CI&CEQ
Chemical Industry & Chemical Engineering Quarterly

Available online at
Association of the Chemical Engineers of Serbia *AChE*
www.ache.org.rs/CICEQ

Chem. Ind. Chem. Eng. Q. 29 (2) 129−139 (2023)
CI&CEQ

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SCIENTIFIC PAPER

UDC 678:66.047:678.742.2

STUDY ON HEAT EXCHANGERS AND INDUSTRIAL ABSORPTION COLUMN FOR DRYING POLYETHYLENE TEREPHTHALATE

Article Highlights

- The work consisted of an industrial-scale technical investigation
- The industrial process had no impact on product quality or production rate
- The study aimed at industrial optimization
- The results found can be used as a reference in other processes (diagrams)

Abstract

This study proposes the use of mass balance and the method of McCabe-Thiele in the absorption column for the removal of drying air humidity with ethylene glycol and energy balances in heat exchangers for the determination of the optimum operating conditions of a factory to produce recycled polyester fibers from polyethylene terephthalate (PET) flakes. The evaluation of these machines involved the combination of variables such as temperature, flow rate, specific heat, and operational efficiency to guarantee the correct adjustment of the physicochemical properties of the fluids and materials of the process. The efficiency of the absorption column was determined at 25%, and a diagram correlating ethylene glycol humidity, the dew point of the drying air, and the efficiency of humidity removal from the PET flake dryer were constructed to define what is the most appropriate configuration for operation. By the graph curves, it was found that the humidity of ethylene glycol for absorption should be inferior to 1% (w/w) to guarantee a dew point < -27 °C at 175 °C of the drying air introduced in the dryer, which would finally promote a removal with efficiency superior to 91% of the PET flake humidity for values < 0.005% (w/w).

Keywords: humidity, dew point, PET flakes, polyester, McCabe-Thiele.

The production of recycled polyester fibers (PES) occurs in three steps. Initially, the polyethylene terephthalate (PET) bottles are processed post-consumption in a line for decontamination and granulometry adjustment to obtain the PET flakes. Subsequently, the material undergoes extrusion and spinning and draws and cuts the fiber filaments [1–3].

Before PET flake extrusion, the crystallization and drying of the material must be performed to avoid hydrolytic degradation of the polymer molecules. The residence time required by the polymer in the crystallizer and dryer for thermal treatment to be sufficient to meet the operational requirements, and adjustment of the molecular properties must be enough for the removal of PET flake humidity at levels below 0.005% w/w for extruders without vacuum adjustment, and inferior to 0.05% w/w for extruders with this additional vacuum adjustment [4–5].

The adjustment of the PET drying process must be properly configured to guarantee the removal of humidity from the polymer particles to acceptable levels, especially because of the hygroscopic characteristic of PET and the formation of intermolecular bonds between water molecules and the polymer chain [6]. In Figure 1, the schematic representation of the removal of water molecules that penetrated the PET flake or pellet can be observed following an appropriate drying process.

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Paper received: 22 June, 2021
Paper revised: 8 January, 2022
Paper accepted: 15 August, 2022

https://doi.org/10.2298/CICEQ210622020S

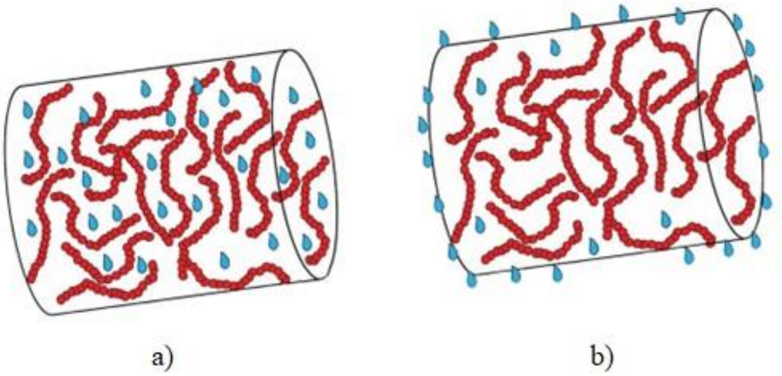

Figure 1. Water molecules penetrated the PET polymeric chain (a) and molecular process of polymeric chain drying (b) according to Plastics Technology® [7].

Virgin PET or recycled PET flakes must be dried immediately before fusion. Four fundamental parameters must be verified: temperature, dew point, drying air flow rate, and operation time. With the temperature rise, water molecules lose attraction to the polymer chains and become prone to migrate to the atmosphere. Nevertheless, the temperature range must be appropriate since the excessive rise favors parallel degradation and thermal oxidation reactions. The dew point is the indirect measurement of air humidity and indicates the temperature of saturation in which the air-water vapor will condense into the first drop of liquid. The lower the dew point, the lower the relative humidity of the drying air; consequently, the higher the drying capacity and efficiency according to the mass transference principles [8–10].

Drying air flow must be properly dimensioned for compatibilization with the dimensions of the system. An insufficient air flow will be unable to transfer the necessary heat in the whole extension of the dryer, thus reducing process efficiency. In contrast, an excessive flow will cause an overload in drying temperature and around the equipment. The PET particles will not absorb this excess heat, and the energy costs and drying performance will not be optimized under this condition. The ideal air flow must provide the system with a vertical profile of homogeneous temperature in the equipment, as presented in Figure 2 [10,11].

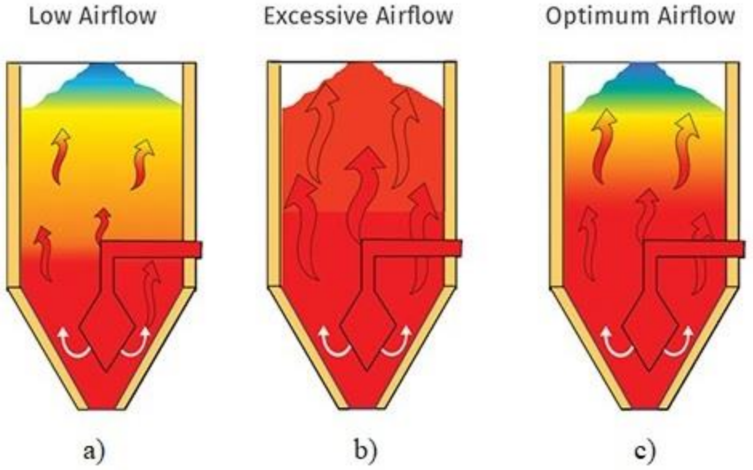

Figure 2. (a) Insufficient airflow will not maintain the necessary heat to dry the PET particles; (b) excessive airflow will provide more heat than PET can absorb, resulting in high air temperatures, unsatisfactory performance of the desiccant, and waste of energy; (c) ideal airflow develops a vertical temperature profile which provides the optimized amount of heat for drying while it uses the cold PET particles as a heat sink to cool the return air coming out of the dryer according to Plastics Technology® [7].

Additionally, the processing time must be high enough since PET drying does not occur instantly. When heat transfer starts on the surface of the material, sufficient time must be provided for internal heat transfer and subsequent elimination of water molecules, which usually occurs between 3 and 5 hours [11,12].

In work on the recycled PET extrusion on an industrial scale, Elamri [4] used a drying system with air at the temperature of 170 °C and dew point below -20 °C for 4 h, obtaining post-drying PET with humidity of 0.05% (the value was relatively high because of the operation conditions and compensated by the vacuum system coupled to the extruder; otherwise the hydrolytic degradation would reach detrimental levels). On the other hand, Whitehead [12] worked with temperatures varying between 150 °C and 200 °C, a dew point of -20 °C, and an operation time of close to 5 h.

Given the context presented for PET flake drying, the operational conditions of the air to be used in the dryer, especially temperature and humidity, must also be considered for industrial projects. In large-scale installations, heat exchangers and absorption columns for temperature and humidity adjustments can be used, following proper equations and scaling. By definition, heat exchangers are designed for heat exchange between distinct fluids or even between fluids of the same nature, which promote direct or indirect contact among fluids of interest and favor energy transfer [13]. In contrast, absorption columns are based on mass transfer among the components used [14].

The study of polyethylene terephthalate is consolidated in the literature, which is noted by the many studies on this important polymer. However, new approaches and experiments can be found despite being a classic material to study. Furthermore, and within the segment of the present work performed, the PET humidity issue is always a critical variable to be considered for the processing of interest, mainly because of the characteristic molecular degradation that happens in the chains of this polymer when melted in wet conditions [15–17].

In the present work, the projecting and scaling-up equations of heat exchangers and an absorption column were studied for the treatment of the air of a PET flake dryer for polyester production on an industrial scale aiming at evaluating the variables of the operation line of the factory without process interruption. Furthermore, for the studies on mass transfer, experiments to compare the optimum operation conditions were also performed, considering the humidity of the fluid for humidity removal, the dew point of the drying air, and the humidity of the PET flakes before the extruder without a vacuum system.

The main contributions of this work are related to the practical results found on an industrial scale after the execution of the procedures. Typically, pilot scale or laboratory scale studies are found in the literature for this type of evaluation. In summary, the application of chemical engineering models could be observed in industrial operations and provide a view of the behavior of the related principles.

EXPERIMENTAL

A detailed description of the process

The process consisted of receiving amorphous recycled PET flakes (with dimensions inferior to 9 mm) directed to a supply silo by transportation in the compressed air tubing. The material was sequentially transported to the crystallizer by vacuum, where, by gravity, the flakes flowed into the equipment. By the action of temperature and agitator shear stress, crystallization occurred. The heating was derived from hot air at (160 ± 10) °C. At the outlet of the crystallizer, there was a blower to direct the material to the dust removal system, composed of one cyclone and bag filter for the filtration of air and retention of contaminating particles.

The material flow of the dust removal system was transported in a vacuum line to two serial feed silos on top of the dryer, designed to keep the constant flow in the drying step and avoid feeding failure. After the dryer outlet, the material followed the gravimetric measurement system, which had four dosing points loaded with different materials, such as masterbatches for pigmentation of molten polymer and specific additives according to the type of polyester to be processed before passing through the extruder.

The extruder was basically composed of the feeding zone, six zones for heating with electrical resistances varying between 255 °C and 280 °C, a shear bolt, and a rotary polymer filter to retain unwanted impurities for the next spinning process. The feeding system was continually cooled with cold water at 5 °C to prevent softening and possible adsorption of the flakes on the inner walls of the feeding zone. In the horizontal extent of the extruder, the heating system should be increasing, with the recommendation of 10 °C below the melting temperature of (250 ± 5) °C in the first zone, the temperature in the melting range of (260 ± 5) °C in the second zone, and from the third zone, 10 °C above the melting temperature of (275 ± 5) °C. This temperature profile aimed at avoiding backflow at the extruder inlet and favoring the screw shear stress, considering that this extruder model did not have a vacuum system for the transportation and flow of the molten material [18].

The molten polymer was directed to the spinning machines by metering pumps, which distributed the polymeric mass evenly for the passage by compression through 20 filter devices containing spinnerets with up to 1804 holes on the order of 2.5×10^{-4} m in diameter to obtain polyester filaments. Immediately after the spinnerets, there was a fast cooling of the threads with compressed air for the solidification of the material [19].

Subsequently, the spun material was taken to the drawing stage for molecular chain orientation with steam at (175 ± 5) °C because the fast cooling in the spinning caused the molecular disorientation of the polymer. In the drawing process, the polyester threads were pulled to shape the material's mechanical properties and cut to lengths from 32 mm to 64 mm for final product shaping.

In Figure 3, an overview of the process of obtaining polyester fibers by recycling PET bottles is presented as a highlight for the dryer, described in detail in the following study section on mass and energy exchange.

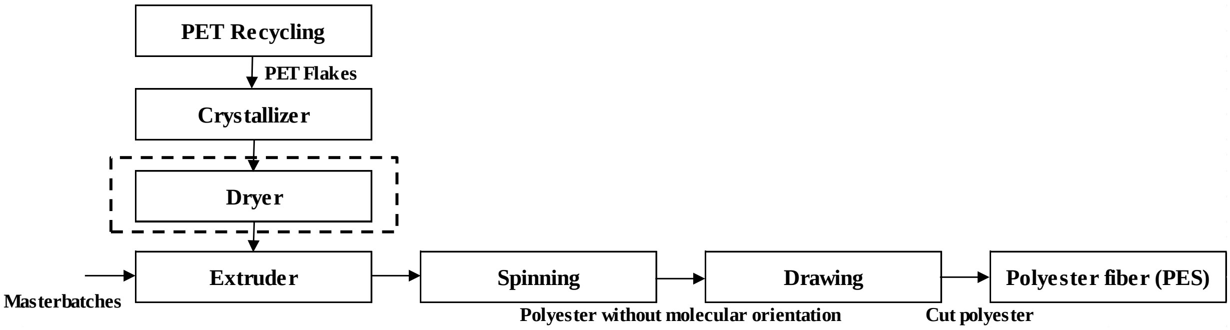

Figure 3. General description of the process of obtaining polyester fibers from PET flakes with the highlight for the dryer where the studies on mass exchange and energy exchange were performed.

Operation parameters for drying PET flakes

To improve the performance of filament spinning, the material underwent treatments before being extruded and receiving the pigmentation of masterbatches, which were the crystallization of the flakes (until ~35%) and drying at (175 ± 25) °C [11].

The dryer had a total volume of 10 m^3, the mass flow of PET flake operation in (700 ± 200) kg/h, and airflow at (1080 ± 30) kg/h at (175 ± 25) °C and with a dew point of approximately (-35 ± 7) °C. The air of the process circulated in a closed circuit, with occasional periodic replacements in cases of pressure drop.

From the dryer outlet, the humid air at about (75 ± 10) °C passed through a cyclone and a paper filter element to remove coarse particles and proceeded to an absorption column for washing with ethylene glycol spray. Ethylene glycol was refluxed at (3000 ± 50) kg/h with a tubular heat exchanger (the cold fluid was cold water at (5 ± 1) °C) to keep the temperature at (10 ± 1) °C, and ethylene glycol had replacement every time the dew point of the drying air was greater than -20°C.

The outlet air from the absorption column, with a temperature of (15 ± 5) °C, was directed to a demister. The contaminants were discarded as overflow, and the airflow was left through the top of the equipment. Then, the purified air passed through a blower and was directed to a heat exchanger of the type shell and tubes, with saturated steam at (210 ± 10) °C as heating fluid, before its dew point was measured by a sensor (RHT-WM sensor from Novus®) and it passed by the dryer. Finally, the humid air after drying was reused for cycle restart (around 75 °C).

Figure 4 presents the simplified block diagram of the drying air system used in the process. In this diagram, it is possible to visualize all the interconnections of the plant's operational streams (flow of PET flakes for extrusion, closed circuit drying air, and ethylene glycol reflux). Additionally, when the diagram is observed, it is possible to understand the applicability of this energy integration study and how to design the equipment and flows.

The process setups can be seen in Table 1, with a summary of the conditions adopted in each step and the possible acceptable variations in operation. In addition, the parameters calculated by the project equations and determined by the dimensioning studies as a function of the plant's operating assumptions were also indicated.

Sizing of the heat exchanger

The equations of Incropera [13] were used to calculate the operation parameters of the heat exchangers, highlighting the considerations for energy balance.

$$Q = \dot{m} \cdot c_p \cdot \Delta T \tag{1}$$

where Q is the heat transfer rate (J/s), $\dot{m}$ is mass flow (kg/s), c_p is the specific heat (J/(kg °C)), and ΔT is the temperature variation of the hot fluid (reference fluid) (°C), Also,

$$Q = U \cdot A \cdot \Delta T_{LMTD} \tag{2}$$

where U is the overall heat transfer coefficient (J/(s m^2 °C)), A is the heat exchange area (m^2), and ΔT is the logarithmic mean temperature difference of

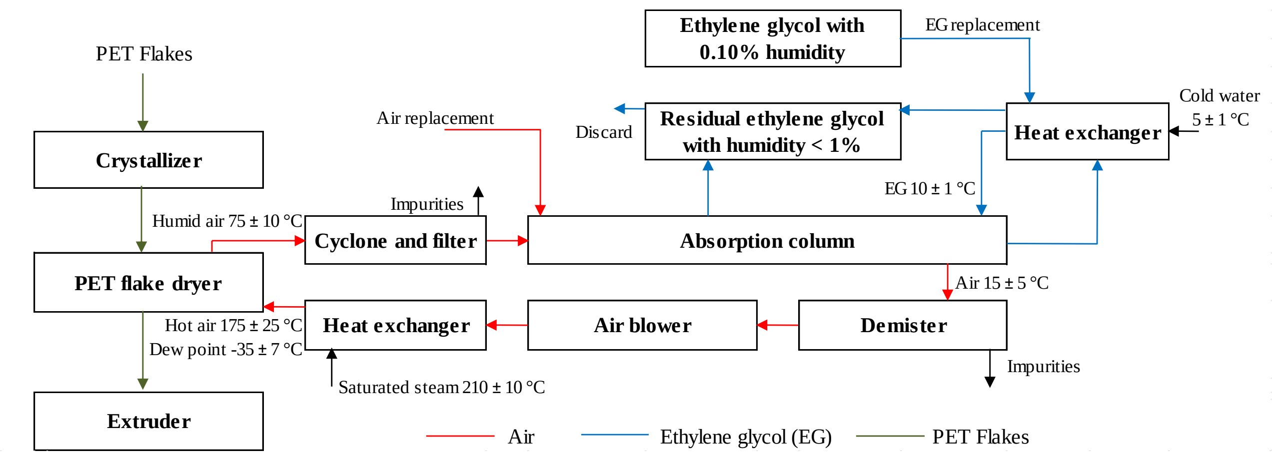

Figure 4. Simplified block diagram of the drying air system.

Table 1. Summary of the conditions adopted in each step and acceptable variations in operation.

Equipment	Parameter	Acceptable Variance + Uncertainty
Crystallizer	Flow - PET Flakes (kg/h)	700 ± 200
	Temperature (°C)	160 ± 10
Dryer	Flow - PET Flakes (kg/h)	700 ± 200
	Flow - Air (kg/h)	1080 ± 30
	Air Temperature at the inlet (°C)	175 ± 25
	Air Dew point at the inlet (°C)	-35 ± 7
	Air Temperature at the outlet (°C)	75 ± 10
Extruder	Flow - PET Flakes (kg/h)	700 ± 200
	Temperature - First Zone (°C)	250 ± 5
	Temperature - Second Zone (°C)	260 ± 5
	Temperature - Third Zone (°C)	275 ± 5
Absorption Column	Flow - Ethylene glycol (kg/h)	3000 ± 50
	Flow - Air (kg/h)	1080 ± 30
	Ethylene glycol Temperature at the inlet (°C)	10 ± 1
	Ethylene glycol Dew point at the inlet (°C)	< -20°C
	Ethylene glycol Temperature at the outlet (°C)	Determined in the dimensioning study
	Air Temperature at the inlet (°C)	75 ± 10
	Air Temperature at the outlet (°C)	15 ± 5
Bitubular Heat exchanger	Heat exchange area (m^2)	15.0 ± 0.5
	Flow - Ethylene glycol (kg/h)	3000 ± 50
	Flow - Water (kg/h)	Determined in the dimensioning study
	Temperature cold fluid water at the inlet (°C)	5 ± 1
	Temperature hot fluid Ethylene glycol at the outlet (°C)	10 ± 1
	Ethylene glycol Dew point at the outlet (°C)	< -20°C
Shell and tubes Heat exchanger	Flow - Air (kg/h)	1080 ± 30
	Flow - Saturated steam (kg/h)	Determined in the dimensioning study
	Air Temperature at the inlet (°C)	15 ± 5
	Saturated steam Temperature at the inlet (°C)	210 ± 10
	Air Temperature at the outlet (°C)	175 ± 25
	Saturated steam Temperature at the outlet (°C)	Determined in the dimensioning study
	Heat exchange area (m^2)	Determined in the dimensioning study
Boiler	Saturated steam production capacity (kg/h)	Up to 1260

the system involving the hot fluid and the cold fluid (°C).

The correction factors based on algebraic equations that consider the fluid temperatures and the counter-current flow operation could also be applied and the heat transfer rates of the exchangers could be determined using the method E-NTU (effectiveness) consulting the tables and graphs available in Incropera [13] for tubular and shell and tubes heat exchangers. The correction factor must be applied to shell and tube heat exchangers with more than one pass in the shell or tubes because, depending on the design of the equipment, the fluid may sometimes be in counter-current flow and, at other times, in co-current flow. Because counter-current flow is the most efficient heat exchange compared to co-current flow, the correction factor will be applied to correct the energy balance in the counter-current heat exchanger equation when the flow is co-current [13].

Sizing of the absorption column

To determine the theoretical and actual plates of the absorption column to remove air humidity using a chain of ethylene glycol, the mass balance from Eq. (3), cited by Welty [14], and the method of McCabe-Thiele, were employed:

$$L'\left(\frac{x_0}{1-x_0}\right)+V'\left(\frac{y_{n+1}}{1-y_{n+1}}\right)=L'\left(\frac{x_n}{1-x_n}\right)+V'\left(\frac{y_1}{1-y_1}\right) \quad (3)$$

where L is the liquid flow in the absorption column (kmol/(h m^2)), V is the flow of steam or gas (kmol/(h m^2)), and x and y are molar fractions of the contaminants to be removed in the respective phases.

The dew point measurement was performed to evaluate the efficiency of removal of air humidity by the absorption column, where the lowest value indicated the highest removal of moisture (water) by mass exchange with ethylene glycol. Additionally, other evaluations performed were the measurement of PET flake humidity by the method of gravimetry before and after the dryer to correlate humidity removal from the polymer with the different conditions of the drying air dew point and also to correlate the drying air dew point with ethylene glycol humidity in the column (the last was analyzed by an automatic titrator using the Karl Fischer solution) [19–22].

PET flake humidity was analyzed after weighing (10.00 ± 0.50) g of sample in stainless steel capsule and leaving it in a convection oven for 180 min at (175 ± 1) °C. Eq.(4) indicates the calculation to quantify this parameter [6,23].

$$Humidity\,(\%)=\frac{m_{ca}-m_{cv}}{m_{ca}-m_{cas}}\cdot 100 \quad (4)$$

where m_{ca} is the mass of the capsule with the wet sample (g), m_{cv} is the mass of the empty capsule (g) and m_{cas} is the mass of the capsule with the dry sample (g).

At the end of the study, a mass correlation curve was also determined between the dew point and the amount of water vapor per cubic meter of air, considering the characteristics of the drying system, such as atmospheric pressure, relative humidity, and room temperature, using a measurement system integrated to the operation line. For this analysis, the air was left to reflux without renewal, so its humidity increased during the test [24].

RESULTS AND DISCUSSION

Sizing of heat exchangers

An important premise to be considered in the studies is that all dimensioning and data collection were performed in the industry. Therefore, the repetition of experimental conditions simulating different variations was not performed not to impact productivity and quality control of the finished goods (differently than in a laboratory where the data could be varied without loss of productivity).

Nevertheless, all the variation in the data and variables presented in the results section was appropriately statistically analyzed. In addition, the associated measurement uncertainty variation was reported, which was also considered in the factory production standards for monitoring by the production operators. For all the temperatures cited, measuring sensors of the Pt-100 type (Novus model® N1030-pr Pt100) were used to confirm the data obtained by the design equations.

According to Figure 4, presented in the experimental section, the present work was performed in a high-productivity industrial factory with interconnection between the process steps. The first stage of drying air heat exchange after passing through the dryer occurred directly in the absorption column since the contact with ethylene glycol promoted thermal exchange between the fluids. Although the absorption column was not designed as the heat exchanger, we can do an energy balance and determine what mean temperature the air should have at the outlet of the column and allow a comparison with the measurements of the process sensors. The process measurements indicated that the air left the dryer at a flow rate of (1080 ± 30) kg/h at (75 ± 10) °C (called moist air), whereas the counterflow of ethylene glycol in the column was (3000 ± 50) kg/h at (10 ± 1) °C. At the end of the heat exchange, the air left the absorption column at (15 ± 5) °C, and ethylene glycol stayed at (20 ± 5) °C.

The process flow rates were used to calculate the theoretical fluid temperatures for analyzing the absorption column as a heat exchanger. First, after comparing the sensors' measurements, the parameters of the heat exchange area and overall heat transfer coefficient were estimated. Then, performing the necessary balances and considerations, such as energy losses to the environment, temperature variation during the day, the sensitivity of the measurement sensors, and starting from a theoretical heat exchange area of (15.0 ± 0.5) m^2 (according to the column dimensions) and overall heat transfer coefficient at (50 ± 2) J/(s m^2 °C), the theoretical air outlet temperature should be (20 ± 5) °C. In contrast, ethylene glycol should leave the process at around (18 ± 5) °C [25].

There was a difference of 5 °C between the theoretical and actual outlet air temperatures, which could be attributed to the heat exchange area and, indirectly, to the overall heat transfer coefficient since it is also a function of the area. An iteration method showed that the heat exchange area inside the column could be up to 40% higher than the estimated initial value, which, in practical terms, represents the possibility of increasing the flow rate of fluids in the drying process in case there is a higher production demand at the factory. For ethylene glycol, a difference of 2 °C was verified. After iterations, this difference was 1 °C, which could be attributed to this fluid's higher heat capacity than the air [13].

Evaluating the tubular heat exchanger applied to maintain ethylene glycol in the range of 10 °C, cold water at 5°C was used to perform this energy exchange. In this analysis node, once more, the area of heat exchange and overall heat transfer coefficient could be analyzed; nevertheless, since this equipment is designed for heat exchange, more in-depth studies began since the area, in this case, would be intrinsic to the number of tubes and passes inside the exchanger. Thus, aiming to expand the vision of operation engineering of the factory, energy balances were performed to determine the cold-water flow at 5 °C that should be fed to the heat exchanger to cool the ethylene glycol outlet in the absorption column to return its temperature to 10 °C before entering the absorption column again.

As a premise of the previous analysis, it was also considered that the water leaving the heat exchanger could be reused in another activity of the factory, such as the preparation of process additives, whose ideal temperature of applicability was 20 °C. In an initial evaluation, it can be concluded that the final water temperature should reach the initial temperature of ethylene glycol, which would imply that even if the specific heats of these fluids are different, the water flow should be lower when compared to the flow of ethylene glycol air [13]. Transforming this empirical analysis to numbers from the energy balance, the water flow should be (1164 ± 20) kg/h (ethylene glycol was (3000 ± 50) kg/h), which is equivalent to 1.16 m^3 of water per hour of production.

Finally, for the last heat exchanger to heat the air before the drying process, there was an exchanger of the shell and tube type (with 1 pass in the shell and 2 passes in the tubes), in which the hot fluid available was steam saturated at (210 ± 10) °C from a boiler with a capacity of up to 1260 kg/h of steam. For this evaluation, we aimed to determine what area of minimum heat exchange should be available in this equipment for steam to remain in the saturation condition and with a temperature between 170 °C and 180 °C, which would allow its outflow to be directed to the step of drawing the polyester fibers and orientation of the filaments [26]. Therefore, combining all process considerations and limitations, it was calculated that the equipment should have a heat exchange area of at least 5.9 m^2, the flow rate of the steam saturated at (210 ± 10) °C should be (1115 ± 18) kg/h, and its outlet temperature for use in the drawing stage should be (175 ± 5) °C.

Evaluation of mass transfer in the absorption column

As previously mentioned, there was a heat exchange between the drying air and ethylene glycol in the absorption column. Nevertheless, the column's primary function was removing humidity from the dryer outlet air before its reuse in a new drying cycle in combination with the new air derived from the blower. Ethylene glycol, used in the absorption column for the removal of air humidity, is a highly desiccant agent because of its hygroscopicity (the solubility of ethylene glycol in water at 10 °C is close to 1 g/ml, which gives a degree of solubility of approximately 100%) [27]. Furthermore, ethylene glycol has a relatively high boiling temperature (197.3 °C), which allows the subsequent separation from water in a distillation column or reuse of this raw material in processes in which humidity is not a determining factor [28].

Pure ethylene glycol presented in its mean composition around 0.1% (w/w) of water (humidity), and during the experiments, an output current with up to 8% (w/w) of humidity was observed. Using the mass balance equation for the absorption column and with the flow rates used for process operation, it was possible to estimate the efficiency of the plates in the absorption column using the method of McCabe-Thiele [14] comparing the number of actual plates in relation to the theoretical amount for the development found in the experiment. After drawing the operation curves and counting the degrees of the curves and molar fractions of water in the air and ethylene glycol currents, the mean efficiency determined for the column was 25% [29].

In addition to the calculation of the efficiency of the plates in the absorption column, we performed the analysis of the optimum operation conditions regarding the amount of humidity in ethylene glycol, the effects on the measurements of the drying air dew point, and, mainly, what are the effects on PET flake humidity at the dryer outlet. During the experiment, 11 different conditions of ethylene glycol humidity were tested, with interruption of the replacement with pure material for higher humidities, maintaining only the reflux. Furthermore, PET flake humidity was measured using a gravimetry method, ethylene glycol humidity with an automatic titrator using the Karl Fischer solution, and the dew point of the drying air was continually measured with process sensors [4].

As cited by Elamri [4] and Jabarin and Lofgren [5], the humidity of PET-based polymers before passing by the extrusion process must be at levels inferior to 0.005% (w/w) in case they pass through extruders without vacuum adjustment to avoid molecular degradation. In a thermodynamic analysis, according to studies presented by Silva [17], PET flakes, after going through the extrusion process, can lose up to 0.200 dl/g of intrinsic viscosity (approximately 25% decrease compared to the original PET flake used as raw material) due to thermal and oxidative molecular reactions. However, this viscosity reduction can be higher. Moreover, an additional decrease of 0.010 dl/g happens for each 0.002% moisture content, which impairs the quality of the final product, mainly because of adjustments in the mechanical properties of polyester fibers (especially tenacity and toughness).

With the PET humidity reference during the drying process to be achieved to ensure polymer quality, it was experimentally determined that the humidity of ethylene glycol should be inferior to 1% (w/w) to obtain the air outlet current with a dew point below -27 °C, so that at the end of the drying process, with all flow rates established in the study, the PET flakes in the dryer output current had humidity inferior to 0.005% (w/w), which, considering the PET flakes input current, corresponding to an efficiency of removal of humidity superior to 91%.

Visualization of the humidity removal efficiency of PET flakes in the dryer (superior to 91% if the best experimental condition is used) as a function of the dew point of the drying air, a summary of different experimental conditions can be seen in Table 2. It is important to note that each condition of drying air was obtained by a different condition of the ethylene glycol used in the absorption column (by the concept of mass exchange, the more humid the ethylene glycol, the highest the dew point of the drying air and consequently the lower the drying efficiency of the PET flakes). The ethylene glycol humidity was measured with an automatic titrator with Karl Fisher's solution, the dew point was measured with an RHT-WM sensor from Novus®, the humidities of the PET flakes were calculated using Eq. (4), and the humidity removal efficiency of the PET flakes was a comparison between before and after the dryer.

Table 2. Evaluation of humidity removal efficiency of PET flakes as a function of drying air conditions.

Run	Ethylene glycol humidity (%)	Air Dew point (°C)	Humidity Flakes before the Dryer (%)	Humidity Flakes after Dryer (%)	Humidity Removal Efficiency of PET flakes (%)
1	8.02 ± 0.03	-3.35 ± 0.07	0.057 ± 0.002	0.012 ± 0.001	78.1 ± 2.8
2	6.78 ± 0.03	-4.53 ± 0.07	0.055 ± 0.002	0.010 ± 0.001	80.3 ± 2.8
3	6.03 ± 0.03	-6.35 ± 0.07	0.055 ± 0.002	0.009 ± 0.001	82.3 ± 2.9
4	5.55 ± 0.03	-9.52 ± 0.07	0.055 ± 0.002	0.008 ± 0.001	83.9 ± 2.0
5	3.07 ± 0.03	-17.97 ± 0.11	0.049 ± 0.002	0.007 ± 0.001	84.9 ± 2.1
6	2.85 ± 0.03	-23.27 ± 0.11	0.049 ± 0.002	0.006 ± 0.001	86.2 ± 2.2
7	1.74 ± 0.03	-25.42 ± 0.11	0.055 ± 0.002	0.005 ± 0.001	89.5 ± 2.2
8	1.10 ± 0.03	-27.85 ± 0.11	0.058 ± 0.002	0.004 ± 0.001	91.6 ± 2.3
9	0.65 ± 0.03	-32.32 ± 0.13	0.053 ± 0.002	0.004 ± 0.001	91.9 ± 2.3
10	0.48 ± 0.03	-34.30 ± 0.13	0.053 ± 0.002	0.004 ± 0.001	92.2 ± 2.4
11	0.10 ± 0.03	-38.37 ± 0.13	0.052 ± 0.002	0.003 ± 0.001	93.2 ± 2.4

For graphical visualization and synthesis of the information, we can observe from the graphs in Figure 5 that the lower the ethylene glycol humidity in the absorption column, the lower the dew point of the drying air that will leave the absorption column after the counter-current and consequently the better the moisture removal efficiency of the PET flakes in the dryer.

Figure 5 verifies that the rise in ethylene glycol humidity increased the air dew point and reduced the efficiency of PET flake drying. Since it was possible to reuse ethylene glycol in another process in which humidity did not cause detrimental effects to the product, discarding and renovating this component was an essential factor in process control. Nonetheless, it is worth highlighting that other parameters influence the

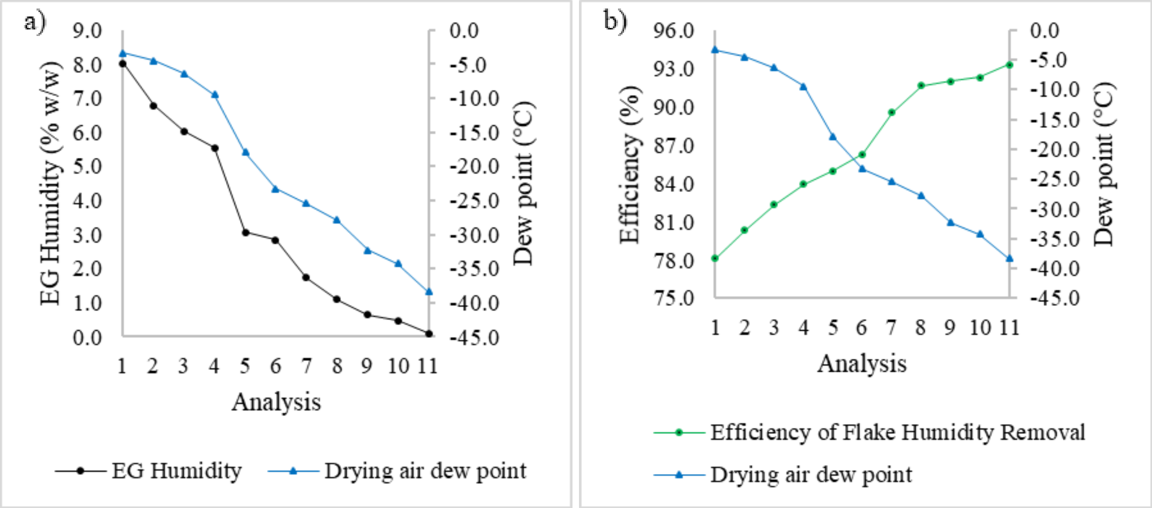

Figure 5. Correlations between (a) ethylene glycol humidity and drying air dew point; (b) drying air dew point and efficiency of PET flake humidity removal.

dew point, such as air temperature, pipe impurities, and the efficiency of the column's mass exchange [14].

Finally, after the energy and mass balances of the proposed study, the construction of a curve between the dew point and the amount of water vapor per cubic meter of air was performed at 175 °C considering a relative air humidity between 40% and 50% at an altitude of approximately 1260 m above sea level (Figure 6). This study provided data that enable equating the mass balance of PET flake humidity removal by the drying action of hot air and with low dew point, besides proving with mass data why a drying air with low dew point (lower amount of water present) presents higher efficiency of humidity removal from solid particles even being at high temperatures [24].

Figure 6 shows the model described by Eq. (5), allowing the extraction of the water vapor present in the air depending on the dew temperature of the drying air. The combination of heating and a low dew point of the drying air will promote a process of mass transfer from the particle to be dried from the mass exchange with the air [14]. In the case of PET, when the flakes are surrounded by air with a dew point < -27 °C at 175 °C, the vapor pressure differential between the surface of the flakes and the drying air will be strengthened, and once the polymer is heated and the attraction between the water molecules and the polymer chains is sufficiently reduced, the water molecules will be released, starting the migration toward the surface of the flakes, which are rapidly dragged through the air:

$$\text{Mass of steam in the air}\left(g/m^3\right)=4.437e^{0.067\cdot T_{dp}} \qquad (5)$$

where the mass of steam in the air is obtained in g/m^3, T_{dp} is the temperature of the dew point of the air (°C)

For the developed model, it becomes possible to compare the saturated vapor, relative humidity, and absolute humidity equations to obtain the amount of water vapor in the drying air under the drying condition studied. Furthermore, comparing with the correlations, models, and tables presented in the ASHRAE Handbook of Fundamentals [30], it was possible to verify that Eq.(5) is in accordance with the thermodynamic models present in the literature, that is, it can be used within the conditions studied for determining the amount of vapor in the air.

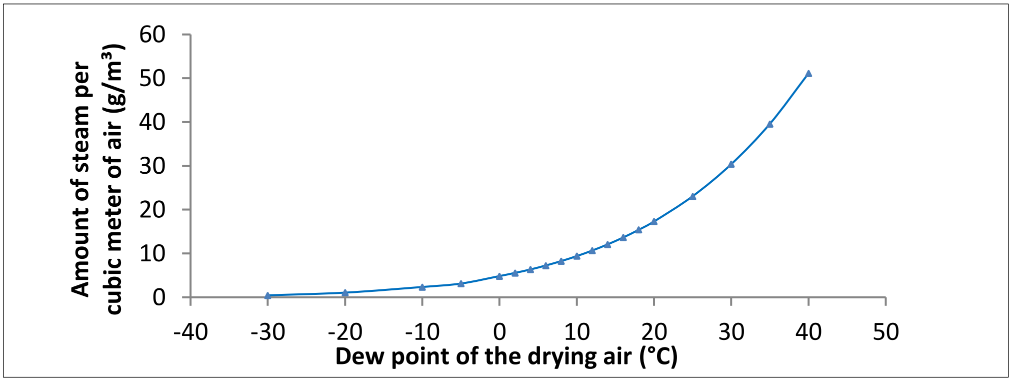

Figure 6. Correlation between dew point and amount of steam per cubic meter of air.

CONCLUSION

In this work, it was possible to apply the concepts of mass and energy transfer in the study of the process variables of a factory for the production of recycled polyester fibers. By analyzing the heat exchangers and absorption column, temperature, flow rates, and operational efficiencies were obtained to guarantee the properties of the PET flakes used as process raw materials. As important points, the efficiency of the absorption column plates was determined at 25%. Furthermore, the humidity of ethylene glycol for absorption should be inferior to 1% (w/w) to guarantee a dew point < -27 °C at 175 °C of the drying air introduced in the dryer, which finally promoted the removal of 91% of PET flake humidity for values < 0.005% (w/w). Finally, a model to determine the amount of water vapor present in the drying air was also obtained as a function of its dew point temperature, which provided data for a future mass balance equation considering the mass exchange between the PET flakes and the drying air.

ACKNOWLEDGMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES) - Finance Code 001.

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NAUČNI RAD

STUDIJA O IZMENJIVAČIMA TOPLOTE I INDUSTRIJSKOJ APSORPCIJSKOJ KOLONI ZA SUŠENJE POLIETILENTEREFTALATA

Ova studija predlaže korišćenje bilansa mase i Makejb-Tileove (McCabe-Thiele) metode u apsorpcionoj koloni za uklanjanje vlažnosti vazduha sa etilen glikolom i energetskih bilansa u izmenjivačima toplote za određivanje optimalnih uslova rada fabrike za proizvodnju recikliranih poliesterskih vlakana od pahuljica polietilen tereftalata (PET). Procena ovih mašina je uključivala kombinaciju veličina, kao što su temperatura, brzina protoka, specifična toplota i operativna efikasnost, kako bi se garantovalo ispravno podešavanje fizičko-hemijskih svojstava fluida i procesnih materijala. Utvrđena je efikasnost apsorpcione kolone od 25%. Konstruisan je dijagram koji povezuje vlažnost etilen glikola, tačku rose vazduha za sušenje i efikasnost uklanjanja vlage iz sušare za sušenje PET pahuljica radi definisanja najprikladnije operativne konfiguracija. Na osn ovu grafikona, utvrđeno je da vlažnost etilen glikola za apsorpciju treba da bude niža od 1% (v/v) da bi se garantovala tačka rose < -27 °C pri temparturi vazduha na ulazu u sušaro od 175 °C, što bi konačno promovisalo uklanjanje sa efikasnošću koja je veća od 91% i vlažnošću PET pahuljica < 0,005% (v/v).

Ključne reči: vlažnost, tačka rose, PET pahuljice, polyester, Makejb-Tileov metoda.