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THE FUZZY SYSTEM FOR RECOGNITION AND CONTROL OF THE TWO PHASE GAS-LIQUID FLOWS

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Abstract. *In this article the fuzzy system for the two phase gas-liquid flows recognition based on the 3D tomography data and the research facility context information is described., The system is also specialized to control the research facility in basis of the fuzzy algorithms and generated diagnostics signals.*

Keywords: fuzzy logic, electrical capacitance tomography, fuzzy inference, two phase gas-liquid flows recognition

ROZMYTY SYSTEM ROZPOZNAJĄCY I STERUJĄCY PRZEPŁYWAMI DWUFAZOWYMI MIESZANIN GAZ-CIECZ

Streszczenie. *W artykule opisano system rozmyty do rozpoznawania przepływów dwufazowych mieszanin gaz-ciecz w oparciu o trójwymiarowe dane tomograficzne oraz informacje kontekstowe. System dedykowany jest również do sterowania pracą instalacji badawczej w oparciu o algorytmy rozmyte i wytworzoną informację diagnostyczną.*

Słowa kluczowe: logika rozmyta, elektryczna tomografia pojemnościowa, wnioskowanie rozmyte, rozpoznawanie przepływów dwufazowych mieszanin gaz-ciecz

Introduction

The two phase gas-liquid flows (example two phase gas-liquid flow is presented in figure 1). recognition still determines the growing trend in the various branches of the industry. The knowledge about the flow regime in the research or industrial set-up has a great importance in a biotechnology, liquid engineering, power plant facilities, heating industry etc.

The recognition of the two phase gas-liquid flows is a well-known problem in a computer science. There are various recognition methods for based on the pattern recognition [6], image processing [2], image reconstruction [8] and even artificial intelligence [4]. Despite of the severity of the above methods, the human expert opinion is still the most important part of the two phase gas liquid flows recognition process. Hence, the use of fuzzy logic which in its concepts imitates the human expert inference process. The methodology described in this paper is an innovative solution considering the raw 3D ECT (Electrical Capacitance Tomography) data [1, 5] and the flow context information combined into common fuzzy inference.

In the second part of the paper there is also a description of the fuzzy control module dedicated to the two phase gas-liquid flow installations. The control module allows to set a particular flow regime on demand and the automatic transmission from one flow type into another.

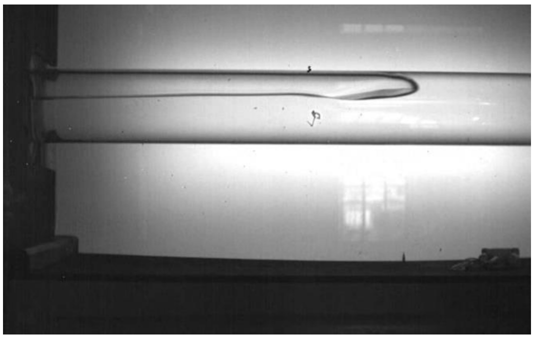

Fig. 1. The plug flow

1. Recognition module

1.1. Data preparation

First step in the two phase flow recognition is a data preparation. On the fuzzy inference input there are three values:

- flow similarity,
- gas flow rate,
- liquid flow rate.

The wide description of the flow similarity determination based on the raw 3D ECT data can be found in the authors previous publication [3]. Shortly, the flow similarity is a result of the fuzzy c-means algorithm that describes the level of the similarity of the investigated flow to the pattern flows.

The gas and the liquid flow rate are the values obtained from the research installation measurement system. Due to the relatively low accuracy of the measuring system and the frequent oscillations, these values can't be threaten as a crisp values. To reduce the impact of the mentioned factors for the final recognition results the authors decided to threat the input values of the gas flow rate and the liquid flow rate as a fuzzy number [10]. The fuzzy number that describes the input value can be interpreted as "*about the value*", and it is expressed by the following membership functions:

- For the gas flow rate (values expressed in m^3/h):

$$\mu_{I_{GFR}}(x) = \begin{cases} 0 \rightarrow x \leq x_m - 1 \\ x - (x_m - 1) \rightarrow x \in (x_m - 1; x_m > \\ -x + (x_m + 1) \rightarrow x \in (x_m; x_m + 1; x_m) \\ 0 \rightarrow x \geq x_m + 1 \end{cases} \quad (1)$$

where: x_m is an average value of the gas flow rate measured during 15-second period;

- For the liquid flow rate (values expressed in m^3/h):

$$\mu_{I_{LFR}}(x) = \begin{cases} 0 \rightarrow x \leq x_m - 0{,}5 \\ 2x - 2(x_m - 0{,}5) \rightarrow x \in (x_m - 0{,}5; x_m > \\ -2x + 2(x_m + 0{,}5) \rightarrow x \in (x_m; x_m + 0{,}5; x_m) \\ 0 \rightarrow x \geq x_m + 0{,}5 \end{cases} \quad (2)$$

where: x_m is an average value of the liquid flow rate measured during 15 seconds.

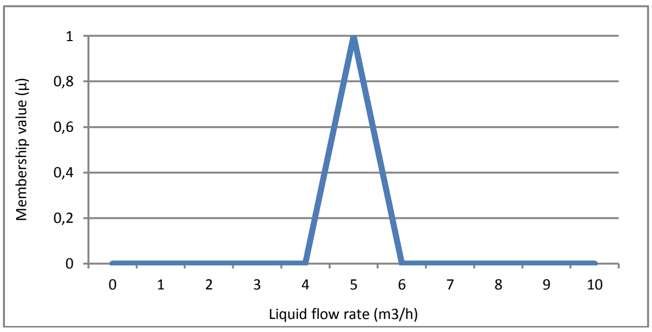

Fig. 2. About 5 m^3/h fuzzy number graphical representation

The time of 15 second is the time also needed to determination of the flow similarity level [3] so it does not affect the time of the final results calculation.

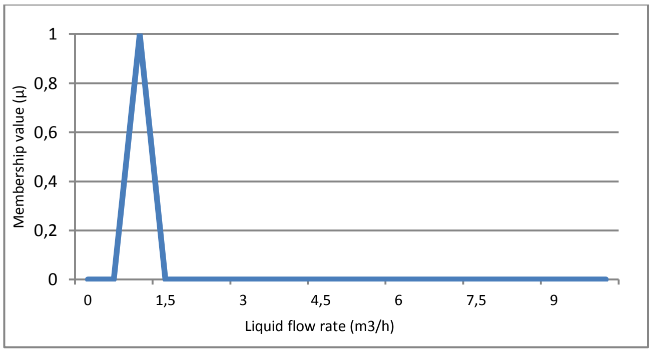

Fig. 3. About 1 m³/h fuzzy number graphical representation

The second step of the research was to determine of the membership function needed in the input values fuzzyfication. The membership functions presented in the fig. 4, fig. 5 and fig. 6. In the figure 4 dark blue color means "*different from...*", red color means "*low similarity to the...*", green color means "*medium similarity to the...*", purple color means "*high similarity to the...*", light blue means "*identical to the...*".

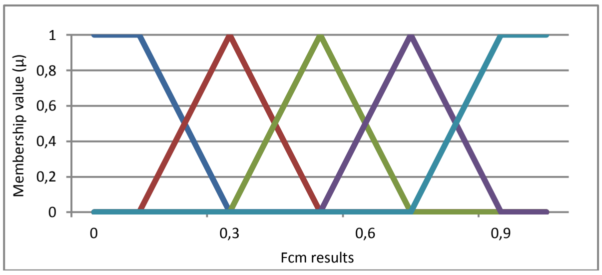

Fig. 4. Flow similarity fuzzy variable membership functions

The membership functions shapes were determined due to the authors opinion and the human expert experience. The membership functions presented in figure 4 are expressed by the following formulas:

$$\mu_{different\ from'}(x) = \begin{cases} 1 \to x \le 0{,}1 \\ -5x + 1{,}5 \to x \in (0{,}1; 0{,}3) \\ 0 \to x \ge 0{,}3 \end{cases} \quad (3)$$

$$\mu_{low\ similar\ to\ the'}(x) = \begin{cases} 0 \to x \le 0{,}1 \\ 5x - 0{,}5 \to x \in (0{,}1; 0{,}3) \\ 1 \to x = 0{,}3 \\ -5x + 2{,}5 \to x \in (0{,}3; 0{,}5) \\ 0 \to x \ge 0{,}5 \end{cases} \quad (4)$$

$$\mu_{medium\ similar\ to\ the'}(x) = \begin{cases} 0 \to x \le 0{,}3 \\ 5x - 1{,}5 \to x \in (0{,}3; 0{,}5) \\ 1 \to x = 0{,}5 \\ -5x + 3{,}5 \to x \in (0{,}5; 0{,}7) \\ 0 \to x \ge 0{,}7 \end{cases} \quad (5)$$

$$\mu_{high\ similar\ to\ the'}(x) = \begin{cases} 0 \to x \le 0{,}5 \\ 5x - 2{,}5 \to x \in (0{,}5; 0{,}7) \\ 1 \to x = 0{,}7 \\ -5x + 4{,}5 \to x \in (0{,}7; 0{,}9) \\ 0 \to x \ge 0{,}9 \end{cases} \quad (6)$$

$$\mu_{identical\ to\ the'}(x) = \begin{cases} 0 \to x \le 0{,}7 \\ 5x - 3{,}5 \to x \in (0{,}7; 0{,}9) \\ 1 \to x \ge 0{,}9 \end{cases} \quad (7)$$

The membership functions of the gas and the liquid flow rate preliminary shapes were determined due to the set of test data presented in figure 7 clustering. The final shapes were determined due to the human expert comments consideration. The final shapes of the gas and the liquid flow rates are presented in the figure 5 and figure 6. The gas and the liquid flow rates fuzzy variables were divided into four terms:

- low flow rate,
- medium low flow rate,
- medium high flow rate,
- high flow rate.

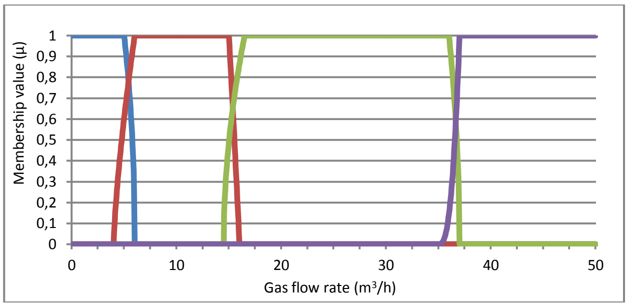

Fig. 5. Gas flow rate fuzzy variable membership functions

The membership functions presented in the figure 5 are expressed by following formulas (values expressed in m³/h):

$$\mu_{l'}(x) = \begin{cases} 1 \to x \le 5 \\ (-x + 6)^{funLG(a)} \to x \in (5; 6) \\ 0 \to x \ge 6 \end{cases} \quad (8)$$

$$\mu_{ml'}(x) = \begin{cases} 0 \to x \le 4 \\ (0{,}5x - 2)^{funMLG1(a)} \to x \in (4; 6) \\ 1 \to x \in <6; 15> \\ (-x + 16)^{funMLG2(a)} \to x \in (15; 16) \\ 0 \to x \ge 16 \end{cases} \quad (9)$$

$$\mu_{mh'}(x) = \begin{cases} 0 \to x \le 14{,}5 \\ (0{,}5x - 7{,}25)^{funMHG1(a)} \to x \in (14{,}5; 16{,}5) \\ 1 \to x \in <16{,}5; 36> \\ (-x + 16{,}5)^{funMHG2(a)} \to x \in (36; 37) \\ 0 \to x \ge 37 \end{cases} \quad (10)$$

$$\mu_{h'}(x) = \begin{cases} 0 \to x \ge 35 \\ (0{,}5x - 17{,}5)^{funHG(a)} \to x \in (35; 37) \\ 1 \to x \le 37 \end{cases} \quad (11)$$

Due to the subjectivity assessments of the presented membership functions shape, the authors gave the potential system users a possibility of a 10 grades function shape manipulation:

$$funLG(a) = 0{,}089a + 0{,}011 \quad (12)$$

$$funMLG1(a) = 0{,}056a + 0{,}444 \quad (13)$$

$$funMLG2(a) = 0{,}11a + 0{,}389 \quad (14)$$

$$funMHG1(a) = 0{,}078a + 0{,}122 \quad (15)$$

$$funMHG2(a) = 0{,}078a + 0{,}122 \quad (16)$$

$$funHG(a) = 0{,}444a + 0{,}556 \quad (17)$$

where: $1 \le a \le 10$.

The function shape for a parameter equals 1 and 10 was also consulted and approved by the human expert in the two phase gas-liquid flows recognition.

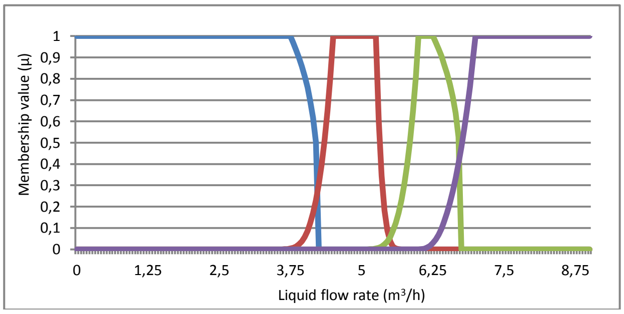

Fig. 6. Liquid flow rate fuzzy variable membership functions

The membership functions presented in figure 6 are expressed by following formulas (values expressed in m³/h):

$$\mu_{l'}(x) = \begin{cases} 1 \to x \le 3{,}75 \\ (-2x + 8{,}5)^{funLL(a)} \to x \in (3{,}75; 4{,}25) \\ 0 \to x \ge 4{,}25 \end{cases} \quad (18)$$

$$\mu_{ml'}(x) = \begin{cases} 0 \to x \le 3{,}5\ m^3/h \\ (x - 3{,}5)^{funMLL1(a)} \to x \in (3{,}5; 4{,}5) \\ 1 \to x \in <4{,}5; 5{,}25> \\ (-2x + 11{,}5)^{funMLL2(a)} \to x \in (5{,}25; 5{,}75) \\ 0 \to x \ge 5{,}75 \end{cases} \quad (19)$$

$$\mu_{mh'}(x) = \begin{cases} 0 \to x \le 5 \\ (x-5)^{funMHL1(a)} \to x \in (5;6) \\ 1 \to x \in <6;6{,}25> \\ (-2x+13{,}5)^{funMHL2(a)} \to x \in (6{,}25;6{,}75) \\ 0 \to x \ge 6{,}75 \end{cases} \quad (20)$$

$$\mu_{h'}(x) = \begin{cases} 0 \to x \ge 6 \\ (x-6)^{funHL(a)} \to x \in (6;7) \\ 0 \to x \le 7 \end{cases} \quad (21)$$

In the similar way to the gas flow rate, the authors also allow the potential system users to manipulate the membership functions shapes by changing the *a* parameter of the following functions:

$$funLL(a) = 0{,}1a \quad (22)$$

$$funMLL1(a) = 0{,}556a + 2{,}444 \quad (23)$$

$$funMLL2(a) = 0{,}889a + 2{,}111 \quad (24)$$

$$funMHL1(a) = 0{,}556a + 2{,}444 \quad (25)$$

$$funMHL2(a) = 0{,}089a + 0{,}011 \quad (26)$$

$$funHL(a) = 0{,}778a + 0{,}222 \quad (27)$$

The membership functions of the liquid flow rate shape determination process was similar to the gas flow rate.

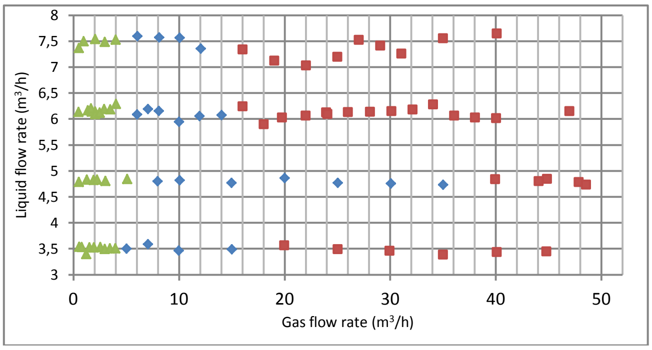

Fig. 7. The test flows recognized by the human expert. Color green recognizes as a plug flow, blue as the transitional flow and the red as the slug flow

1.2. Recognition process

The recognition inference is conditioned by the standard ***if..then*** formulas. All of them used in the inference schema look as follows:

If

Gas flow rate is low/medium low/medium/medium high/ high

And

Liquid flow rate is low/medium low/medium/medium high/ high

And

Analyzed flow is deferent from/low similar to/medium similar to/high similar to/identical to plug/slug/transitional flow

Then

Analyzed flow is plug/slug/ transitional

All fuzzy recognition rules used in the studies are presented in table 1.

The fuzzy rules as well as the membership functions shapes were designed that in the worst case, the inference results are two types of flow types in different degrees of realization [7, 9] while using most common Zadeh implication (28) (the realization level of the particular fuzzy rule is determined by the fuzzyfication of the input signal).

The defuzzyfication is realized by the standard *maximum* rule [10].

$$\max\{\min\{a,b\},1-a\} \quad (28)$$

Table 1. Recognition fuzzy rules base

Lp.	Gas flow rate	Liquid flow rate	Similarity level	Recognition result
1	Low	Low	Identical to the plug flow	Plug flow
2	Low	Medium Low	Identical to the plug flow	Plug flow
3	Low	Medium High	Identical to the plug flow	Plug flow
4	Low	High	Identical to the plug flow	Plug flow
5	Low	Low	Medium similar to the plug flow	Plug flow
6	Low	Medium Low	Medium similar to the plug flow	Plug flow
7	Low	Medium High	Medium similar to the plug flow	Plug flow
8	Low	High	Medium similar to the plug flow	Plug flow
9	Medium Low	Low	High similar to the plug flow	Transitional flow
10	Medium Low	Medium Low	High similar to the plug flow	Transitional flow
11	Medium Low	Medium High	High similar to the plug flow	Transitional flow
12	Medium Low	High	High similar to the plug flow	Transitional flow
13	Medium Low	Low	Medium similar to the plug flow	Transitional flow
14	Medium Low	Medium Low	Medium similar to the plug flow	Transitional flow
15	Medium Low	Medium High	Medium similar to the plug flow	Transitional flow
16	Medium Low	High	Medium similar to the plug flow	Transitional flow
17	Medium High	Medium Low	High similar to the slug flow	Transitional flow
18	Medium High	Medium Low	Identical to the slug flow	Transitional flow
19	Medium Low	Medium Low	Medium similar to the slug flow	Transitional flow
20	Medium Low	Low	Medium similar to the slug flow	Transitional flow
21	Medium Low	Medium High	Medium similar to the slug flow	Slug flow
22	Medium Low	High	Medium similar to the slug flow	Slug flow
23	Medium High	Low	High similar to the slug flow	Slug flow
24	Medium High	Medium High	High similar to the slug flow	Slug flow
25	Medium High	High	High similar to the slug flow	Slug flow
26	Medium High	Low	Identical to the slug flow	Slug flow
27	Medium High	Medium High	Identical to the slug flow	Slug flow
28	Medium High	High	Identical to the slug flow	Slug flow
29	High	Low	Identical to the slug flow	Slug flow
30	High	Medium Low	Identical to the slug flow	Slug flow
31	High	Medium High	Identical to the slug flow	Slug flow
32	High	High	Identical to the slug flow	Slug flow

2. Control module

2.1. Data preparation

In the fuzzy inference for the control module there are four input values:

- gas flow rate,
- liquid flow rate,
- current flow type,
- given flow type.

The gas flow rate and the liquid flow rate values are fuzzyficated exactly the same as the input signals in recognition module, applying the membership functions presented in the fig. 5 and 6. The current flow and the given flow types have crisp values, where the current flow type is the defuzzyficated result of the recognition module and the given flow is the system user assessment.

2.2. Control process

The fuzzy rules used in the control module look as follows:

If

Current flow type is slug/plug/transitional

And

Given flow type is slug/plug/transitional

And

Gas flow rate is low/medium low/medium/medium high/high

And

Liquid flow rate is low/medium low/medium/medium high/high

Then

Set gas flow rate to low/medium low/medium/medium high/high

And

Set liquid flow rate to low/medium low/medium/medium high/high

All used in the studies fuzzy control rules are presented in table 2.

Table 2. Recognition fuzzy rules base

Lp.	Current flow type	Given flow type	Gas flow rate	Liquid flow rate	Result gas flow rate	Result liquid flow rate
1	Plug	T	Low	Low	ML	Low
2	Plug	T	Low	ML	ML	ML
3	Plug	T	Low	MH	ML	MH
4	Plug	T	Low	High	ML	High
5	T	Plug	ML	Low	Low	Low
6	T	Plug	ML	ML	Low	ML
7	T	Plug	ML	MH	Low	MH
8	T	Plug	ML	High	Low	High
9	T	Plug	MH	ML	Low	ML
10	Plug	Slug	Low	Low	MH	Low
11	Plug	Slug	Low	ML	MH	Low
12	Plug	Slug	Low	MH	MH	MH
13	Plug	Slug	Low	High	MH	High
14	Slug	Plug	MH	Low	Low	Low
15	Slug	Plug	MH	MH	Low	MH
16	Slug	Plug	MH	High	Low	High
17	Slug	Plug	High	Low	Low	Low
18	Slug	Plug	High	ML	Low	ML
19	Slug	Plug	High	MH	Low	MH
20	Slug	Plug	High	High	Low	High
21	T	Slug	ML	Low	MH	Low
22	T	Slug	ML	ML	MH	Low
23	T	Slug	ML	MH	MH	MH
24	T	Slug	ML	High	MH	High
25	T	Slug	MH	ML	MH	Low
26	Slug	T	MH	Low	MH	ML
27	Slug	T	MH	MH	MH	ML
28	Slug	T	MH	High	MH	ML
29	Slug	T	High	Low	MH	ML
30	Slug	T	High	ML	MH	ML
31	Slug	T	High	MH	MH	ML
32	Slug	T	High	High	MH	ML
33	Plug	Plug	Low	Low	Low	Low
34	Plug	Plug	Low	ML	Low	Low
35	Plug	Plug	Low	MH	Low	Low
36	Plug	Plug	Low	High	Low	Low
37	T	T	ML	Low	ML	Low
38	T	T	ML	ML	ML	Low
39	T	T	ML	MH	ML	Low
40	T	T	ML	High	ML	Low
41	T	T	MH	ML	ML	Low
42	Slug	Slug	MH	Low	High	High
43	Slug	Slug	MH	MH	High	High
44	Slug	Slug	MH	High	High	High
45	Slug	Slug	High	Low	High	High
46	Slug	Slug	High	ML	High	High
47	Slug	Slug	High	MH	High	High
48	Slug	Slug	High	High	High	High

ML = Medium Low, MH = Medium High, T = Transitional

The output values are translated to the crisp values with the center of sums defuzzyfication method, expressed by the following formula:

$$\bar{y} = \frac{\int_Y y \sum_{k=1}^{N} \mu_B k(y) dy}{\int_Y \sum_{k=1}^{N} \mu_B k(y) dy} \quad (29)$$

where: y – value of each point covered by the output fuzzy set expressed in m^3/h

Finally, the two parameters are produced on the control module output:

- the setting of the gas flow rate expressed in m^3/h,
- the setting of the liquid flow rate expressed in m^3/h.

3. Research results

The results of the recognition process correctness was validated with 45 test flows. In the first step, each test flow type was recognized both by the human expert and the presented system. The results for each from three flow type are presented in table 3. The results of the control process are presented in table 4.

In table 3 the flows types are marked by the following symbols:

- P – for the plug flow,
- T – for the transitional flow,
- S – for the slug flow.

The flows recognized by the presented system were validated by the human expert. The differences in the flows recognition results were marked in red color. As it can be noticed there were only 3 differences in 45 test flows (2 in plug flow recognition and one in transitional flow recognition) which should be threaten as an excellent result. These differences occurs due to the different expert opinion used. Opinion of the first expert was used during the membership functions designing and the opinion of the second expert was used in the validation process. This situation confirms the authors assumptions of necessity to provide the access to manipulation of the membership functions shape by the system user. After changing the *a* parameter value for the gas flow rate membership function there were no differences in the recognition results between the human expert and the presented system.

In table 4 the flows transition are marked as follows:

- P->T – for plug flow into transitional flow,
- P->S – for plug flow into slug flow,
- T->P – for transitional flow into plug flow,
- T->S – for transitional flow into slug flow,
- S->P – for slug flow into plug flow,
- S->T – for slug flow into transitional flow,
- P->P – for plug flow into plug flow,
- T->T – for transitional flow into transitional flow,
- S->S – for slug flow into slug flow.

The validation routine was as follows:

- The human expert set the flow parameters (the gas flow rate and the liquid flow rate);
- If the presented system recognition results was equal to the expert opinion, the expert set the desired flow type in the system user panel;
- After 30 seconds the recognition of new flow type was made by the system and the expert. Recognition results of the starting and the output flow was placed in table 4.

As it can be noticed there was only one difference in the recognition of the output flow (flow number 4). The reason of that difference was the same as in the recognition process (results in table 3). When the shapes of the membership functions of the gas flow rate were adjusted due to the human expert opinion there was no differences between the presented system and the expert recognition of the output flows results.

Table 3. Recognition process results

Flow Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Expert recognition	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
Fuzzy system recognition	P	P	P	P	T	P	P	P	P	T	P	P	P	P	P
Flow Number	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Expert recognition	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Fuzzy system recognition	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Flow Number	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Expert recognition	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
Fuzzy system recognition	T	T	T	T	T	P	T	T	T	T	T	T	T	T	T

Table 4. Control process results

Flow Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Expert recognition	P->T	P->T	P->T	P->T	P->T	P->S	P->S	P->S	P->S	P->S	T->P	T->P	T->P	T->P	T->P
Fuzzy system recognition	P->T	P->T	P->T	P->P	P->T	P->S	P->S	P->S	P->S	P->S	T->P	T->P	T->P	T->P	T->P
Flow Number	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Expert recognition	T->S	T->S	T->S	T->S	T->S	S->P	S->P	S->P	S->P	S->P	S->T	S->T	S->T	S->T	S->T
Fuzzy system recognition	T->S	T->S	T->S	T->S	T->S	S->P	S->P	S->P	S->P	S->P	S->T	S->T	S->T	S->T	S->T
Flow Number	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Expert recognition	T->T	T->T	T->T	T->T	T->T	P->P	P->P	P->P	P->P	P->P	S->S	S->S	S->S	S->S	S->S
Fuzzy system recognition	T->T	T->T	T->T	T->T	T->T	P->P	P->P	P->P	P->P	P->P	S->S	S->S	S->S	S->S	S->S

4. Conclusions

The methods of the two phase gas-liquid flows recognition and the research installation control presented in this paper are innovative solution in this field. The fuzzy logic based algorithms allow to imitate the human expert decision and give the proper recognition results for such dynamic process as the two phase gas-liquid flows. Also the research installation control algorithms can be very useful in the industry. All presented in this paper algorithms and solutions are easy scalable and may be applied to any installations equipped with the ECT diagnostic system and the basic measurement equipment.

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