, the compressor requires more energy to reach its operating capacity, and the constant cycling prevents the system from maintaining a steady, efficient operation, resulting in higher overall energy consumption. Replacing the on-off controlled compressor of the chiller with a Variable Speed Drive-controlled compressor can be useful for energy savings at part-load conditions [21].

Compressed air systems in industries are usually not an efficient way of energy usage. From the total energy demand of the compressed air unit, only 15-25% could be utilised as useful work, and the rest is lost as waste heat [22]. Replacing the compressed air sub-units with energy-efficient alternatives such as electrical devices could be a solution for energy savings in flexographic machines. If some of the compressed air sub-units cannot be replaced due to easiness, flexibility, and safety in operation, the waste heat rejected from the compressed air unit could also be investigated to explore the possible scope of recovery for other processes. Energy savings can be made possible by finding the lowest operating air pressure for the compressed air sub-units without losing the end-service quality. A proper monitoring system can be installed to eliminate the leaks, and de-centralization of the compressed air unit from the industry to the machine level could also save energy.

The electric motors used in industrial machines are generally oversized for safety reasons and operate at lower load conditions. As motor efficiency varies with load, appropriate motors can be selected for the machine at their most efficient load condition for energy savings. Replacing the impeller of the ventilation fans with efficient ones or redesigning the ducts in the machine could also be investigated for further energy savings [23]. Innovative nozzles could be used in the drying unit for efficient drying and energy savings. Finally, using environmentally friendly inks, recycling the waste solvents and substrate for reuse options, and upgrading the conventional hot air-drying systems with innovative drying technologies such as

LED-UV and Electron beam drying could not only save energy but also largely reduce the environmental impact to a greater extent.

4. Conclusion

The study identified the existing research gaps in the flexographic printing process, followed by a literature review and aimed to provide a proper methodology for identifying the energy saving opportunities and sustainability solutions in flexographic printing. A case study on a flexographic printing machine was considered to explore future research possibilities. A life cycle-oriented in-depth analysis is presented for the use phase (production phase) of the machine, which includes the energy, emissions, and consumables study at a sub-unit process level of the machine by identifying all the input and output flows. The main parameters that influence the energy consumption of the machine were identified to explore the scope of optimisation of process parameters for energy savings.

A detailed measurement test plan is proposed at a sub-unit level to identify the unknown flows through the machine in the Life cycle analysis. The waste heat rejected from various processes in the flexographic machine is the main hot spot where improvements can be made for energy savings. Heat recovery techniques can be implemented for the drying unit and chiller to recover energy lost to the atmosphere and utilise it efficiently. Heat recovery techniques not only reduce the natural gas consumption (thermal demand) needed to heat the air during the drying process but also minimise the corresponding direct emissions from it. Process parameters can be optimised with in-line measurement sensors to improve the quality of the printed substrate and save energy. Implementing AI and machine learning techniques in flexographic printing could also save energy by optimising process parameters for different types of job conditions. Installing variable speed drive-controlled compressors for the chiller, replacing the oversized motors and inefficient pumps with efficient ones, changing impeller fan configurations, and upgrading the nozzles of the drying unit could also save energy, improve machine efficiency, and reduce carbon footprint.

The feasibility of the proposed ideas can be validated through the results of the measurement test campaign. After that, feasible solutions can be developed and implemented in the relevant sections of the flexographic printing machine for long-term energy savings and production efficiency. Thus, the packaging print and conversion industries can reduce their carbon footprint and achieve sustainability goals in the manufacturing of flexographic printed substrates, along with economic benefits.

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