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New energy-saving technology for industrial stretch foil production

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ABSTRACT

The article presents a project of an innovative technological line for producing stretch foil. The technological innovation consists of the fact that the foil is produced from a material composed of primary raw material and up to 80% recyclate. The new product cannot be used differently from the traditional one, as it is produced 100% from primary raw material. Additionally, recyclate is produced from waste originating mainly from agriculture. The production line includes systems allowing the use of materials contaminated with organic particles without needing a thorough cleaning. Another innovation is the use of low-temperature waste heat in the production process. It comes from the cooling of the first calender roll. Until now, this heat has dissipated in the atmosphere. Low-temperature waste heat was transformed into high-temperature heat and used in the technological process to prepare the raw material. A heat recovery line was designed based on two cascaded, hydraulically coupled compressor heat pumps to transform low-temperature waste heat into high-temperature technological heat. The designed system can be expanded and adapted to current production needs. The developed technological line solves several problems. It helps to manage difficult-to-manage post-production waste from agriculture and other sectors of the economy. It reduces energy consumption and raw materials from non-renewable sources, significantly reducing CO_2 and other greenhouse gas emissions. This is in line with the assumptions of the European Green Deal, which implements a circular economy and is based on renewable energy sources. Currently, the technology is being developed and implemented.

Keywords: stretch foil, recyclate, technological process, heat pump, greenhouse gas reduction, carbon footprint.

INTRODUCTION

The desire to reduce the impact of synthetic polymer materials on the environment and climate, especially as packaging and disposable products, has led to the need for changes in the processes of their production, distribution, use, recovery, and disposal [1, 2]. According to the sustainable development goals of the Paris Agreement [3, 4], it is necessary to bring environmentally friendly materials to market, improve recycling, and reduce the energy intensity of technological processes. For this reason, some polymer products have already been replaced or will soon be replaced by natural, biodegradable, or compostable materials with a smaller carbon footprint [5–7]. Some products have been abandoned or replaced with reusable products, e.g., returnable bottles, and others have been changed to make recycling easier [8]. The recycling process itself also requires changes. So far, most polymer materials have been subject to energy recycling. It involves energy recovery through direct combustion or indirectly through producing solid, liquid, and gaseous fuels [9]. An example is gasoline production from polyethylene terephthalate (PET) [10]. Only a few polymers were subject to material recycling, which involves reusing waste as raw materials to produce new materials [11]. Due to the need to reduce greenhouse gas emissions, primarily carbon dioxide, further energy recycling will be difficult and eventually impossible. Of course, reducing polymer production will reduce the problem of recycling and disposal, but it will not eliminate it. New polymer products will continue to be produced, and there is also a considerable amount of products produced so far that are stored in landfills and that need to be sensibly managed. Moreover, despite the rapid development of technology for producing more environmentally friendly materials, new solutions will only come into everyday use after some time. Therefore, in the transition period, existing materials and products will continue to be used, in the case of which their negative impact on the environment must be limited. Polymer materials, contrary to popular belief, are not easy to recycle. Scientists are developing new technologies to improve the efficiency of recycling and upcycling, such as thermomechanical processing, chemical recycling (glycolysis and pyrolysis), and biological depolymerization using catalysts, enzymes, and microorganisms [12–15]. Despite these efforts, challenges in recycling technologies still exist. In order to reduce the carbon footprint, it is also necessary to reduce the primary energy carriers consumed during the polymer production process as well as during the recycling process. Both of these processes mainly use electricity. In Poland, commercial power generation is still based on large generating units producing electricity from coal and lignite [16, 17]. For this reason, CO_2 emission penalties are imposed by the EU [18]. The reduction of CO_2 emissions resulting from the combustion of conventional fuels used in the production of electricity, contrary to appearances, is not at all so simple and obvious. The increase in the share of renewable energy sources generating electricity installed mainly in households in the form of PV installations and wind turbines used in commercial solutions does not guarantee an effective reduction in CO_2 emissions. This is due to the stochastic nature of solar [19–21] and wind [22–24] energy and, as a result, the matching of commercial power generation capacity to current electricity supply and demand as a function of the instantaneous variability of available solar and wind resources. Matching electricity production to current demand is very difficult and yet necessary to ensure the required power quality in the grid [25]. The solution to this problem is the implementation of distributed energy, which requires the restructuring of the public electricity grid or the introduction of electricity storage, such as in the form of biogas plants, and the creation of an intelligent power grid [26]. At the moment, the implementation of both solutions in Poland, among other things, due to cost-intensity and legal legislation, is not possible in the near future. Therefore, at the moment, in order to reduce the carbon footprint in the production of plastic products, the best solution is to implement a closed loop economy. Scientists from the Warsaw University of Life Sciences and TW Plast have taken up this challenge by developing a technology for producing stretch foils by adding up to 80% of the volume of recycled material.

TECHNOLOGICAL PROCESS OF STRETCH FOIL PRODUCTION

The most commonly used technological process of producing stretch foil using the cast method consists of the following processing operations [27–29] (Fig. 1):

- extrusion (Fig. 2) – during which the raw material granulate, which is most often low-density polyethylene (LDPE), is heated in a single- or multi-screw extruder to a liquid state (above the pour point) and homogenized and degassed,
- casting (Fig. 3) – during which the molten material is evenly poured onto a rapidly rotating, intensively cooled metal cylinder, where it solidifies but remains in a viscous-liquid state (above the softening temperature and below the glass transition temperature),
- calendering – in which the material, already in the form of a thin film, changes from a viscous-liquid state to a viscous-elastic state; at this stage, the film is rewound several times through successive calender rollers of different diameters and different rotational speeds,

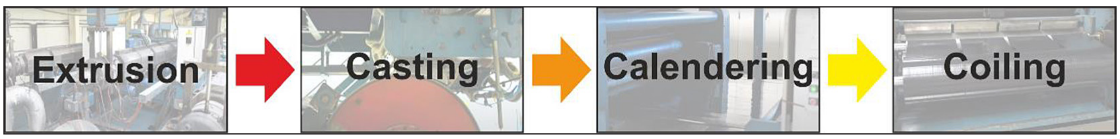

Figure 1. Typical technological process of producing stretch foil using the cast method

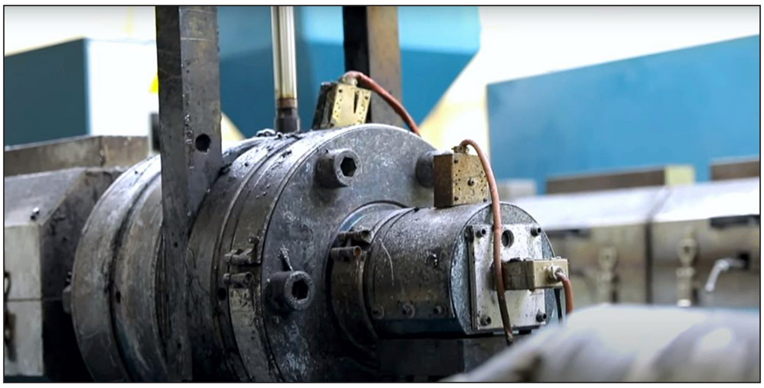

Figure 2. Extrusion die head

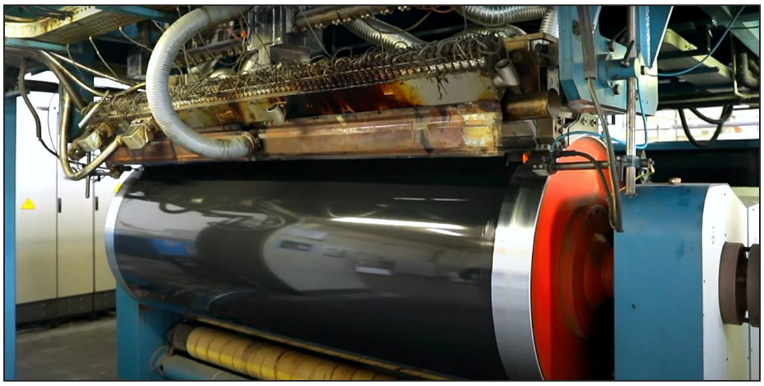

Figure 3. Casting the foil on the first calender roll

as a result of which it is stretched, obtains the intended thickness and strength parameters,
- coiling (Fig. 4) – during which the web of finished foil is initially or finally wound onto transport or commercial rolls.

In the standard stretch foil production process using the cast method, fresh (i.e., from primary polymerization) plastic granulate is used, or the addition of recycled plastic is small. It does not exceed 20% of the volume [30]. Such a material is characterized by a statistically stable molar mass of the polymer molecules it comprises. This ensures the production process's stability and the finished product's repeatability.

Polymers undergo partial or complete degradation during primary processing, use, and as a result of aging. This mainly consists of shortening the chains of macromolecules [31]. Since these processes are difficult to control and have many variables, the waste materials derived from

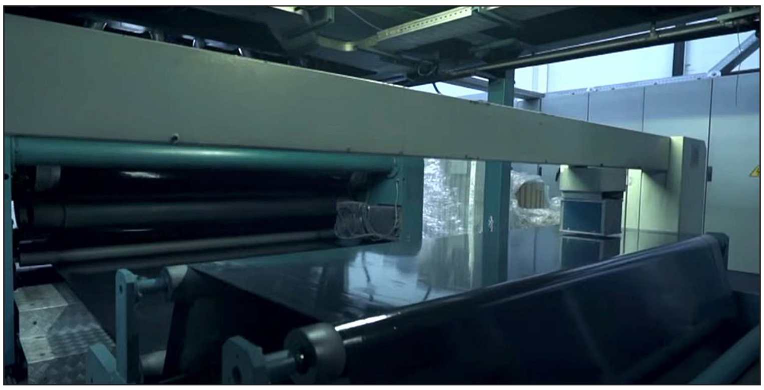

Figure 4. The process of forming, cooling and winding the film

them may differ significantly. Reprocessing such materials into finished products carries a high risk of lack of repeatability. Therefore, in an attempt to use waste materials as raw material for the production of new stretch foil, the issue of process stability, which is an essential factor in obtaining repeatability of the properties of the final product, is crucial. In addition, the foil already used once may be contaminated with inorganic and/or organic substances of natural and artificial origin, particularly other polymers. Not all these contaminants can be removed while preparing the waste to produce regranulate. This will affect the quality of the regranulate and, as a result, the stability of the production process and the repeatability of the properties of the final product. Additionally, pollutant substances may have a decomposition temperature lower than the temperature of the foil production process and produce, among other things, volatile substances with an intense and/or unpleasant odor, which may also pose a threat to the health and life of foil production workers, users or may generally be harmful to the natural environment.

INNOVATIVE STRETCH FOIL PRODUCTION TECHNOLOGY

Recycling plastic waste requires its selection, which can be difficult and complex, primarily since many products consist of several components and types of plastics [32]. Very often, the material produced from recyclates has worse properties than the newly produced one. Therefore, it is necessary to mix recyclates with raw materials. Until recently, the share of material recovered from waste did not exceed 20% [30]. Therefore, for the repeatability of production effects, it is crucial to ensure the supply of raw materials with parameters that do not differ significantly. This is extremely difficult or even impossible in the case of production from waste raw materials that have already undergone production and use processes. Therefore, in the discussed project, the focus was on limiting the number of raw material sources. It was assumed that the number of suppliers of used LDPE would be limited. Despite such a limitation, significant differences in the properties of the raw material are possible. Therefore, it is always recommended that strict control of deliveries be applied on the recipient's side, at least until the suppliers are trusted (certification), to ensure stable properties of the used polymer supplied as raw material. The supplier certification process should be long-term (the appropriate amount of the material provided, equal to at least the annual production demand). Until the supplier's certification is obtained, each delivery batch should be tested in accordance with the standard statistical testing procedure. A delivery register containing the test results of each raw material batch should be used for each supplier, allowing for statistical analysis of the results. The register will identify the supplier, each batch of raw waste material supplied, and its type, quantity, and delivery date. A given supplier can be considered reliable if all test results of each batch of raw material provided by it fall within the confidence interval determined by the tolerances assumed for a given variable.

Ensuring the repeatability of the properties of the produced foil is possible by modernizing the design of the production line and the course of the production process to monitor these properties continuously and, in feedback, change such production parameters that affect the product's properties. These observations and changes would have to take place in real-time. The analysis of available market solutions for cast stretch foil production lines did not provide a solution that could even potentially be adapted to continuously regulate the production process, taking into account the final properties of the product with widely variable production parameters of the raw material [27]. It can, therefore, be assumed that such a solution does not currently exist. On the other hand, adapting one of the available production lines to the control method described above is not possible without performing at least preliminary studies of the variability of the dependence of the properties of the finished stretch foil produced from a raw material with a high share of polymer recyclate on the production parameters and widely variable properties of the recyclates above. This results from the fact that there is a gap in knowledge regarding the issues described above, which the research results of this project aim to fill only in its subsequent stages. Due to the above, it was assumed that at this stage of the project, the first solution would be used, limiting the number of suppliers and narrowing the tolerance ranges of the properties of the supplied raw material. Only obtaining the test results of the finished foil at subsequent stages of the project can be a premise for using the second solution, i.e., modifying the course of the process as a function

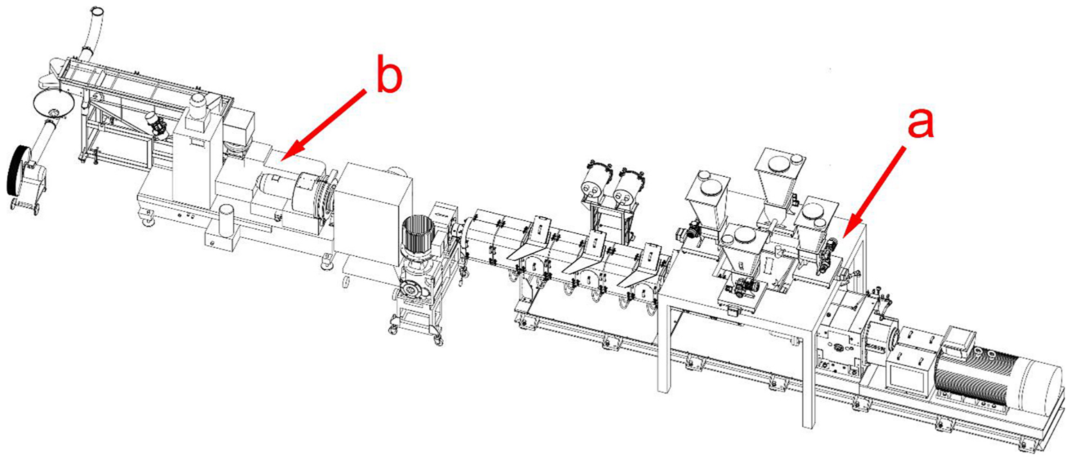

Figure 5. Drawing of the technological line for producing regranulate: (a) co-rotating twin screw extruder, (b) grinder and cooling system

of time to stabilize the properties of the produced foil. Another way to increase the probability of obtaining stretch foil with repeatable properties will be to use in the technological process the operation of mixing the raw material from all suppliers and the operation of averaging in the first stage of the production process, i.e., the stage of producing regranulate. These operations are ensured by supplementing the production line with silo mixers dosing the raw material to the regranulate extruders.

The solution to another technological problem is using a refresher (odor freshener) in the production line. Its task is to neutralize/remove any volatile substances that may be a source of unpleasant odor and may pose a threat to people and the natural environment. This device will be connected to the technological process between the operation of producing regranulate from waste raw material and the main operation of casting the foil. The most important element of the refresher is the absorbent deposits. Their chemical composition and structure are subject to the supplier's trade secret and cannot be disclosed in this report. The refresher will be delivered as a ready-made device, and it will not be possible to perform any technical and technological adaptations or modifications due to maintaining the terms of the granted warranty. Its mode of operation is not continuous but staged - batch. The residence time of a portion of the refreshed material is 180 minutes. This makes it difficult to carry out a continuous process of foil production. To ensure a constant amount of material throughout the process, a buffer tank will be installed both before and after the refresher station.

MODIFIED TECHNOLOGICAL PROCESS FOR STRETCH FOIL PRODUCTION

The foil production process consists of several stages. Waste material from various suppliers is sent to the factory. In the first stage, delivery control, it is subjected to tests of its technological parameters, mainly the mass flow rate and humidity, which are crucial to future foil production. If the delivered material has too high humidity, it is dried. A roof dryer was developed to dry the regranulate. The heat source in the dryer is a heat exchanger powered by hot water, which is the upper heat source of the heat pump. The air heated in the heat exchanger flows through the bed (regranulate layer) and dries it (also heats it). The dried regranulate moves downwards, and another regranulate is introduced in its place (from above). Because the raw material from different suppliers may have other properties, it must be averaged. For this purpose, it is sent to 4 silos equipped with mixers, where it is mixed. Here, granulate of new, not yet used material is also added.

This granulate comes directly from the manufacturer. Its amount constitutes 20% of the waste material. The mixed material, via a pneumatic transport system, goes to the tanks of two co-rotating twin-screw extruders (Fig. 5a). At this stage, it melts between 190 and 240 °C. In a semi-liquid form, it moves through the extruder channels thanks to the rotation of the screws, where it is homogenized. It is intensively cooled, solidifies, and cut into tiny granules when it escapes through the extruder nozzles (Fig. 5b). In this way, regranulate, i.e., recycling raw material, is created. Since the supplied waste material's exact chemical composition is unknown, the newly created recyclate may contain organic compounds of both natural and artificial origin, which, during the previously described processing, release volatile substances, often a source of unpleasant odor. In addition, these substances may be harmful to human health and the natural environment. Therefore, the recyclate goes to the refresher, where all volatile substances are removed. In the refrigerator, the regranulate stays for 3 hours at a temperature of 60 °C. In the device's sealed chamber, chemical reactions occur between the released volatile substances and the purification beds' chemical compounds. The types of chemical compounds that are components of the beds and the course of the physicochemical processes taking place in the refrigerator are covered by the trade secret of the supplier of this device and cannot be disclosed. It is worth mentioning, however, that after this treatment, the recyclate not only has a neutral smell but does not release harmful substances to humans and the environment.

The recycled material prepared in this way is transported using a pneumatic conveyor to the second part of the production line, where the actual stretch foil is created. At the beginning of this stage, the regranulate is filled into buffer tanks (Fig. 6a, 6b, 6c), which provide an appropriate substrate supply for production.

The recycled material from the tanks is melted and liquefied again in six extruders operating simultaneously (Fig. 6d). The process temperature is between 190 and 250 °C. This time, however, the semi-liquid material reaches the first calender roller, rotating at a constant speed (Fig. 6e). This calender roller is the most important, as it removes heat from the material, which, when cooling (Fig. 6f), becomes solid. At the same time, it forms the individual layers of the foil, giving them the appropriate thickness and width. This process takes place at a speed of 600 running meters of foil per minute. This provides an efficiency of around 7 tons per minute. After passing through the calender, the material forming the foil passes to the following rollers, which rotate synchronously with the calender. On these rollers, the subsequent layers of foil are stretched and joined, creating a seven-layer stretch foil with strictly defined strength parameters and dimensions, i.e., width and thickness. The entire process is automated (Fig. 6h). Depending on the customer's preferences, the foil is wound onto drums or rolls in the final stage.

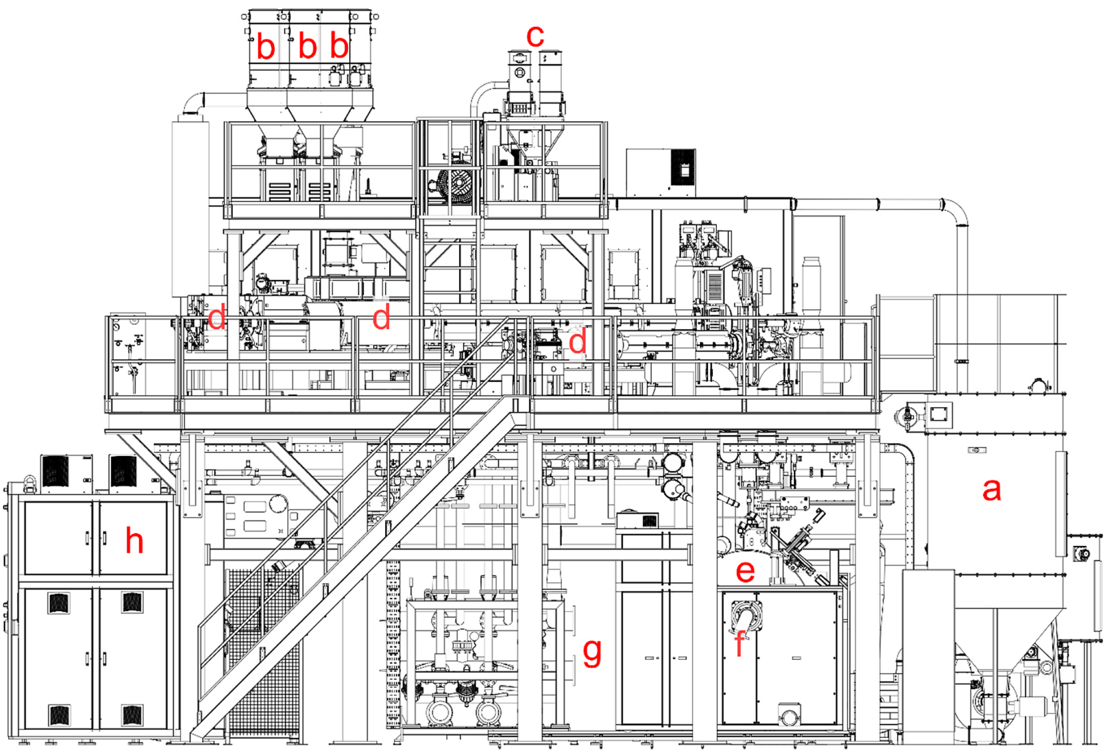

Figure 6. View of the production line of stretch foil using the cast method: (a) regranulate tank, (b) extruder buffer tanks – 4 pieces, (c) extruder buffer tanks – 2 pieces, (d) extruders – 6 pieces, (e) first calender roller, (f) connection of the cooling system of the first calender roll, (g) foil cooling system, (h) control and monitoring system

WASTE HEAT RECOVERY TECHNOLOGICAL LINE

The stable operation of a technological line producing stretch foil largely depends on the stable temperature of the first calender roll, to which the liquid regranulate is fed. The roll acts as a cooler, and the technological heat from the roll cooling process (Fig. 6f) has been treated as waste heat and dispersed in the environment. Increasing the share of the recycled material fraction in the regranulate, which can come from various sources, is associated with the need to standardize it. For this reason, the technological heat, treated as waste heat, can be used to pre-dry the recycled material.

This line consists of two hydraulic systems separated by a plate heat exchanger with a nominal power of 400 kW (Fig. 7). The primary side of the exchanger is supplied by heat pump evaporators or fan coolers, constituting a source of technological cooling. The load for the secondary side of the plate heat exchanger is the hydraulic system enabling the collection of the previously mentioned technological heat from the first calender roll. The uniform temperature on the surface of the rotating roll is achieved using water flow, and the inlet temperature of which is 15 °C and the outlet temperature is 16 °C. Such a small gradient of 1K between the inlet and outlet temperatures of water is achieved using a water flow through the calender of 150 m^3/h. As can be easily calculated, during the technological process of foil production, approximately 176 kW of low-temperature waste heat is generated, which would normally be dispersed in the atmospheric air. The process innovation is to increase the temperature level of waste heat and use it to dry regranulate. The increase in the temperature level of low-temperature waste heat is achieved using a specially designed heat recovery system based on two compressor heat pumps powered by ecological refrigerants, i.e., agents with low ODP and GWP coefficients. The main technological problem is to ensure a stable and constant in-time temperature of the water inlet to the cylinder, which is the coolant. This problem was solved by using two parallel-connected buffer tanks, Z1 and Z2, with a volume of 2000 dm^3 each, as the input stage, which constitutes cold storage and, at the same time, increases the water charge in the installation, which a positive impact on the inertia of the installation. The flow of water constituting the coolant through the calender is forced using the P1 pump with the possibility of smooth capacity regulation. The PI 1 controller regulates the circulation pump capacity as a function of the gradient between the water temperature measured by temperature sensors installed in the capillaries

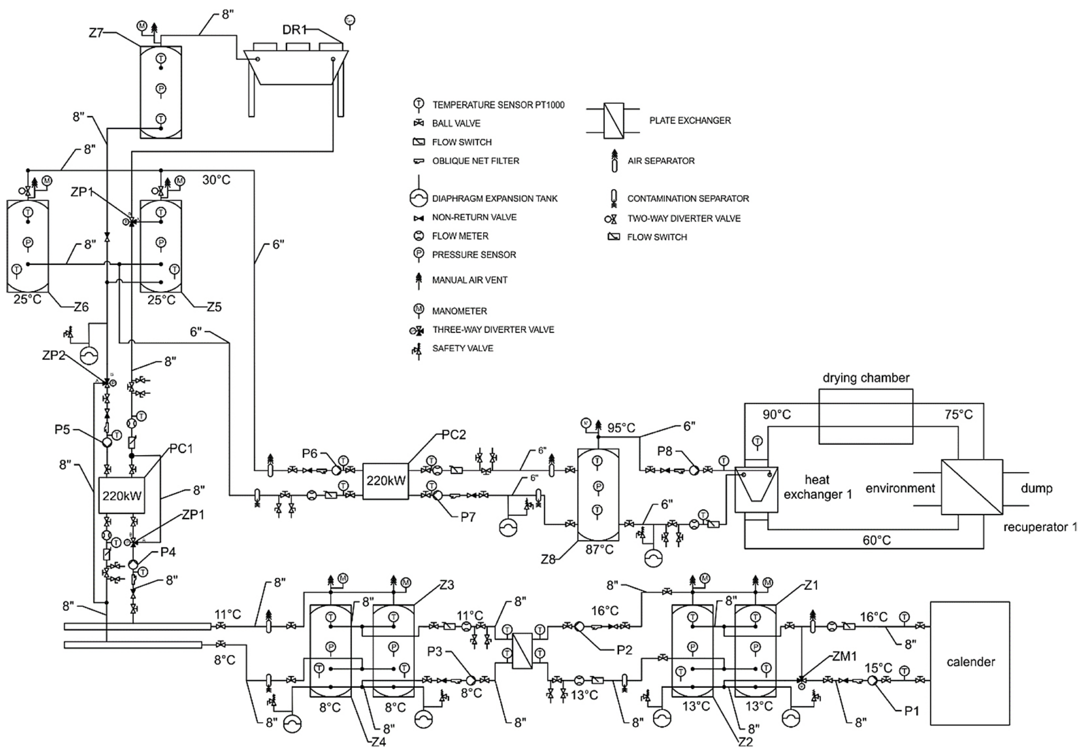

Figure 7. Diagram of the hydraulic installation for technological heat recovery

on the inlet and outlet nozzles to the cylinder. The required high quality of cooling water inlet temperature control is achieved through a three-way mixing valve ZM1, smoothly regulated by a PI 2 controller. The basic source of cooling and, at the same time, the first stage of technological heat recovery is specially designed by the employees of the Department of Fundamentals of Engineering and Energy at the Institute of Mechanical Engineering at the Warsaw University of Life Sciences (SGGW), PC1 compressor heat pump with a nominal power of 220 kW, for which the lower heat source is the energy necessary to cover the cooling demand of the rotating calender. The nominal power of the heat pump was determined according to the PNEN 14511 standard for a lower source temperature of 10 °C and an upper source temperature of 35 °C. The device is based on two semi-hermetic piston compressors. The heat pump cooling power adjustment to the current demand for cooling of the calender is carried out using compressor capacity regulation through the use of inverters enabling the regulation of the compressor volumetric capacity by changing the supply voltage frequency in the range of 30–50 Hz. The heat pump evaporator PC1 is hydraulically coupled with buffer tanks Z1 and Z2 via tanks Z3 and Z4 with a volume of 2000 dm^3 each and a plate heat exchanger. The heat exchanger is intended to ensure separation between glycol, a heat or cooling carrier in the hydraulic system on the primary side of the exchanger, and water, a carrier of technological cooling on the secondary side of the exchanger. The water flow between the secondary side of the exchanger and the Z1 and Z2 tanks is carried out using the P2 pump, the capacity of which is regulated using the PI 3 controller. The role of the Z3 and Z4 buffer tanks is to increase the glycol charge on the primary side of the exchanger, which is intended to increase the system's inertia and, as a result, achieve a stable lower source temperature over time. The glycol flow between the Z3 and Z4 buffer tanks and the primary side of the plate exchanger is carried out using the P3 pump, the capacity of which is regulated smoothly using the PI 4 controller. The smooth regulation of the glycol flow on the primary side of the plate exchanger is intended to ensure a constant temperature gradient of 3K. The glycol flow between the Z3 and Z4 buffer tanks and the heat pump evaporator is carried out using the P4 pumps. The capacity of the P4 pump is regulated continuously using the PI 5 controller. The smooth regulation of the glycol flow is intended to match the flow to the current thermal load of the evaporator. The setpoint for the PI 5 controller is a constant gradient value between the inlet and outlet temperature of glycol to the evaporator, which is 3K, intended to ensure the high efficiency of heat pumps. The heat load of the PC1 heat pump condenser, depending on the operating mode, can be buffer tanks Z5 and Z6 with a volume of 2000 dm^3 each or a DR1 fan cooler. The heat pump operating mode depends on the current heat demand of the high-temperature technological process of preliminary preparation of regranulate. It is implemented by changing the position of the three-way switching valves ZP1 and ZP2. The first operating mode of the PC1 heat pump, corresponding to the position of the PZ1 and ZP2 valves in position B, consists in supplying medium-temperature technological heat to buffer tanks Z5 and Z6, which constitute the heat load for the evaporator of the high-temperature heat pump PC2, which generates high-temperature technological heat used in the preliminary drying process of regranulate. If there is no demand for medium-temperature heat, or when the temperature in buffer tanks Z5 and Z6 has reached the set point, to ensure a constant temperature of the coolant supplying the calender and thus the continuity of foil production, two operating modes are possible. The first operating mode is implemented when the ambient temperature is higher than 3 °C. Then the heat pump PC1 is switched on, which uses the process heat as the lower heat source, thus providing the technological cooling necessary for cooling the calender. At the same time, the generated medium-temperature heat is dispersed in the environment using the DR1 fan cooler. The applied Z7 buffer tank is intended to increase the glycol charge in the installation, which, as a result, increases the inertia and thus has a positive effect on the length of the heat pump operation cycle. The second possible operating mode is the dispersion of medium-temperature process heat in the atmosphere using the DR1 fan cooler. This operating mode is implemented when the glycol temperature in buffer tanks Z5 and Z6 has reached the set point, and the ambient temperature measured by the T_{amb} temperature sensor is lower than 3 °C. Then, the switching valves ZP1 and ZP2 are switched to position A, and the glycol flow between the buffer tanks Z3 and Z4 and the fan cooler DR1 is forced using pump P4. This solution significantly saves the electrical energy to drive the heat pump compressor. The system for generating high-temperature technological heat is based on the high-temperature compressor heat pump PC2, for which the lower source is the buffer tanks Z5 and Z6. The heat load of the CP2 heat pump condenser is the buffer tank Z8, which is a high-temperature heat source for the WC1 type V heat exchanger. Air flows through the heat exchanger, which acts as a heat carrier used in the initial drying process of the regranulate. The drying medium flows through the drying chamber and then goes to the recuperator, where the process of preheating the fresh air supplied takes place, reducing the process's energy consumption. An industrial control system manages the hydraulic system of the heat recovery line. The project adopted a classic, layered structure of the control system. The lowest layer contains all the devices that generate input signals and respond to output signals. Input signals are those that carry information about the current state of the system. Input devices, in this case, are sensors, primarily temperature and flow. They can provide information, for example, about the current temperature of the coolant flowing through the calender cylinder. In turn, output devices, also called executive devices, directly affect the control object by changing its current state. In this system, these will mainly be valves, pumps and inverters.

The designed technological heat recovery system is modular and can be expanded with additional modules, reaching a power of up to 1 MW (Fig. 8). Depending on the required temperature of the high-temperature process heat, the minimum COP of the high-temperature heat pump is 2.6, and that of the low-temperature heat pump is 4.5.

TECHNOLOGICAL LINE OPERATION CONTROL SYSTEM

The next layer of the system is the control layer. It contains PLC controllers. In short, PLC controllers are microprocessor devices dedicated to working in industrial conditions. Additionally, the controllers perform four main tasks: collecting measurements, processing the user program, generating control signals, and communicating with other automation components. Collecting measurements is related to input signals, i.e., the previously mentioned sensors. In turn, the control signals direct the operation of output devices. The instantaneous values of the control signals are determined based on the algorithm, i.e., the installation's operation method. The algorithm is written as a program consisting of various instructions and function blocks available within the programming language – in the case of PLC controllers, it is ladder language. The last function of the controllers is communication. Due to the location of sensors and actuators in different, distant places of the installation

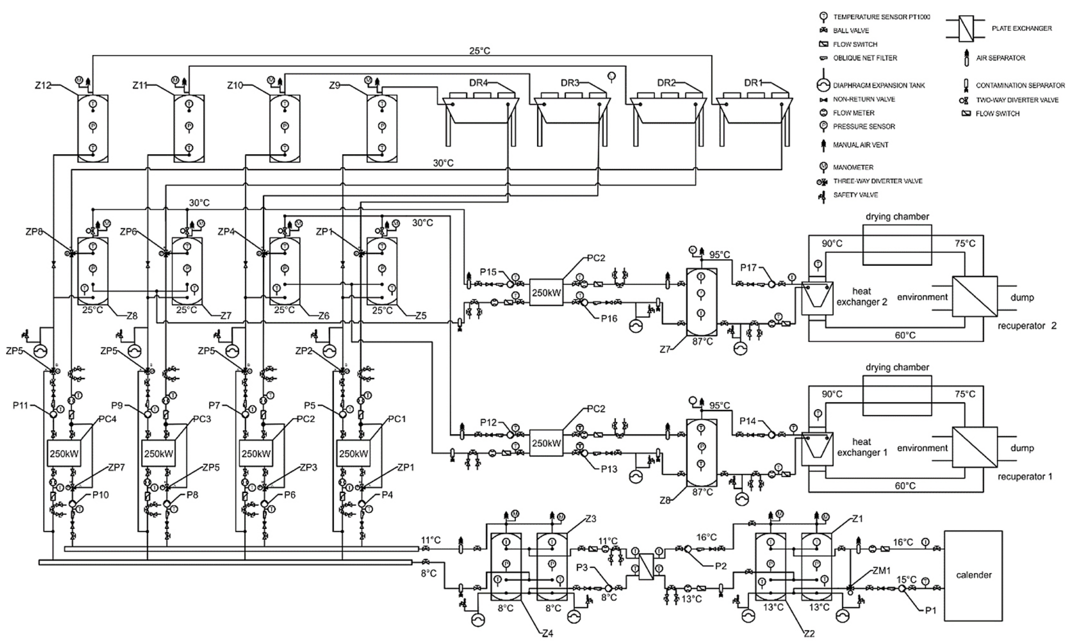

Figure 8. Diagram of the hydraulic installation for technological heat recovery in the development version

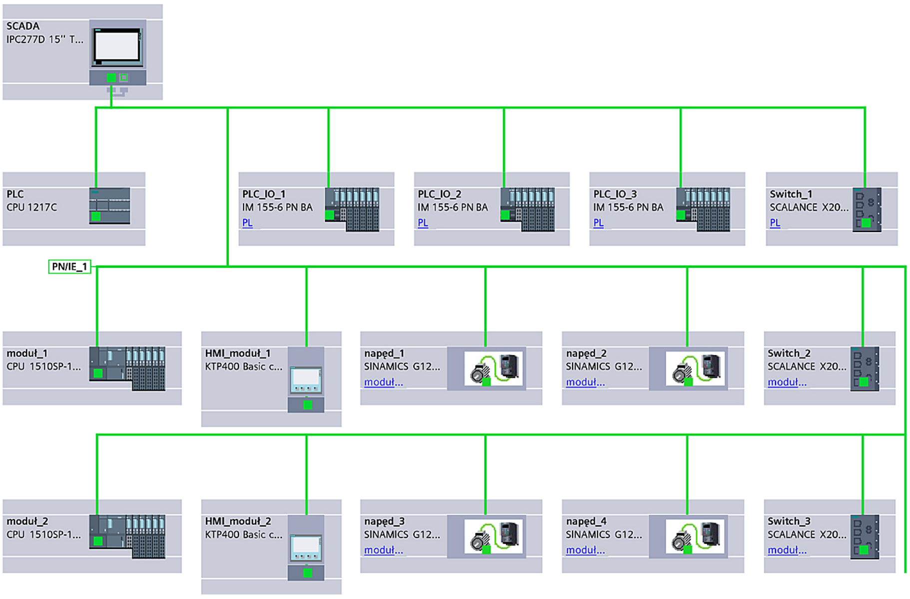

Figure 9. Example control structure diagram

and the separation of specific functional areas of the installation, e.g., local subsystems controlling the hydraulic installation of heat pumps, a distributed control layer was used. The essential components used in the control layer are the central PLC controller, distributed input/output modules, and additional PLC controllers. The central PLC controller manages the entire installation, collects all input signals, and controls all actuators. These signals are processed in input and output modules. Distributed input/output modules were decided upon to reduce the number of cable connections. This means the module is not located outside the main control cabinet but closer to the measurement points. The connection between the modules and the central unit is carried out digitally using the Profinet communication protocol. The hydraulic installation of each heat pump is equipped with its own PLC controller, which is responsible for local control of the heat pump. In such a system, the central controller has access to all statuses describing the current operating state of the heat pump and can also send commands related to starting or stopping the device and changing the main operating settings. Similarly to the case of distributed modules, communication here also takes place using the Profinet protocol.

The control system also assumes a superior layer about the layer containing controllers. This control layer consists of HMI operator panels and an IPC industrial computer with a SCADA (Supervisory Control And Data Acquisition) application (Fig. 9). HMI panels make it easier for operators to operate machines and devices. In the case of a heat collection installation, HMI panels will be placed at each local PLC controller controlling a single heat pump module. The panels facilitate, among other things, detailed parameterization of the inverter controlling the heat pump compressor. However, the main element of this control system layer is an industrial computer with a SCADA application. In this case, the main emphasis is on collecting data from the entire heat collection installation and exchanging data with MES or ERP programs used in the company.

CONCLUSIONS

The advantage of the developed heat recovery system is its modularity. The system, depending on the needs of the entrepreneur, the availability of low-temperature waste heat and the demand for high-temperature heat, can be expanded by adding oil cements of the system.

The designed innovative technological heat recovery system, managed by the developed industrial control system, allows increasing the efficiency of the stretch film production process, increasing the proportion of waste polyethylene up to 80%, which enables the management of difficult-to-recycle waste, saving material and reducing electricity and, as a result, reducing the carbon footprint.

Acknowledgments

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