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APPLICATION OF A FUZZY CONTROLLER IN THE PROCESS OF AUTOMATED POLYETHYLENE FILM THICKNESS CONTROL

Abstract

The present article aims to describe the design of a fuzzy controller used for automated control of the thickness of the extruded polyethylene film effected by the adjustment of the actuator in the cooling ring. In order to determine whether the designed controller operates properly, a model extruder was created and a simulation study was carried out. The Simulink programming environment integrated with Matlab was used for the development of the fuzzy controller and the simulation. The conducted simulation study demonstrated that the implementation of the designed controller would enable the adjustment of thickness on the perimeter of the film tube and quick reaction to possible departure in the assumed film thickness in mass production.

1. INTRODUCTION

Decisions taken with regard to the production process are very complex. It is caused by a large, hard to define number of factors influencing decision-making and the fact that they are human decisions. The value of the same data or indicators can be variously assessed by different people. Having to account for the subjective uncertainty of decision-making is a serious drawback. Today, the system of decision-making can be optimized by the application of fuzzy inferencing (Lutomirski, Mazur & Strzelecki, 1995). Fuzzy inferencing is used in many fields of activity. It is found in computer-controlled systems for operating machines, robots and vehicles, data exploration tasks or creation of expert systems (Wachowicz, 2002). The main principle of fuzzy logic is a departure from the conventional division of responses into true (1) or false (0). Fuzzy logic makes it possible to calculate the degree of membership; that is, any state between 1 and 0. In this method, values and conditions relating to a certain phenomenon are expressed linguistically, not numerically. The output, in turn, can be calculated on the basis of comparison and correlation of these conditions (Lofti, 1988). Thanks to satisfying results of the application of the algorithm in many areas of technology, fuzzy logic is often selected in regulation systems. Fuzzy logic enables smoother

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regulation and in the case when some information is missing, it yields better decisions than typical numerical methods (Ciloglu, 2010). Fuzzy inferencing enables the control of non-linear objects when their non-linearity renders their description by means of analytical methods difficult. Fuzzy control has the following characteristics:

- it enables the modeling of highly complex nonlinear dependencies where analytic description is difficult or impossible,
- it enables the application of adaptive parameter choice strategy on the basis of learning dataset (ANFIS – Adaptive Neuro-Fuzzy Inference Systems),
- it is flexible and it tolerates imprecise data,
- it is able to perform parallel calculations,
- it can be combined with conventional control systems (Driankov, Hellendoorn & Reinfrank, 1996).

The need to design algorithms for production scheduling and control has led to an increased interest in artificial intelligence tools. One of its calculation methods is fuzzy logic, whose application is very broad. The fuzzy logic algorithm is invaluable in solving numerous optimization problems, including engineering issues connected with the operation of production plants and other machines (Pasupathi Nath & Nishant Balaj, 2014).

Item (Czapaj, Kamiński & Benalcazar, 2020) on the reference list presents some thoughts on fuzzy logic and includes possible applications of fuzzy logic, e.g. in electrometry and industrial heating, control of cooling devices and mechanical hard disks, image processing and speech recognition. The authors of (Zou, Yan, Wang & Zhang, 2020) present the application of fuzzy logic algorithm in controlling the operation of photovoltaic systems. The study offers an improved algorithm of maximum power point tracking based on the principle of fuzzy control and differential flatness control theory. Firstly, due to the application of differential flatness control, the output voltage of a PV cell increases linearly and a maximum power point voltage is found. Then, a fuzzy logic algorithm is used to stabilize the PV cell output voltage. The applicability of the algorithm is verified by MATLAB simulations and an equipment experiment. An interesting application of fuzzy logic in motion control is described in (García-Martínez et al., 2020). In this study, a new strategy is presented for tuning a proportional-integrative-derivative (PID) fuzzy logic controller (FLC), which relies on direct fuzzy relations in order to compute PID constants. Another interesting and innovative approach is presented in (Skobiej & Jardzioch, 2019). This paper discusses the ways in which the design of a given fuzzy logic system influences the construction of rules for a particular agent. The article focuses on the problem of coding the agent's rules and modification of the coding by genetic algorithm. The agent's task is to make an effective decision on which order, from the set of the awaiting orders, should be transferred into a production zone next. The decision is based on the response of the fuzzy logic system.

The objective of the present study is to introduce the design of a fuzzy controller used for automated control of thickness of the extruded polyethylene film effected by the adjustment of the actuator in the cooling ring. In order to determine whether the designed controller works properly, an operational model of an extruder was developed with the application of fuzzy control. The paper is divided into five sections. The first one includes a review of the literature on the applications of fuzzy logic to optimize the operation of devices and processes. Section two presents the research problem connected with the control of a PE film extruder. In section three, the developed fuzzy controller used for the adjustment of the actuators in the cooling ring is described. Section four presents the results of tests used to indicate whether the developed controller adjusting the actuators in the cooling ring works properly, which were carried out in the operational model of the extruder. The operation of the controller was validated in the MATLAB and Simulink environments. The final section of the paper presents conclusions and suggestions for further study.

2. RESEARCH PROBLEM

One of the major difficulties that arise in the operation of a PE film extruder is the retention of film thickness on the perimeter of the tube, as in the next step the PE film is welded to produce plastic bags. The bags are tested for weld seam resistance. If the film's thickness is not even on the perimeter of the tube, it will not be resistant enough to pass the tests. The bags will crack primarily on the weld seams, generating production waste and increasing the cost of production process. It can therefore be assumed that failure to retain an even thickness of the film will result in:

- decreased mechanical resistance of the PE film and products made of it,
- increased raw material consumption,
- decreased quality of the film on the yarn,
- lower efficiency or impossibility of running technological processes which use PE film (printing, welding) (Lutomirski, Mazur & Strzelecki, 1995).

There are two types of deviation in PE film thickness:

- deviation of the mean value from the nominal value of the film thickness measured along the axis of the extruded film. This is usually caused by wrong relation between the speed of the extruder screw and the extraction speed. It follows from a lack of stability of the speeds; a variable bulk density of raw material, pressure pulsation and interrupted flow of raw material leading to fluctuation in temperature in cylinder and head heating zones, resulting in flow resistance variation. The latter is significant for extruders with high wear of the plasticizing system,
- deviation in the film thickness in the cross section, which mainly results from fluctuation in the intensity of the flow of the extruded film through the nozzle and inappropriate cooling conditions. It may be caused by contamination of the nozzle, uneven aperture in the nozzle of the extruder head, thermal heterogeneity of the material inside the head and the tube cooling asymmetry in the cooling unit or errors in construction of the head or cooling ring.

The application of gravimetric dosing system in the process of PE film production enables the restriction of film density tolerance limits measured in length. The application of such a method of feeding raw material also significantly limits its intake (Lutomirski, 2005).

This paper focuses on presenting a solution for the control and adjustment of film thickness and the elimination of deviation in film thickness in cross section. The paper discusses the application of a fuzzy controller which is meant to assist the setting of appropriate setpoints accompanying the extruder's start-up, but also to retain the pre-set values for film thickness within the limit of +/– 3 sigma.

The object of the study is the production process of polyethylene film by blow extrusion. Figure 1 presents a diagram of a blow extrusion machine.

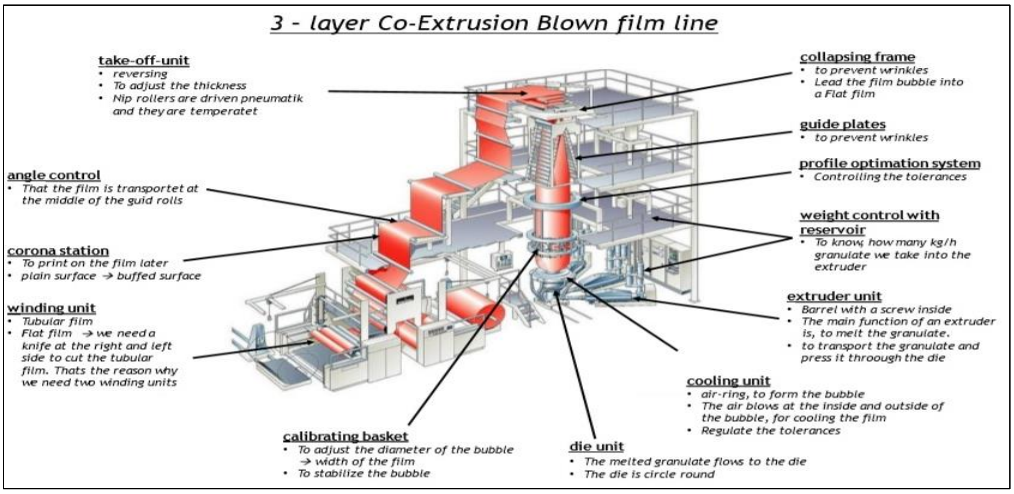


Fig. 1. A diagram of a blow extrusion machine

The most important objective is to obtain film of even thickness on the perimeter that falls within the tolerance limits determined by the customer. The machine is man-operated. Film thickness is measured manually and the operator manually sets the screws that determine the slit-width on the head of the blower. A description of the steps taken by operators and of the production process itself can be found in (Jardzioch, Marczak & Krebs, 2018; Jardzioch, Marczak & Skobiej, 2019; Jardzioch & Marczak, 2020). Paper (Jardzioch & Marczak, 2020) presents a diagram of a blow extrusion machine without automated control of film thickness. It describes a concept for ap-plication of Fuzzy Logic control in measuring film profile and automated adjustment of film thickness with the use of automatic cooling ring.

In order to set the required thickness of the produced PE film, the operator takes the following main steps:

- setting machine parameters according to the parameter chart (incl.: density: gr/m^2, feed rate: kg/h, screw revolutions u/min, calender rolls speed m/min),
- observation of the position and shape of the blown bubble, and, depending on the operator's subjective assessment, taking subsequent steps (figure 2 presents a diagram of the position and shape of the blown bubble),
- manual setting of the screws that determine the slit-width on the head of the blower,
- another observation of the position of the bubble – if it is stable, according to the opera-tor's subjective assessment, no subsequent steps are taken before another thickness measurement is conducted on a sample from the PE film yarn,
- after film thickness measurement when uneven thickness appears, the procedure of adjusting regulatory screws is continued.

Setting of the screw that determines the slit-width on the head of the blower is conducted on the basis of the human knowledge and experience. Consequently, it is possible for each opera-tor to take different action concerning the regulation of the machine to solve a given problem. Operators have varying knowledge and experience, which may entail differences in the regulatory action taken, and the effect may be different than expected. Sometimes the time in which a satisfying level of film thickness is achieved is different, increasing the amount of production waste.

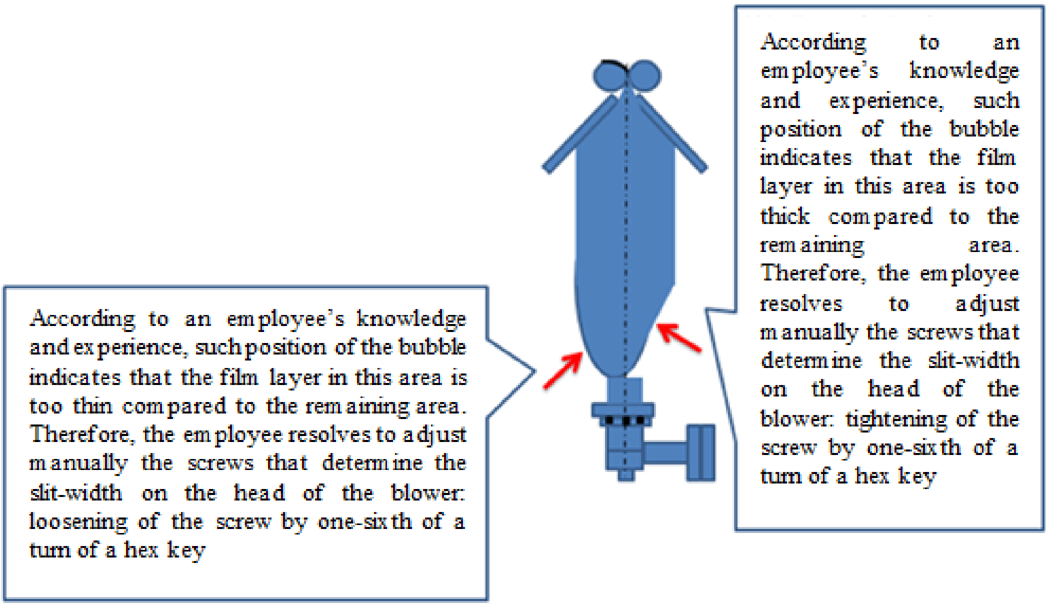


Fig. 2. Position and shape of the blown bubble

Another example of a situation when a problem with uneven film thickness on the perimeter may arise is a change in ambient temperature during the three production shifts, such as a nightly drop in temperature by 15 degrees Celsius. Then the adjustment of film thickness is achieved by setting the cooling from the cooling ring. This, however, does not enable segmental, local adjustments of the film thickness. The cooling is increased or de-creased over the whole perimeter of the tube. Other possible situations that cause inconsistencies in film thick-ness include: incorrect setting of the slit-width on the head of the blower, insufficient tightening of the bolts and their loosening during operation, and a build-up of scale at the head during machine operation.

Considering prolonged reaction time with regard to the implementation of corrective measures, varying action taken depending on the operator, their knowledge and experience, as well as machine design constraints, a decision was made to develop and apply a fuzzy controller that would automatically set and control the thickness of extruded film in mass production. This study presents a fuzzy controller which controls one of the 32 actuators regulating air cooling in the cooling ring.

3. THE DESIGN OF A FUZZY CONTROLLER TO CONTROL POLYETHYLENE FILM THICKNESS

In this paper, the authors introduce their own concept of a fuzzy controller tailored to the needs of the production process in question, drawing upon the experience of the experts con-trolling the PE film production process.

Experimental studies on the testing facility demonstrated that it is the time of reaction to a disturbance that has the biggest impact on correct film thickness control. Another crucial issue is to be able to take regulatory action on the film tube exactly where the deviation outside the assumed tolerance occurred.

In order to develop the concept, the application of a controller to measure film thickness directly on the machine was suggested. It was assumed that the information obtained from measurements should be transmitted to the main computer, where the data would be verified with the aid of an intelligent controller based on fuzzy inferencing. The signals formulated by the controller would be passed to the cooling ring located at the base of the machine. In the case when the film is too thick in certain areas, the cooling should be decreased. When the produced film is too thin, the intensity of cooling in the given areas should be increased. The measurements of film thickness should be taken throughout the whole cycle of production. Figure 3 presents the diagram of the application of a fuzzy controller in PE film production with different signal paths.

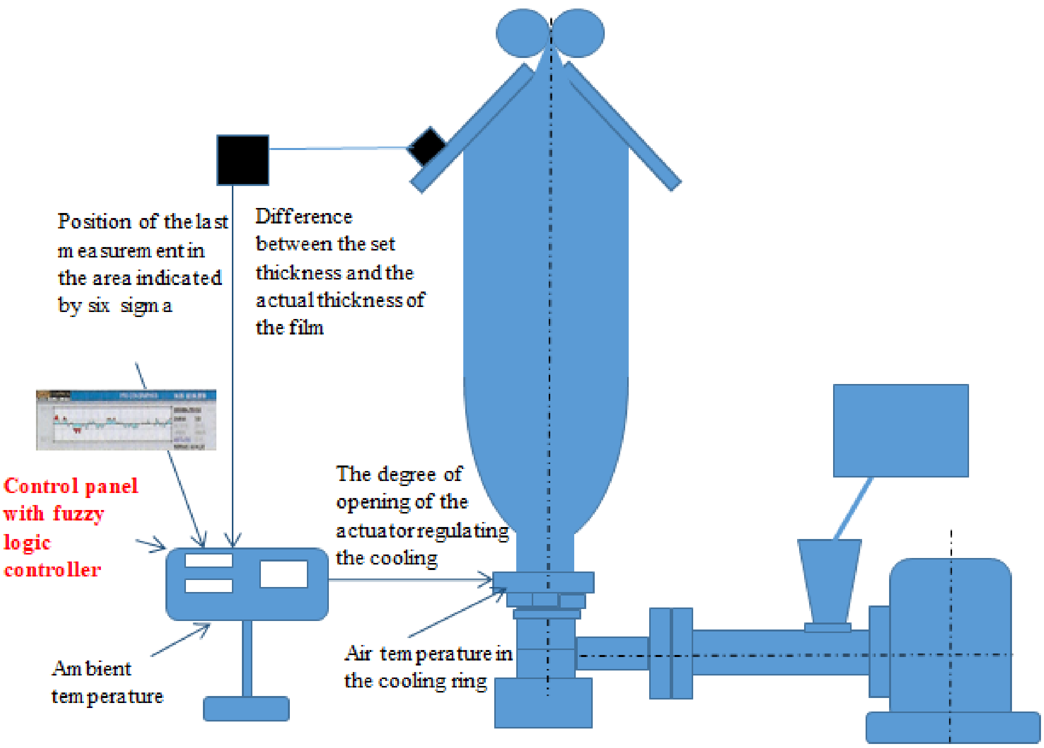


Fig. 3. A diagram of the application of a fuzzy controller in PE film production and the signal paths

Measurement results are sent to the main computer with a fuzzy controller on an ongoing basis; followed by verification and appropriate reaction. Controlled air-flow cooling provides on-target impact on film thickness in the material zone.

The system for adjusting film thickness operates continually. It retrieves information on the current state of the production system. Then the process of inferencing is conducted, as a result of which a parameter is generated that determines whether to decrease or increase air-flow cooling on the extruded film bubble. The cooling is performed by means of regulatory actuators on the cooling ring. The data used for the development of the fuzzy controller refers to film thickness measurements carried out directly on the extruder, in the conditions of mass production.

To fulfill the research objective, two systems were developed. One is fuzzy controller 1, which will control the operation of the cooling ring and adjust the degree of opening of its actuators which regulate the cooling. As a target, fuzzy controller 1 is meant to be fitted on the extruder, but in the research phase there is no such possibility. It results from financial concerns related to high cost of assembly, the need to involve additional staff members from the IT and engineering departments and the amount of time required to complete the task. Consequently, a decision was made to develop another system, the extruder operation model. It is meant to simulate the operation of the extruder so that the application of fuzzy controller 1 that adjusts the cooling in the cooling ring can be examined.

Three input variables: x1, x2 and x3 were used for fuzzy controller 1. The first variable (variable x1) is the difference between the set thickness and the actual thickness of the film. It may assume positive or negative values. The maximum negative value is –10, while the maximum positive value is +10. Both maximum values, positive and negative, serve to indicate the range to be covered by the fuzzy sets. The second input variable (variable x2) is the position of the last measurement in the area indicated by six-sigma. Variable x2 may assume positive or negative values. The maximum negative value of the position of the last point is –3. In this area, the points whose value is below the center line on the control chart are found. The maximum positive value is +3. In this area, there are those points whose value is above the center line on the control chart. The values of variable x2 are defined by the ranges of positions of the points within the distance of +/– 3 sigma from the mean value of film measurements recorded on the control chart. It is relevant in which zone below or above the center line the last measurement is, as it may suggest process deregulation and consequently possible significant deviations in the thickness on the perimeter. The third variable (variable x3) is the ambient temperature. Here, the values can range from the minimum +10°C to the maximum +35°C. They represent the lowest and the highest ambient temperature recorded during the tests. The ambient temperature has to be considered as a change in the value influences the thickness of the extruded film at a given time. Input variable values for fuzzy controller 1 were divided into intervals. Variables x1 and x2 were divided into 7 intervals: very large positive (bdd), large positive (dd), small positive (md), close to zero (bz), small negative (mu), large negative (du), very large negative (bdu). Variable x3 was divided into 5 intervals: very small (bm), small (m), medium (s), large (d) and very large (bd). The output variable is the degree of openness of actuators regulating the cooling in the automatic ring (y). As with variables x1 and x2, it was divided into 7 intervals.

In the case of fuzzy controller 1 the process of inferencing based on fuzzy logic was applied in order to determine the settings of the actuators regulating air-flow cooling with the aim of obtaining the expected film thickness. The inferencing process consists of three stages: fuzzification, i.e. converting input variables into fuzzy variables; inferencing with the use of linguistic rule base; and defuzzification, i.e., obtaining a single number from the output variable. Figure 4 presents the particular stages of the inferencing process based on fuzzy logic for the system of fuzzy controller 1.

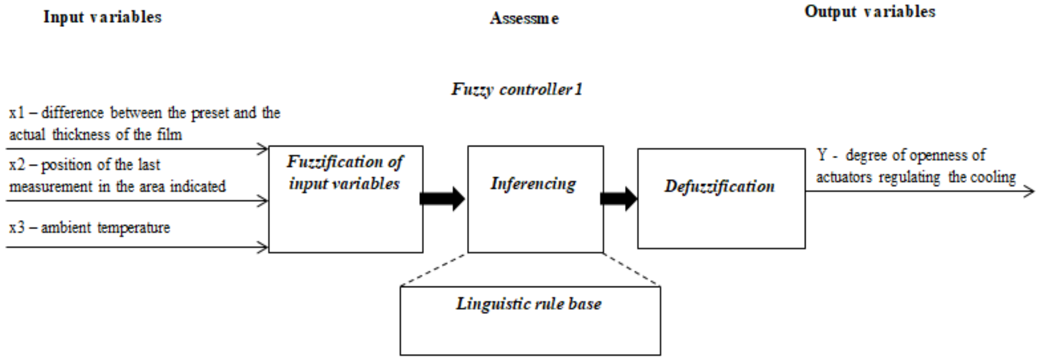


Fig. 4. Stages of the inferencing process based on fuzzy logic for the system of fuzzy controller 1

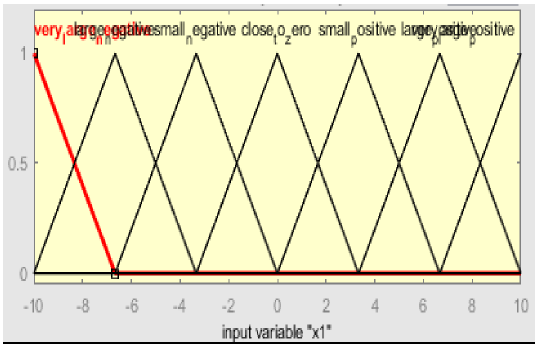
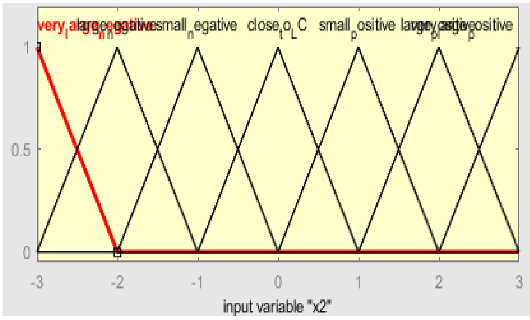
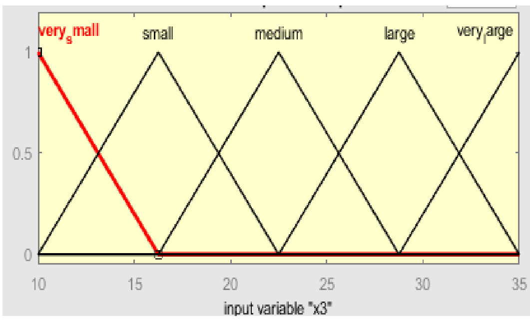
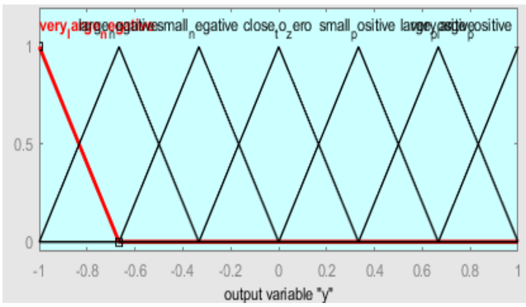
At the fuzzification stage, the particular input variable values are ascribed the values of fuzzy sets that describe them. The input variable is interpreted here as a linguistic variable with appropriately defined values. A classic theory of sets assumes that any given element can "partially belong to a set" and this membership can be expressed by a real number from the range (0, 1) whose value is determined by a properly defined membership function (Jardzioch, 2009).

Table 1 presents the particular linguistic variables and their ascribed membership functions.

In fuzzy logic, the conclusion block is where the degree of activation of the premises is calculated on the basis of fuzzy rules. The rule base is composed of a set of conditional instructions (premises). They are derived from the experience of the process operator.

The rules are composed of a conditional block (a premise, IF-statement) and a conclusion block Yj starting after the word THEN. The fuzzification of input variables enables direct use of rules expressed in linguistic terms, as sentences. Figure 5 presents sample linguistic rules used for assessing the degree of opening of the actuators regulating the cooling. For fuzzy controller 1 there are 245 rules in the controller's rule base. They determine the degree of opening of the actuators regulating the cooling. The number of rules is the product of the numbers of fuzzy sets.

Tab. 1. Linguistic variables and their ascribed membership functions for the developed *fuzzy controller 1*

No.	Indication	Linguistic variable description	Membership functions
1.	*Fuzzy controller 1*	X1 – difference between the preset and the actual thickness of the film [µm]; values: very large positive (bdd), large positive (dd), small positive (md), close to zero (bz), small negative (mu), large negative (du), very large negative (bdu).	
2.		X2 – position of the last measurement in the area indicated by six sigma; values: very large positive (bdd), large positive (dd), small positive (md), close to zero (bz), small negative (mu), large negative (du), very large negative (bdu)	
3.		X3 – ambient temperature [°C]; values: very small (bm), small (m), medium (s), large (d) and very large (bd).	
4.		Y – degree of openness of actuators regulating the cooling; values: very large positive (bdd), large positive (dd), small positive (md), close to zero (bz), small negative (mu), large negative (du), very large negative (bdu)	

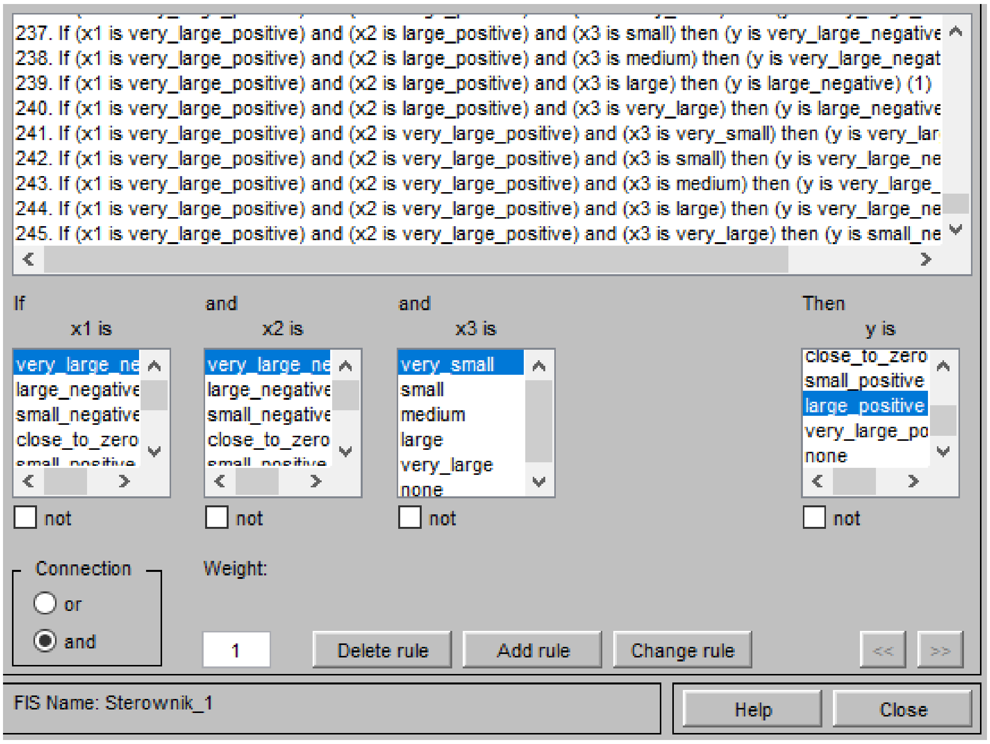


Fig. 6. Examples of rules used for assessing the degree of opening of the actuators regulating the cooling in the fuzzy controller

The fuzzy inference value is transferred to the defuzzification block.

As a result of the defuzzification process, the value is obtained for the degree of opening of the actuators regulating the cooling in the automatic ring. In the devised controller, defuzzification is performed with the use of Mean of Maximum method (MOM).

4. SIMULATION TESTS PRESENTING THE OPERATION OF THE DEVISED FUZZY CONTROLLER

Simulation tests were conducted with the use of Matlab program with Fuzzy Logic Toolbox and SIMULINK modules. To develop the simulation model, four different Simulink blocks were used, namely: From SpreadSheet, Mux, Fuzzy Logic Controller with Ruleviewer, To Workspace. Actual data obtained in the process of polyethylene film production were used in the studies.

Figure 7 shows the extruder operation model developed to test the operation of the devised fuzzy controller which controls the cooling in the cooling ring, along with and its variables.

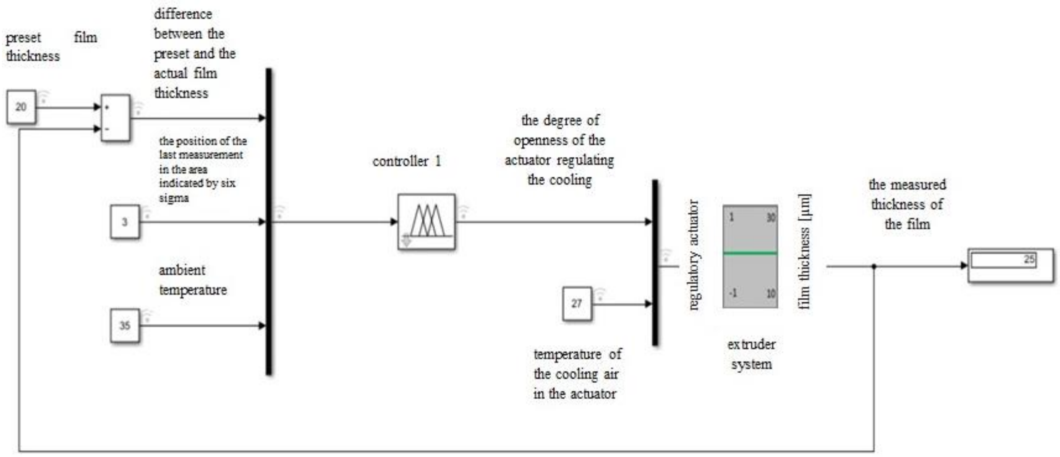


Fig. 7. The concept of simulation model to verify the operation of fuzzy control

Two input variables x4 and x5 were used for the concept of the extruder operation model. The first input variable for the extruder operation model (variable x4) is the output variable (y) of fuzzy controller 1, that is the degree of opening of the actuators regulating the cooling in the automatic ring. The maximum value assumed by variable x4 is +1 and the minimum value is –1. The second input variable for the extruder operation model (variable x5) is the temperature of the cooling air in the actuator. Its values range from a minimum +19°C to the maximum +35°C. These are the lowest and the highest temperatures recorded in the actuator during the tests. The temperature of the cooling air in the actuator matters a lot, because any change in the temperature of the cooling air influences the thickness of the extruded film. Input variable values for the extruder operation model were divided into intervals. Variable x4 was divided into 7 intervals: very large positive (bdd), large positive (dd), small positive (md), close to zero (bz), small negative (mu), large negative (du), very large negative (bdu). Variable x5 was divided into 5 intervals: very small (bm), small (m), medium (s), large (d) and very large (bd). The output variable is the measured film thickness (y2). It was divided into 5 intervals: very small (bm), small (m), small close to nominal (mbn), large close to nominal (dbn), large (d) and very large (bd).

With regard to the extruder operation model, the inferencing process based on fuzzy logic was applied to test the operation of fuzzy controller 1. Figure 8 presents an example of fuzzy controller 1 in operation. It presents the way in which the rules of fuzzy inference influence the data transferred to the fuzzy controller. As for fuzzy controller 1, in figure 8, three vertical lines indicate the values supplied to the fuzzy controller: the difference between the set and the actual thickness of the film = 10, the position of the last measurement in the area indicated by 6 sigma = 3 sigma, ambient temperature = 35°C. The yellow color indicates that the particular variable belongs to fuzzy sets. The blue color indicates that the output variable belongs to fuzzy sets. The value of this variable – here, the degree of opening of the actuators regulating the cooling – is determined during the defuzzification process. In this case, the de-gree of opening of the actuators regulating the cooling after the first cycle equals –0.34. This means that the opening of the actuators is reduced, which leads to a reduction of cooling air-flow and as a result, film thickness is decreased.

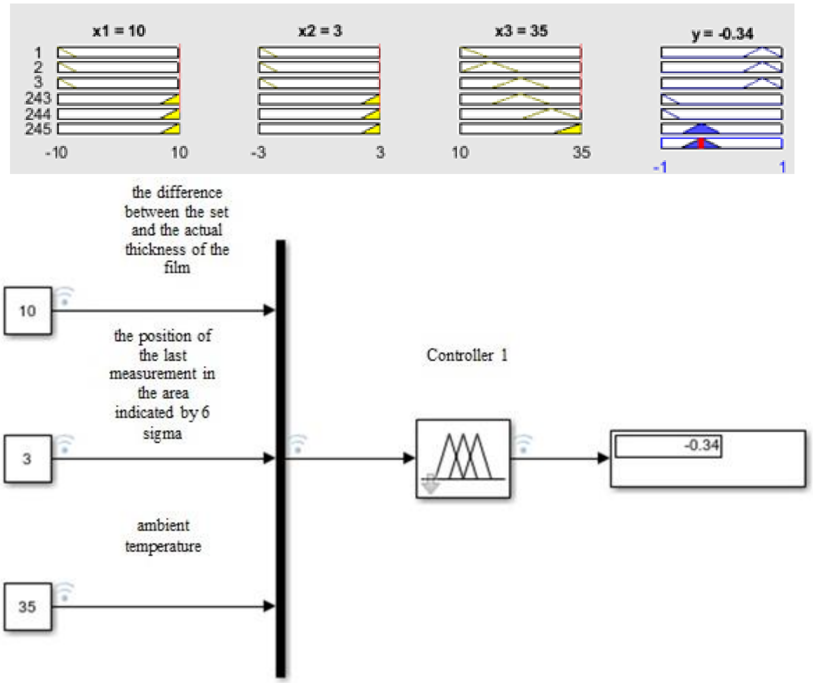


Fig. 8. Example of the operation of fuzzy controller 1 – the degree of opening of the actuators regulating the cooling

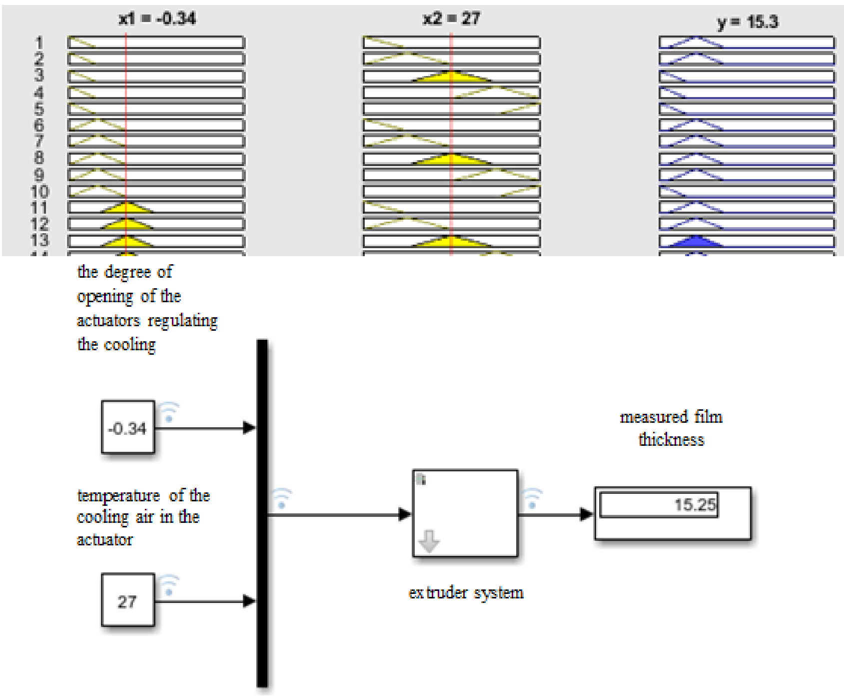


Fig. 9. Extruder operation model

In the case of the extruder operation model whose task is to simulate the operation of an extruder and test the application of a fuzzy controller controlling the cooling in the ring (Figure 9), there are two vertical lines indicate the values supplied to the extruder operation model: the degree of opening of the actuators regulating the cooling. This value was the fuzzy controller’s output and equaled –0.34 in the first cycle of the study. The second supplied value referred to a disturbance in the cooling air temperature and equaled 27°C. The output variable for the extruder operation model is the measured film thickness. In the first round of tests, the measured film thickness was 15.3 μm. This means that the nominal thickness of 20 μm was not attained.

Table 2 present the simulation results, including subsequent rounds of tests. Each cycle was further divided into variables belonging to the fuzzy controller and to the extruder operation model.

In the part referring to the fuzzy controller the first three columns contain input variables. These input variables were: the difference between the set and the actual thickness of the film (variable x1), the position of the last measurement in the area indicated by 6 sigma (variable x2), ambient temperature (variable x3). In the last column there is the output variable Y indicating the degree of opening of the actuators regulating the cooling. In the row below the variables, comments about the results can be found. In the part referring to the extruder operation model the first two columns contain input variables: the degree of opening of the actuators regulating the cooling in the automatic ring (variable x4) and the temperature of the air in the actuator (variable x5). The third column contains the output variable Y2, that is, the measured film thickness. In accordance with the assumed procedure, if no interference in the process is necessary, such as the adjustment of the airflow by means of actuators, then the degree of opening of the actuators regulating the cooling is 0. If the degree of the opening is higher than 0, then the cooling airflow is increased, which leads to increased thickness. When the degree of the opening is lower than 0, the opening is reduced; consequently, a decrease in the cooling airflow leads to decreased thickness of the film. In the extruder operation model a disturbance referring to air temperature in the regulating actuators was accounted for.

Tab. 1. Selected simulation results

<table>
<tr><td colspan="4">First cycle of tests</td></tr>
<tr><td colspan="4">Fuzzy controller 1</td></tr>
<tr><td>x1
the difference between the set and the actual thickness of the film</td><td>x2
the position of the last measurement in the area indicated by 6 sigma (s)</td><td>x3
ambient temperature (°C)</td><td>Y
the degree of opening of the actuators regulating the cooling in the automatic ring</td></tr>
<tr><td>+10</td><td>+3</td><td>35</td><td>-0.34</td></tr>
<tr><td>Comment</td><td colspan="3">A reduction in the degree of the opening of the actuators is required to the level of –0.34, which will result in decreased film thickness.</td></tr>
<tr><td colspan="4">Extruder operation model</td></tr>
<tr><td colspan="2">x4
the degree of opening of the actuators regulating the cooling in the automatic ring</td><td>x5
air temperature in the actuator (°C)</td><td>Y2
measured film thickness (µm)</td></tr>
<tr><td colspan="2">-0.34</td><td>27</td><td>15.3</td></tr>
<tr><td>Comment</td><td colspan="3">Setting the degree of opening of the actuators at -0.34 and accounting for the disturbance in the form of air temperature in the actuator, the measured film thickness is 15.3 µm, which means that the expected thickness 20 µm is not achieved.</td></tr>
<tr><td colspan="4">Second cycle of tests</td></tr>
<tr><td colspan="4">Fuzzy controller 1</td></tr>
<tr><td>x1</td><td>x2</td><td>x3</td><td>Y</td></tr>
<tr><td>-4.7</td><td>-1.5</td><td>35</td><td>0.33</td></tr>
<tr><td>Comment</td><td colspan="3">An increase in the degree of opening of the actuators regulating the cooling to the level of 0.33 is required, which will result in increased thickness of the film.</td></tr>
<tr><td colspan="4">Extruder operation model</td></tr>
<tr><td colspan="2">x4</td><td>x5</td><td>Y2</td></tr>
<tr><td colspan="2">0.33</td><td>27</td><td>24.88</td></tr>
<tr><td>Comment</td><td colspan="3">Setting the degree of opening of the actuators at 0.33 and accounting for the disturbance in the form of air temperature in the actuator, the measured film thickness is 24.88 µm, which means that the expected thickness 20 µm is not achieved.</td></tr>
<tr><td colspan="4">Third cycle of tests</td></tr>
<tr><td colspan="4">Fuzzy controller</td></tr>
<tr><td>x1</td><td>x2</td><td>x3</td><td>Y</td></tr>
<tr><td>4.88</td><td>1.5</td><td>35</td><td>0</td></tr>
<tr><td>Comment</td><td colspan="3">A reduction in the degree of opening of the actuators regulating the cooling to the level of 0 is required, which will result in decreased thickness of the film.</td></tr>
<tr><td colspan="4">Extruder operation model</td></tr>
<tr><td colspan="2">x4</td><td>x5</td><td>Y2</td></tr>
<tr><td colspan="2">0</td><td>27</td><td>20.13</td></tr>
<tr><td>Comment</td><td colspan="3">Setting the degree of opening of the actuators at 0 and accounting for the disturbance in the form of air temperature in the actuator, the measured film thickness is 20.13 µm, which means that it is very close to the expected 20 µm.</td></tr>
</table>

5. CONCLUSIONS

The aim of the present study was to develop two systems. One of them was fuzzy controller 1, whose task was to control the operation of the cooling ring and adjustment of the degree of opening of the actuators regulating the cooling which are set in that ring. Fuzzy controller 1 is eventually meant to be installed on the machine, but it is impossible in the phase of experimental study owing to financial obstacles connected with high costs of assembly, involving additional staff members from IT and engineering departments, or extra time required to fulfill the task. With these limitations in mind, a second system called the extruder operation model was developed. It simulated the operation of an extrusion machine and was used to test the application of fuzzy controller 1 for the control of cooling in the cooling ring; specifically, in one of the 32 actuators built into it. The devised systems: fuzzy controller 1 and extruder operation model were developed in the MATLAB SIMULINK environment. On the basis of conducted simulations, it was concluded that the solution based on the application of fuzzy controller 1 is helpful in the setting of appropriate set points accompanying the extruder's start-up, but also in retaining the pre-set values for film thickness. Fuzzy controller 1 enables prompt reaction to disturbances in the process of blow extrusion. Due to the application of fuzzy controller 1, which adjusts the cooling in the cooling ring by adjusting the degree of opening of the actuator, the system will work better as in some cases such adjustments cannot be made manually by the operator. The tests administered so far indicate that the application of the devised fuzzy controller 1 will facilitate a quick reaction, and consequently a retention of homogenous film thickness on the perimeter in the process of mass production. The implementation of a fuzzy controller made it possible to use the knowledge and experience of the operators and to express it in the form of linguistic rule base. As part of further study, the authors intend to develop another concept of the extrusion machine operation; this time, relying on artificial neural networks and their integration with fuzzy logic. Additionally, the model will be extended by a system presenting the operation of an extruder, including all 32 actuators regulating the cooling airflow in the cooling ring. The authors also plan to put forth a strategy for tuning a proportional-integrative-derivative (PID) fuzzy logic controller (FLC), which relies on direct fuzzy relations in order to compute PID constants.

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