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Optimizing the production technology of eco-friendly foam polyurethane panels on the continuous line

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Abstract. With the preeminent features of polyurethane (PU) panels such as sound insulation, heat insulation, fire resistance, high load capacity, light weight, high aesthetics, especially they are simple to use and easy to assemble and move, so new PU panel is now the first choice for construction projects. In this work, the authors study a new generation physical foaming agent cyclopentane that is environmentally friendly and does not destroy the ozone layer at all. The effect of the content of physical foam cyclopentane on free expansion density, reaction time of rigid polyurethane foam (R-PUF), and reaction time values (cream time, gel time, tack-free time, and rise time) were investigated and evaluated. The closed-cell morphology and size of the R-PUF samples with an increase in cyclopentane concentrations from 0 % to 20 % were observed by optical microscope images and the closed-cell size distribution chart was determined by IT3 software. In addition, the physical and mechanical properties of dimensional stability and compressive strength were analyzed to evaluate the quality of the expanded R-PUF insulation in the mold using a cyclopentane physical foaming agent. Experimental procedures according to Taguchi's analysis on a continuous production line were aimed at giving optimal parameters for the industrial PU panel manufacturing process. The research results provide an excellent reference value for manufacturers to further improve the performance and quality of PU panels.

Keywords: Polyurethane, PU panel, Cyclopentane, Rigid polyurethane foam.

Classification numbers: 5.7.2., 5.6.2., 5.1.1.

1. INTRODUCTION

Polyurethane (PU) belongs to the group of polymer materials with high strength and mechanical properties, in addition to the ability to combine with a variety of materials with different properties such as paints, elastomers, liquid coatings, insulators, elastomers, etc. so it is widely applied in biomedical, construction, automation, textile and many other fields. In addition, PU can be synthesized from many different sources of raw materials, so it has many different properties and is classified into many types based on its properties such as hard foam, soft foam, thermoplastic, binder, adhesives, coatings, sealants, and elastomers [1].

Today, environmental impacts and climate change are becoming the top concern of mankind. Due to the development needs of society, humans have released into the atmosphere polluting emissions such as SO_x, NO_x, CH_4, and other toxic wastes through daily production activities. To reduce the impact on the environment, physical foaming agents are used in the polyurethane manufacturing industry, especially polyurethane rigid foam (R-PUF). In which, R-PUF is classified as a good insulation material and is commonly used today. It belongs to the group of optimal measures in saving energy sources [2, 3]. R-PUF has a high cross-linking density, therefore, has high stiffness, very low ductility, and cannot be fully recovered after compression [4, 5]. The important property of R-PUF is that in its structure there is a closed foam content (containing gases with low thermal conductivity), above 90 %. Therefore, R-PUF has superior thermal insulation compared to other similar insulation materials [6, 7].

However, the biggest concern in the PU foam insulation industry is to find an environmentally friendly physical foaming agent that still gives high working efficiency. The first types of physical foaming agents used in the industrial production of R-PUFs were chlorofluorocarbons (CFCs), typically trichlorofluoromethane (CFC11) which are commonly used due to their low molecular weight, boiling point close to room temperature, non-flammable, low toxicity and low thermal conductivity [8, 9]. But CFC11 has been identified as the main cause of ozone depletion with an ozone depletion potential (ODP) of approximately 1 and it causes the greenhouse effect with a global warming potential (GWP) of up to 4600, thousands of times higher than that of CO_2 [10, 11]. The substitute compound for CFC11 used was then 1,1-dichloro-1-fluoro ethane (HCFC-141b) [12]. However, with ODP and GWP indices of 0.11 and 630, respectively, this H-CFC also contributes to ozone depletion and increased greenhouse effect. The requirement for the PU manufacturing industry is to use foaming agents that completely replace CFCs and are environmentally friendly. Cyclopentane with ODP = 0 and GWP = 11 can replace all kinds of CFCs foaming agents. Besides, with a relatively low density, cyclopentane is perfectly suitable as a foaming agent in the manufacturing process to create hard PU for products with high porosity, stable mechanical properties, and high compressive strength [13, 14].

In recent years, many domestic scientists have conducted research and found ways to apply porous PU materials, but the research results are still very limited and only at the laboratory scale. The implementation of research in the production of these special materials has just stopped at the experimental production stage, so the scope of use, as well as the value of the product, have not been properly evaluated. With the purpose of introducing the technology of manufacturing porous materials based on PU materials to create useful, environmentally friendly materials that can be applied in industry and life, the authors went into experimental research according to the Taguchi method to provide an optimal set of parameters for the production of environmentally friendly PU Panels on a continuous line.

2. POLYURETHANE

Recent studies have mainly focused on porosity morphology, influence of some parameters on the PU foaming process, and their influence on some quality parameters [15]. There have been no studies on the effect of the foaming process on the quality parameters of R-PUF materials on continuous production lines (density, hygroscopic ratio, tensile strength, compressive strength). Studies on the design, manufacture, and influence of the technological system on the PU sheet manufacturing process on real machine systems are still lacking and incomplete.

To overcome this problem, the authors followed Taguchi's experimental analysis method to provide optimal parameters for the continuous PU panel production process to create productivity and quality of PU panels, thereby achieve the goal of optimizing the PU sheet manufacturing process.

PU is a product made by reacting polyisocyanates with polyalcohols. As a result, isocyanates react with alcohol to produce amines. But when reacted with alcohol, it produces an amino carboxylic ester called urethane.

$$\mathrm{R-N{=}C{=}O + R_1OH \rightarrow R-NH-COOR_1}$$

If mono isocyanate and monatomic alcohols are substituted for diatomic alcohols, straight polyurethanes are produced. (Tri-isocyanate and Triol) give products with spatial structure.

$$\mathrm{nO{=}C{=}N-R-N{=}C{=}O + nHO-R_1-OH \rightarrow \left[OCNH-R-NH-COOR_1\right]_{\mathit{n}}}$$

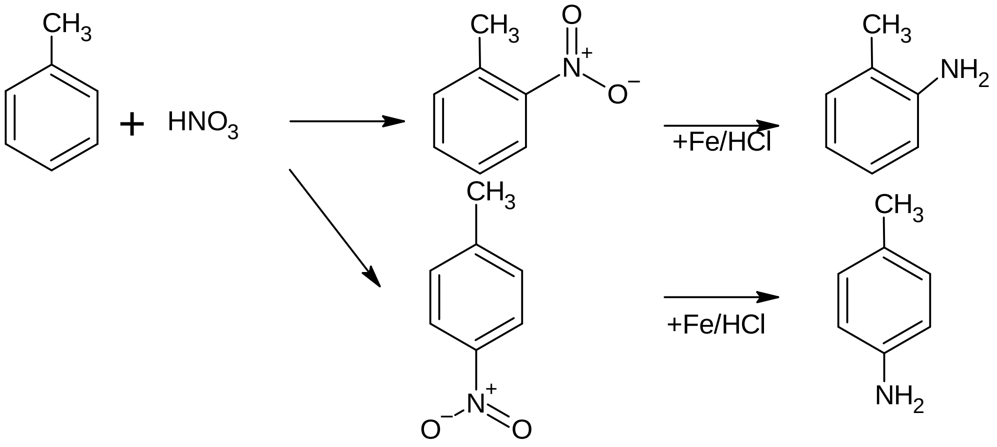
Research by Buyer *et al*. [16] created a straight chain polyurethane suitable for spinning. Polyurethane fibers have properties similar to polyamides because they contain amide groups (−NH−CO−) capable of forming hydrogen bonds, so the force between the molecules is large, but they are softer than polyamides because the main chain of the polymer contains oxygen atoms.

The basic method is based on the reaction of isocyanates and tri-isocyanates in a solvent medium (toluene, o-chlorobenzene, p-chlorobenzene) under temperature conditions of 0 - 150 ℃).

$$\mathrm{H_2N-R-NH_2 + 2COCl_2 \rightarrow OCN-R-NCO + 4HCl}$$

Isocyanates and tri-isocyanates are substances with a pungent and toxic odor.

Compounds containing the –OH group are used to produce glycols, straight and branched polyethers.

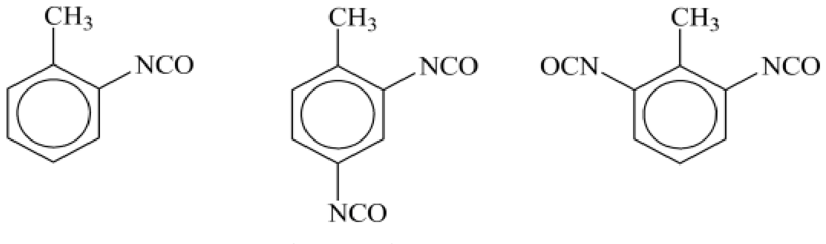


Isocyanate materials are synthesized based on organic compounds:

$$\mathrm{R_2SO_4 + HNCO \rightarrow RNOC + K_2SO_4}$$

$$H_2N-R-NH_2 + HCl \rightarrow H_2N-R-NH_2.HCl$$

$$H_2N-R-NH_2.HCl + COCl_2 \rightarrow H_2N-R-NCO + HCl$$



(2,4 TDI) (2,6 TDI)

The resulting reactions give the following products:

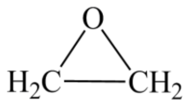
In particular, it is possible to separate 2.4 TDI and 2.6 TDI, but research in industrial production often uses a mixture in which both 2.4 and 2.6 TDI exist with the ratio of 80/20 or 65/35 isocyanates straight and loop form HNDI, IPDI, MDI, NDI.

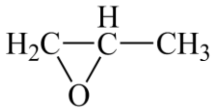
There are about 450 types of Polyol materials containing mobile hydrogen atoms. In principle, all products containing two mobile hydrogen atoms are used for the synthesis of polyurethanes. Compounds containing OH, NH, or COOH groups are the most commonly used groups to make $H(O\text{-}CH_2\text{-}CH_2)_nOH$ and $H(O-CH_2-)_nOH$:

$$HO\left(CH_2-O\right)_n H \rightarrow H(O\text{-}CH_2\text{-}CH_2)_nOH$$

$$HO\left(C_3H_6-O\right)_n H \rightarrow H(O-CH_2-)_nOH$$

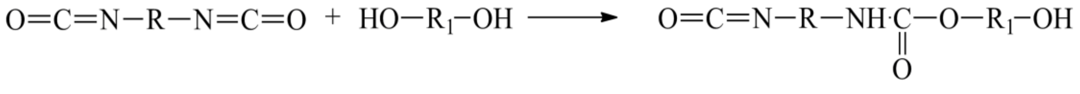
However, in the process of denaturing the product, it is also used additionally:





Polyol is a compound with a small molecular weight, convenient for synthesis. In addition to the multifunctional types with a small molecular weight, two types of polyester polyol and polyether polyol are mainly used.

Structures with straight chains or polyol polyester rings are used more sparingly with yields close to 10 %. Types of polyesters and polyester products, depending on the purpose of use, have molecular weights from 200 to 2000. Compounds with a low molecular weight are often used to make flexible or rigid foam:



$$O{=}C{=}N-R-N{=}C{=}O + HO-R_1-OH \longrightarrow O{=}C{=}N-R-NH\cdot\underset{\underset{O}{\|}}{C}-O-R_1-OH$$

The activity depends on the N=C=O group. High molecular weight products are used to make elastomers, paints, and hard and soft adhesion products.

3. CALCULATION OF SPEED AND FLOW OF PU NOZZLE ON PRODUCTION LINE

3.1. Circuit consisting of m equal parallel flowing branches

The flow chart of PU injection on the production line is shown in Fig. 1. In which, Pn is the pressure in the injection hole; d_1 is the nozzle diameter; p is the pressure at the injection site z; d_2 is the diameter of PU outlet hole where m is the number of holes determined by $m = x \times y$, x is the number of holes per row; y is the number of rows of holes; z is the injection distance. When switching each hole as 1 resistor, then the circuit model includes m resistors R_2 connected in parallel, R_1 is the input resistance, the relationship between p and P_N, R_1, R_2 is determined as follows:

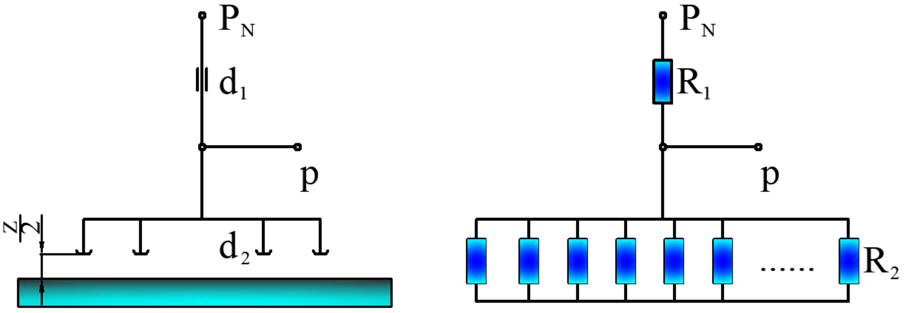
$$p = \frac{P_N}{R_1 + R_{td}} \times R_{td} \tag{1}$$

$$R_{td} = \frac{R_2}{m} \tag{2}$$

$$p = \frac{R_2 \times P_N}{\left(R_1 + \frac{R_2}{m}\right) \times m} = \frac{P_N}{\left(1 + \frac{m \times R_1}{R_2}\right)} \tag{3}$$

$$R_1 = \frac{1}{F_1^2}; R_2 = \frac{1}{F_2^2} \tag{4}$$

$$\Rightarrow \frac{R_1}{R_2} = \frac{F_2^2}{F_1^2} = \left(\frac{4d_2}{d_1}\right)^2 \times \left(\frac{z^2}{4}\right) \tag{5}$$



a) b)

Figure 1. Process flow diagram for continuous PU Panel spraying.

The equation represents each relationship between the pressure at the nozzle P and the source pressure P_N.

$$p = \frac{P_N}{\left(\frac{a \times z}{\sqrt{m}}\right)^2 + 1} \tag{6}$$

where

$$a = \left(\frac{4 \times d_2}{d_1}\right)$$

It can be seen that the injection pressure P depends on the source pressure P_n, d_1, d_2 and the injection distance z and the number of holes m.

Calculate the maximum gear ratio:

$$i_{max} = \frac{-0.65 \times a \times P_N}{\sqrt{m}} \tag{7}$$

Spray limit z: $$z_1 = \frac{0,4.\sqrt{m}}{a};\ z_2 = \frac{0,8.\sqrt{m}}{a}$$

Compared with the case of a 1-hole nozzle with a single-flow nozzle, the case of a 1-hole nozzle with m parallel-flowing branches has a reduction ratio of $\sqrt{\text{m}}$ times and a working range of $\sqrt{\text{m}}$ times.

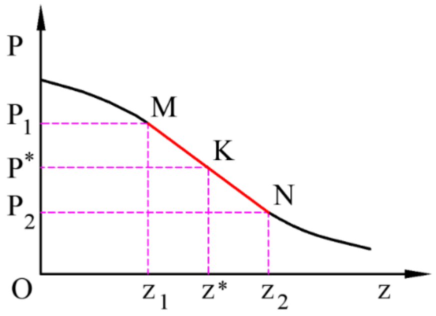


Figure 2. Pressure relationship characteristic curve P and distance Z.

The characteristic curve of the pneumatic conversion is shown in Fig. 2. The characteristic curve with the inflection point at K and the segment around K is considered to be a linear segment. K is the reference point to determine the working segment of the nozzle. The MN section is the working section of the nozzle, the part before the M point has high pressure but the flow rate is high, so the adhesion of the PU chemicals is not good, the part after the N point has low pressure so it should not be used for work. Therefore, the most suitable segment for spraying is the height in the range Z_1- Z_2.

3.2. Spray flow on the production line

On a solution flow with a constant pressure P_1, the constriction at the cross-section F_1 will impede the flow of the solution through it. After flowing through F_1, the pressure drops to P_2, the flow-through F_1 is Q. According to the Bernoulli equation, we have the equation to determine the flow through F_2:

$$\left[\begin{array}{ll} Q = \mu P_1 F_1 \sqrt{\dfrac{2k}{(k-1)\,gRt}\left\{\dfrac{P_2}{P_1}\right\}^{\frac{2}{k}} - \left\{\dfrac{P_2}{P_1}\right\}^{\left(\frac{k+1}{k}\right)}} & \text{when } \dfrac{P_2}{P_1} \geq \beta \\ Q = \mu P_1 F_1 \sqrt{\dfrac{2k}{(k-1)\,gRt}\left\{\dfrac{2}{k+l_1}\right\}^{\left(\frac{2}{k-1}\right)}} & \text{when } \dfrac{P_2}{P_1} \leq \beta \end{array}\right. \tag{8}$$

where μ: flow coefficient refering to the compressive strength of the flow; g: acceleration due to gravity (g = 9.81 m/s^2); R: solution constant; t: the absolute temperature of the chemical; P_1, P_2:

absolute pressure of chemicals before and after obstructing F_2; k: adiabatic index (k = 1.4); flow critical point: β = 0.528.

Table 1. Basic parameter table of nozzles.

Number	Parameters	Calculation formula	Calculation results
1	p	$\frac{P_N}{\left(\frac{az}{\sqrt{m}}\right)^2 + 1}$	P = 0.797
2	i*	$-0.65P_N.a\frac{1}{\sqrt{m}}$	i* = -0.07
3	z*	$0.6\frac{1}{a}\sqrt{m}$	z* = 41.396
4	Z_1	$0.4\frac{1}{a}\sqrt{m}$	Z1 = 27.597
5	Z_2	$0.8\frac{1}{a}\sqrt{m}$	Z2 = 55.195
6	p*	$0.75Pn.\frac{1}{\sqrt{m}}$	p* = 1.148

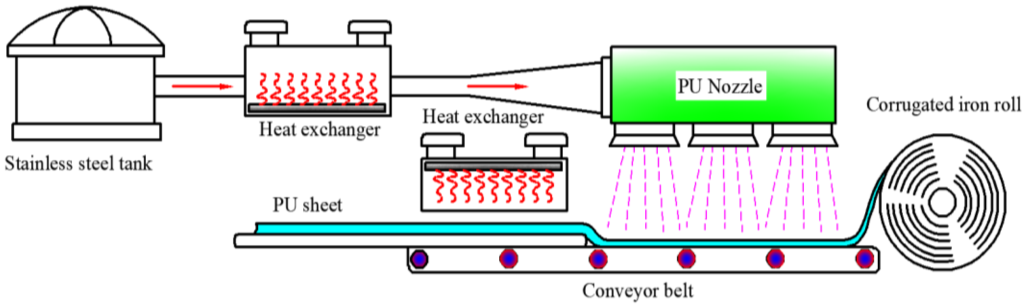


Figure 3. Diagram depicting the manufacturing processes used to create rigid polyurethane foam insulation.

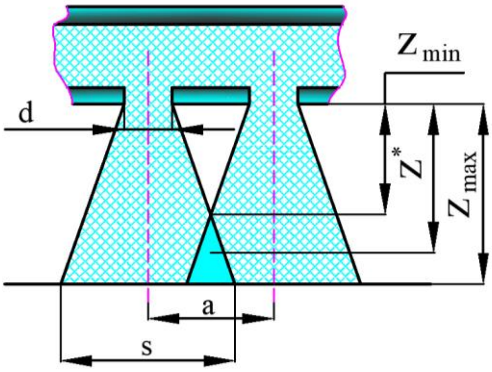


Figure 4. Diagram of PU injection flow calculation.

For the most effective cleaning, the pressure P and spray distance L will be within a range of the most reasonable values for each type of nozzle with the basic parameters described in Table 1. A schematic representation of the manufacturing processes used to create rigid polyurethane foam insulation is shown in Fig. 3. The method of determining the spray distance is described as shown in Fig. 4. If L is too small, the machine will overload the pressure causing danger to workers and equipment. But if L is too large, the cleaning efficiency is reduced. In the working condition P = 7 - 8 (bar), it can be determined L = 100 - 200 (mm).

4. EXPERIMENTAL SETUP

Through the requirements of the experimental steps, adjust the density and volume of chemicals. After weighing, test the chemical pressure pump system to ensure that there will be no problems during the experiment. Clean the valve head, electrical circuits, chemical stirrer and measure the temperature of the chemical when it is pumped. Check and replace empty chemical tanks with new ones to ensure the most convenient testing process. After testing the chemicals and nozzles, adjust the temperature of the presser to satisfy the requirements of the test through the presser temperature control panel. Replace defective and deformed molds, adjust the distance between two injection mold surfaces.

After checking and adjusting the temperature, chemicals, compressed air, start to boot the whole working system. The experimental processes on the continuous production line are visually depicted as shown in Fig. 5, the products after the experimental steps are described in Fig. 6 and experimental steps are as follows:

Step 1: Roll the waves. According to the requirements of the test, the corrugated iron is cut to size and then put into the corrugated iron mill to adjust the die and rolling speed for optimal performance.

Step 2: Chemical treatment. Measure chemical temperature and compressed air flow, adjust the chemical stirring chamber for stable chemical circulation, handle chemical problems during the experiment.

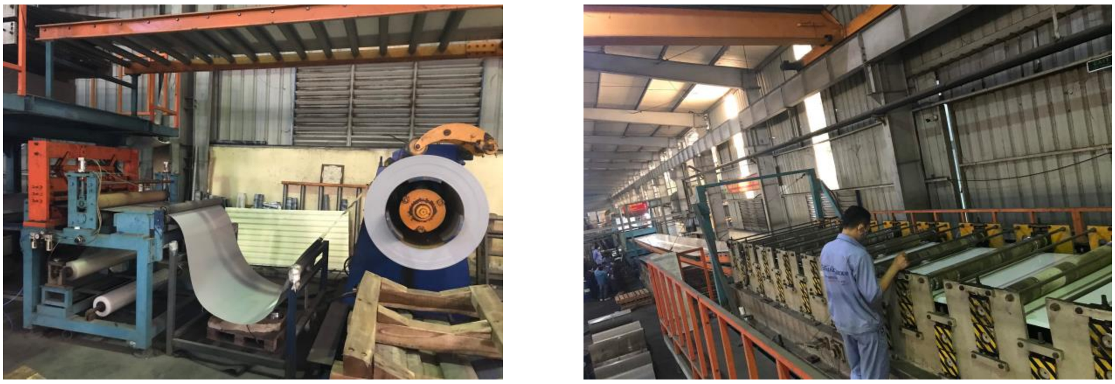
Step 3: Adjust the chemical injection system and press the table. Adjust chemical parameters (ratio of chemical composition, chemical temperature); parameters of the hydraulic press table (pressing temperature, pressing force, etc.) so that the quality of the test product is the best.

Step 4: Put corrugated iron into the pressing table and proceed to work. After being rolled, the sheet is put into the press, sprayed with an appropriate amount of chemicals. Carry out adjustment of presser table to ensure technical requirements.

Step 5: Clean. After pressing, the corrugated iron is cleaned of the remaining chemicals and burrs, polishing the PU part at the top of the corrugated board and the sides of the corrugated iron for easier assembly.

Step 6: Pack. The cleaned corrugated iron will be transferred to the product packaging stage.

Taguchi method is an experimental optimization method that is widely used in the industrial design proposed by Taguchi [17]. According to the Taguchi method, experiments are performed by orthogonal array on the basis of the principle that pairs of states of control elements in any two columns have a similar probability of occurrence [18]. In a set of technological parameters, the measuring parameters of each factor of concern, such as compressive strength, tensile strength, hygroscopicity, heat transfer coefficient must be measured many times to ensure a precise reflection of the effects of technological factors on the output of interest.

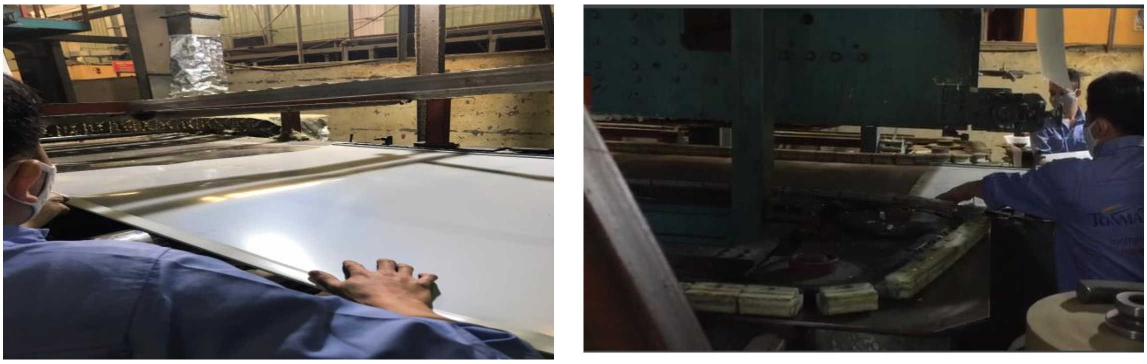


Flattening corrugated iron

Checking out the corrugated ironing process

Pressing the top of corrugated iron

Test spraying and cleaning the nozzle



Putting corrugated iron into the fixture

Positioning the corrugated iron into the PU injection mold

Figure 5. Experimental process on the continuous production line.

Experimental processes were conducted according to the Taguchi L9 method with different parameters of pressing speed, plate temperature, and chamber temperature as described in Table

2. The test results show that the quality parameters at different outputs corresponding to different experimental conditions are different.

Table 2. Experimental parameters according to Taguchi L9.

Numbers	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Pressing speed (m/min)	5	4	4	3	4	5	3	4	5
Plate temperature (°C)	50	65	50	65	65	65	75	75	75
Chamber temperature (°C)	30	30	25	25	25	25	30	20	20

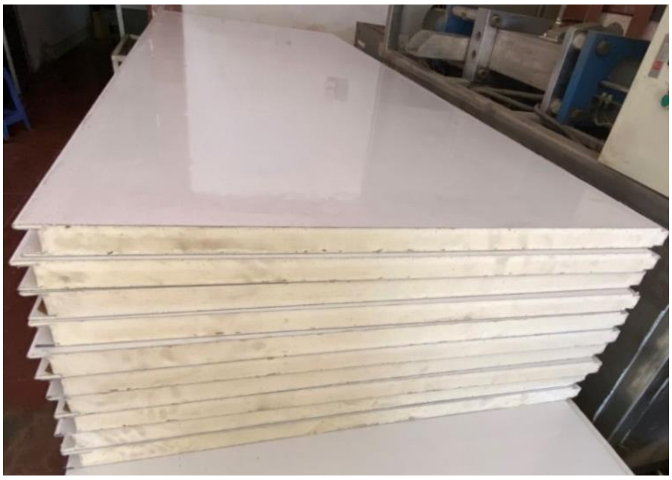


Figure 6. Experimental product.

5. RESULTS AND DISCUSSION

The experimental results of the factors affecting the density, as described in Fig. 7, show that the influence of the corrugated iron layer temperature and the chamber temperature on the density G is the largest, the influence of pressure is minimized to density G. Table 3 shows the combination of density maximization factor (G) levels over the tested region. The analysis results indicate the area where optimization will be performed. Thereby it is possible to set the value of one or more factors to a constant, by setting low and high limits for that value.

Table 3. Density optimization (G).

Coefficient	Min	Max	Optimal	Unit
Pressing speed (V)	3.0	5.0	4.89	m/min
Corrugated iron layer temperature (TT)	50.0	75.0	50.0	°C
Chamber temperature (TH)	3.0	5.0	4.89	°C

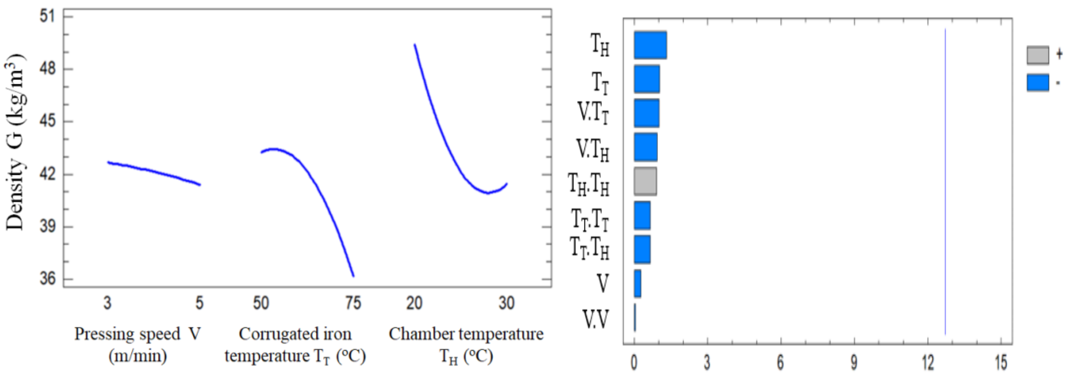


Figure 7. Graph of factors affecting the density of G (kg/m^3).

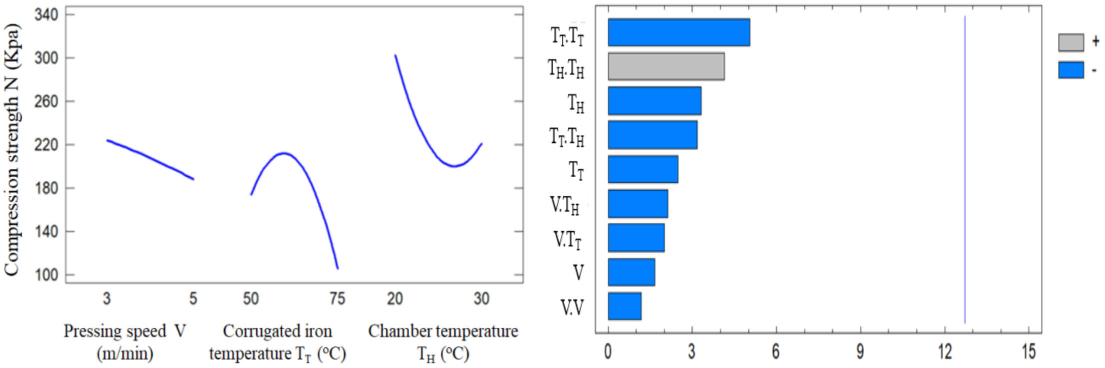


Figure 8. Graph of factors affecting compressive strength and influencing factors.

The experimental results of the factors affecting the compressive strength are described in Fig. 8. The survey results show that the influence of the corrugated iron layer temperature and the chamber temperature on the compressive strength is the largest, the influence of pressing speed is minimum. The analysis results in Table 4 show that the pressing speed is 4.43 (m/min), the corrugated iron layer temperature is 62.12 °C, and the chamber temperature is 20 °C for the best compressive strength.

As shown in Fig. 9, the survey results show that the corrugated iron layer temperature, the chamber temperature, and the pressing speed have a great influence on the tensile strength K. The analysis results show the optimal parameters of the machining technology as described in Table 5. It can be seen that the greatest tensile strength is achieved at a pressing speed of 3.65 (m/min), corrugated iron layer temperature of 50 ^{o}C, and chamber temperature of 30 ^{o}C.

Table 4. Optimized compressive strength N (kPa).

Coefficient	*Min*	*Max*	*Optimal*	*Unit*
Pressing speed (V)	3.0	5.0	4.43	m/min
Corrugated iron layer temperature (T_T)	50.0	75.0	62.12	°C
Chamber temperature (T_H)	20.0	30.0	20.0	°C

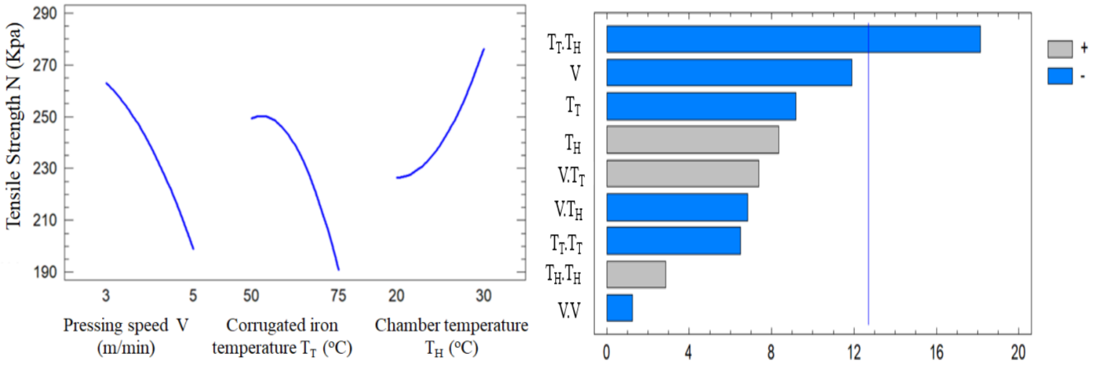


Figure 9. Graph of factors affecting tensile strength and coefficients of regression function.

Table 5. Optimizing tensile strength K (kPa).

Coefficient	Min	Max	Optimal	Unit
Pressing speed (V)	3.0	5.0	3.65	m/min
Corrugated iron layer temperature (T_T)	50.0	75.0	50.0	°C
Chamber temperature (T_H)	20.0	30.0	30.0	°C

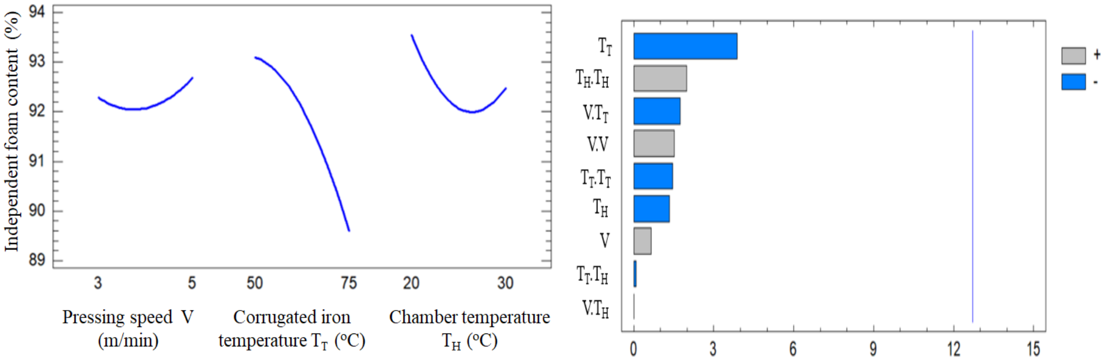
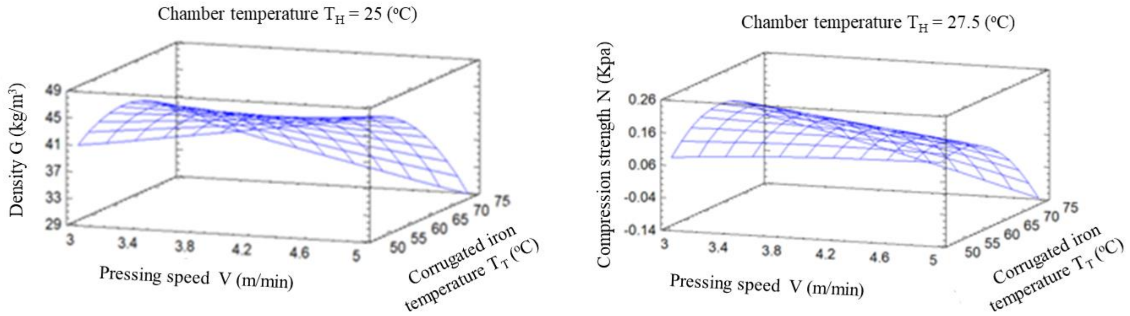


Figure 10. Graph of factors affecting independent foam content and regression coefficients.

The experimental results of the independent factors that cause the amount of foam described in Fig. 10 show that the influence of the corrugated iron layer temperature is the largest on the foam content B, the chamber temperature and the pressing speed have less influence. In Table 6 the analysis results show that the pressing speed of 5 m/min, the corrugated iron layer temperature of 50 °C, and the chamber temperature of 30 °C give the highest independent foam content.

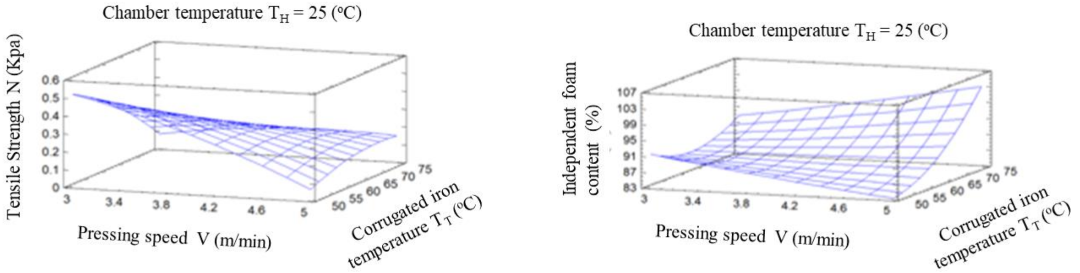
Table 6. Independent foam content optimization.

Coefficient	*Min*	*Max*	*Optimal*	*Unit*
Pressing speed (V)	3.0	5.0	5.0	m/min
Corrugated iron layer temperature (T_T)	50.0	75.0	50.0	°C
Chamber temperature (T_H)	20.0	30.0	30.0	°C



a) Effect of technological parameters on the density G

b) Effect of technological parameters on the Compression strength



c) Effect of technological parameters on the Tensile Strength

d) Effect of technological parameters on the Independent foam content

Figure 11. Relationship between technological parameters and density, compressive strength, tensile strength and water absorption rate.

The analysis results are shown visually as depicted in Fig. 11. It can be seen that as the pressing speed increases, the density decreases, and when the temperature of the corrugated layer increases, the density increases, but to 57 °C, the density will decrease. In addition, as the chamber temperature increases, the density decreases, but to 28 °C, the density will increase.

5. CONCLUSION

In this work, methods of determining chemicals used in manufacturing PU panels, injection flow calculation, and technological parameters in the PU Panel production line are continuously given. In which, the problems of density G, the durability of PU layer, and the ability to absorb moisture and absorb water have been optimized along with the problem of safe chemicals to the environment. Based on the experimental results according to the Taguchi method, the article has presented the factors affecting the quality and productivity when manufacturing PU panels on a continuous line. The experimental processes have produced highly commercial PU panels that have met the requirements of actual use. The main results when analyzing and optimizing the factors affecting the quality indicators are described as follows:

- The experimental results show that the influence of corrugated iron temperature and chamber temperature on the density G is the largest, the effect of pressing speed is the smallest on the density G. The parameters for the corresponding optimum density with technological conditions are: pressing speed 4.89 m/min; corrugated iron layer temperature 50.0 °C; chamber temperature 20.63 °C.

- The analysis results show that the influence of the corrugated iron layer and the chamber temperature on the compressive strength is the largest, the effect of pressing speed is the smallest. The optimal compressive strength corresponds to the following technological parameters: pressing speed 4.43 m/min; corrugated iron layer temperature 62.12 °C; chamber temperature 20 °C.
- The analysis results show that the influence of corrugated iron layer temperature is greatest on foam content, chamber temperature and pressing speed have less influence. The optimal compressive strength results correspond to the following technological parameters: pressing speed 5 m/min; corrugated iron layer temperature 50 °C; chamber temperature 30 °C.

The obtained results provide excellent reference value to further improve the productivity and quality of PU panel factories.

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Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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