CONTRIBUTION TO THE RESEARCH AND DEVELOPMENT OF RADIATION CHAMBERS IN STEAM REFORMING. PROBLEM-ORIENTED APPLICATION OF A FUZZY EXPERT SYSTEM

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An application of a fuzzy expert system intended for estimating some parameters of steam reforming can also be one of the examples of an ever increasing utilization of expert systems in practice. The present contribution deals with the method making use of a verified mathematical model for simulating thermal chemical processes in reforming furnace radiation chamber in order to create knowledge base. This base includes linguistic values of selected independent and dependent variable quantities. Examples given illustrate an evaluation of dependent variable quantities (methane conversion into carbon dioxide and monoxide, reaction tube service life) by means of the said expert system based on queries.

At present the process of steam reforming of natural gas and light hydrocarbons is the most important and economical method for producing hydrogen or synthesized gas in the petrochemical industry. The products are used for hydrogenation purposes or for the production of ammonia and methanol. In this case the radiation chamber of a primary reformer is a key technological equipment both from the point of view of investment costs and from that of energy consumption.

The application of a mathematical model of a reforming furnace verified by measuring on an industrial unit[1] enables various operating modes (regimes) to be simulated facilitating furnace designing and particularly its operation. The above model can, however, considerably contribute to fill knowledge base of the expert system[2].

The expert system – as it already follows from its name – is intended for solving rather complicated problems being usually solved by experts of extraordinary qualities. The expert approach is known first of all from the sphere of economy but also from that of reliability or from technical diagnostics. A distinct advantage of the expert system is the fact that it enables to work with terms, i.e. linguistic values and linguistic variable quantities. That means that the knowledge base can include data obtained from different information sources. These are both experience of experts and data determined by calculation or also data obtained by studying the literature. This advantage affects the extension of the sphere of system utilization.

An example can be an application of the expert system to estimate operating conditions of steam reforming furnace or possibly also an indication of dangerous conditions, such as for instance a prediction of methane conversion into carbon dioxide and monoxide, of the maximum temperature of reaction tube surface or their service life.

Fuzzy Expert System

The expert system applied differs somewhat from the classical expert system making use of the principle of the so-called chaining. The fuzzy expert system enables to work with linguistic values of variable quantities. These values are transformed in "numerical" ones based on the theory of fuzzy sets. A fuzzy set enables to take into consideration on the one hand uncertainty (inaccuracy, vagueness), on the other hand it enables to apply a very effective evaluating algorithm (rule of inference) when searching for answer to a query.

The expert system consists therefore both of a deductive inference engine and of the knowledge base. The quality of the expert system depends, however, especially on the quality of the knowledge base at present. The knowledge base includes available information relating to a specific problem. If the expert system is given a query, the answer is looked for on the principle of maximum similarity.

The expert system works with linguistic variable quantities. Any variable quantity can be considered a linguistic variable quantity. As linguistic variable quantities such linguistic values must be defined being used by the expert when evaluating (describing) the process.

Let us consider for instance the description of heat losses in reforming furnace radiation chamber. The expert for instance uses the following linguistic values to estimate heat losses, such as: UNR (unreal), VL (very low), S (standard) and H (high). It is necessary to say what losses the above data express. A fuzzy set enables not only a partial "fuzzyfication" of the linguistic value but it also includes the already mentioned uncertainty.

The heat flux loss is considered a specific percentage share of heat flux liberated when burning fuel gas. If we accept such a division of losses where the losses from 0.25% up to 0.8% are very low (VL) and those from 0.8% up to 1.5% are standard (S), then it is a contradiction to reality. That means for instance that the 0.799% losses are very low but those of 0.801% are standard. The above sharp division without any transition region can be classified as "unjust".

The fuzzy set enables the element to belong partially to the set. It is then possible that also the value 0.799 belongs at least partially to the linguistic value S. At the same time it is also possible that the value 0.801 partially belongs to the linguistic value VL. In this way the reality of ambient world, the uncertainty can be described. For that reason a grade of membership (GM) of the fuzzy set and the function of membership are used describing the course of an element grade of membership of certain set[2].

Figure 1 illustrates graphically linguistic values and fuzzy models of respective values. The introduction of fuzzy models also enables a similarity of linguistic values to be included at the same time.

The knowledge base is in fact a set of statements stating if *A*11 and *A*12 and *A*13 and . . . and *A*1m then *B*1 with *w*1, where values *A*ij represent independent variable quantities influencing the value of the dependent variable (investigated) quantity *B*i. The weight of such a statement is evaluated by the value *w*i. The set of such statements represents a multidimensional knowledge base. The expert system searches for the answer to the query given by means of deductive evaluating algorithm based on fuzzy similarity. As answer all statements being similar to the query given are offered.

The advantage of the fuzzy inference engine is above all a considerable rate in searching for the answer, the whole base being practically evaluated at the same time.

Application of the Expert System to a Primary Reformer Radiation Chamber

In the above case the fuzzy expert system can be applied in a fully untraditional way. A relatively long and demanding calculation can be substituted by an expert estimate, the knowledge base being able to store results of a simulation calculation, literary data, estimates of experts and other information.

Usually an estimate of methane conversion into carbon dioxide and monoxide, the maximum temperatures of reaction tube surfaces etc. are required. The values of the above quantities depend on a number of factors (independent variables). These dependences can be investigated by means of repeated simulation calculations[3]. It is, however, necessary to take into account that one simulation calculation by means of the mathematical model[1] takes about 25 min when carried out by computer PC AT. In this case it is possible to make use of verified mathematical model as one of the means used to fill the knowledge base.

As independent variable quantities the following have been selected:

1. Emissivity of tube surface (ε_t).
2. Burner flame length (L_p, m).
3. Radiation chamber inlet excess air ($\lambda^{(1)}$).

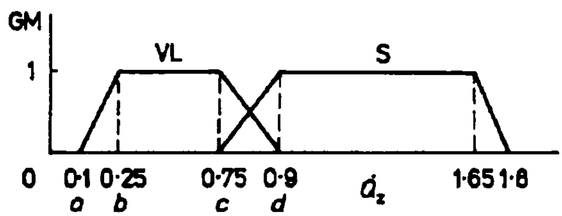

FIG. 1
Illustration of fuzzy models

4. Radiation chamber outlet excess air ($\lambda^{(2)}$).
5. Heat losses ($\dot{Q}_v$, % $\dot{Q}_{sp}$).
6. Catalyst activity (r_{01}, mol kg^{-1} s^{-1}).
7. Activation energy (E, kJ mol^{-1}).
8. Water vapour to hydrocarbons rate (H_2O/C). (Note: This depends on the number of kilomoles of inlet water vapour per kilogramatom of carbon bonded in reaction mixture hydrocarbons.)
9. Amount of fuel gas (burners input) ($\dot{V}_{tp}$, m_n^3 h^{-1}). (Note: Numerically expressed by one burner input.)

The importance of individual parameters has been discussed in detail in literature[3]. It can be stated that the quantities Nos 3, 8 and 9 are controlled by operator in operation based on requirements of the operating mode applied.

For each variable quantity a vocabulary of values must be defined with which it is to work. This vocabulary is different for various variable quantities. The expert must, however, also define respective fuzzy sets together with the value vocabulary. For instance in case of the variable No. 1 (ε_t) three linguistic values have been defined (L low, M medium, H high). A definition of the fuzzy sets is clearly listed in Tables I and II.

By means of defined linguistic quantities the expert formulates a statement set for a specific problem (Table III). The knowledge base includes therefore linguistic statements in an easily legible form. The importance of the statement (e.g. statement No. 3 – see Table III) can be expressed as follows:

if the emissivity of reaction tube surface is high and the burner flame length a medium one as well as the inlet excess air a medium one and . . . and the amount of fuel gas is also mean, then the methane conversion is mean and reaction tube service life is low.

There is an analogy between the function and fuzzy model and so it is possible to determine the value of dependent variables (conversion, tube surface life) for the selected values of independent variables by means of a suitable programming system. The fuzzy model can be, however, also applied to classical numerical input data. It practically means that fuzzy set is reduced to a real number. The shape of the course of membership function (Fig. 1) changes since $a = b = c = d$. This also relates to the input data No. 4 in Table IV. The remaining queries are specified by fuzzy sets whose linguistic values have been used in models. To an objective presentation of the example results referred to in Table IV a graphical interpretation is applicable (see Figs 2, 3). From Figs 2 or 3 it follows what values of dependent variables (conversion or service life) can be expected in the events in question. The result of each example is a fuzzy set. It is necessary to realize that the linguistic example itself is rather "fuzzy" (unclear). The fuzzy model gives therefore a "more fuzzy" answer to an uncertain query than the deterministic query. The practical importance of fuzzy queries lies in the fact that they simulate a situation where we cannot be certain about the values of the

TABLE I
Linguistic values of independent variables (definition of fuzzy sets)

Variable number	Variable symbol	Linguistic value	*a*	*b*	*c*	*d*
1	ε_t	L	0.680	0.700	0.780	0.800
		M	0.780	0.800	0.900	0.920
		H	0.900	0.920	0.980	1.000
2	L_p	SH	0.500	0.800	1.600	2.000
		M	1.600	2.000	3.000	3.200
		LG	3.000	3.600	4.400	5.000
3	$\lambda^{(1)}$	UNA	1.000	1.000	1.010	1.015
		L	1.010	1.015	1.030	1.040
		M	1.030	1.040	1.060	1.080
		H	1.070	1.080	1.120	1.130
4	$\lambda^{(2)}$	L	1.030	1.040	1.060	1.080
		M	1.070	1.080	1.140	1.145
		H	1.140	1.145	1.160	1.180
5	$\dot{Q}_z$	UNRE	0.000	0.000	0.100	0.250
		VL	0.100	0.250	0.750	0.900
		S	0.750	0.900	1.650	1.800
		H	1.650	1.800	2.650	2.800
6	r_{01}	L	0.005	0.008	0.012	0.015
		S	0.014	0.018	0.024	0.030
		H	0.028	0.030	0.040	0.043
		VH	0.040	0.045	0.055	0.060
7	E	L	70.00	76.00	84.00	90.00
		S	84.00	90.00	100.0	110.0
		H	100.0	110.0	130.0	140.0
		VH	135.0	140.0	160.0	165.0
8	H_2O/C	UNA	1.600	1.900	2.100	2.400
		L	2.200	2.400	2.800	3.000
		M	2.900	3.200	4.500	5.000
		H	4.700	4.800	5.200	5.500
		LIM	5.300	5.600	6.200	6.500
9	$\dot{V}_{tp}$	VL	145.0	147.0	153.0	155.0
		L	153.0	155.0	160.0	162.0
		M	160.0	162.5	168.5	171.0
		H	169.0	171.0	174.0	176.0
		VH	174.0	177.0	180.0	185.0

TABLE II
Linguistic values of dependent variables

Variable		Linguistic value	a	b	c	d
number	symbol					
10	x	ABSUNA	0.000	0.000	0.330	0.400
		UNA	0.330	0.400	0.510	0.580
		L	0.520	0.570	0.620	0.670
		M	0.630	0.680	0.720	0.760
		H	0.720	0.750	0.780	0.810
		VH	0.780	0.810	1.000	1.000
11	L_b	UNA	0.000	0.000	35 000	40 000
		L	35 000	40 000	46 000	49 000
		M	47 000	49 000	54 000	56 000
		H	54 000	56 000		

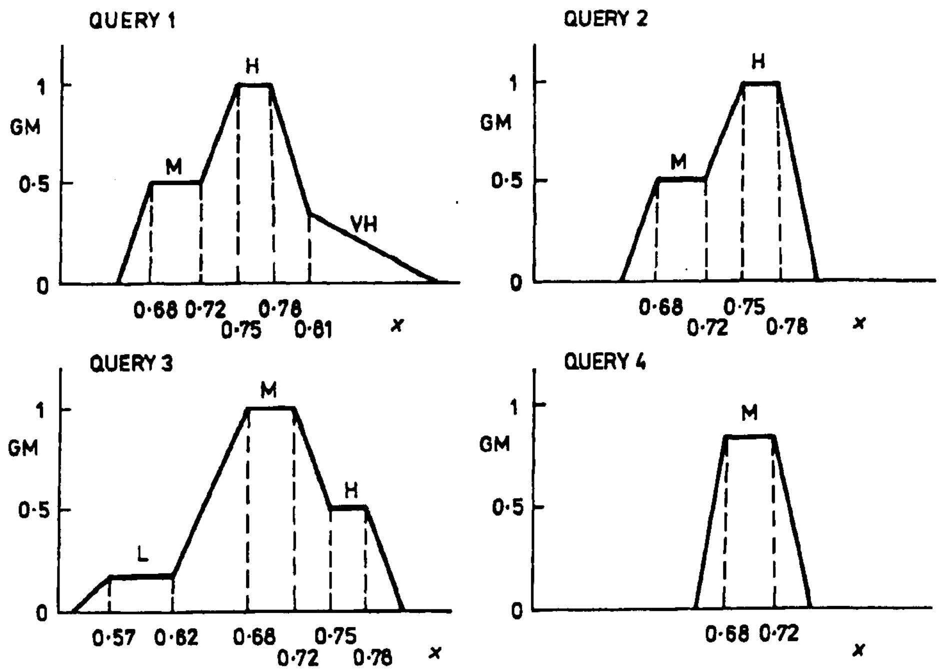

FIG. 2
Graphical interpretation of the example results (conversion)

TABLE III
System knowledge base (expert statements set)

Statement number	Independent variable									Depend. variab.	
	1	2	3	4	5	6	7	8	9	10	11
1	L	LG	H	H	H	L	L	L	VL	UNA	M
2	H	SH	L	L	VL	VH	VH	LIM	VH	VH	L
3	H	M	M	M	S	S	S	M	M	M	L
4	H	M	H	H	S	S	S	M	M	M	M
5	H	M	M	M	S	S	S	LIM	M	VH	L
6	H	M	L	H	S	S	S	M	M	M	M
7	H	M	L	H	H	S	S	M	M	M	M
8	H	M	L	L	H	S	S	M	M	M	M
9	H	M	M	M	S	H	H	M	M	M	M
10	H	M	M	M	S	H	H	M	H	M	M
11	L	M	M	M	S	VH	VH	M	M	M	H
12	L	M	M	M	S	VH	VH	H	H	H	M
13	L	M	M	M	VL	S	S	L	L	UNA	H
14	H	M	L	L	S	S	S	M	M	M	L
15	H	M	M	M	S	S	S	M	VH	M	L
16	H	M	M	M	S	S	S	M	VL	L	M
17	H	LG	M	M	S	S	S	M	M	M	L
18	M	LG	M	M	S	S	S	H	H	H	L
19	H	M	M	M	S	L	L	H	M	H	UNA
20	M	SH	L	H	S	S	S	M	M	M	M
21	M	M	L	H	H	S	S	L	VL	UNA	H
22	M	M	M	M	S	S	S	L	VL	UNA	L
23	M	M	M	M	S	S	S	LIM	VL	VH	M
24	M	M	M	M	S	S	S	LIM	VH	VH	L
25	L	M	M	M	S	VH	VH	H	L	H	H
26	L	M	M	M	S	VH	VH	H	VH	VH	M
27	H	M	M	H	H	S	S	H	M	H	M
28	M	M	M	M	S	S	S	M	M	M	M
29	H	M	H	M	S	L	L	M	M	L	L
30	L	M	M	M	S	VH	VH	M	H	M	M
31	H	SH	H	M	VL	S	S	H	L	H	M
32	H	LG	H	H	S	S	S	H	H	H	L
33	M	M	M	H	H	S	S	M	M	M	M
34	M	M	L	L	S	H	H	L	VH	UNA	M
35	H	M	L	H	H	S	S	H	L	H	M
36	H	M	M	M	S	S	S	M	M	M	L

variables. In engineering practice a numerical result is usually expected. Then it is necessary to interpret the set in a numerical way followed by an analogous information loss as if a probability distribution is substituted by an average value. As a numerical

TABLE IV
Input data of examples solved

Query no.	Independent variable									
	1	2	3	4	5	6	7	8	9	9′
1	L	M	M	M	S	VH	VH	H	H	H
2	L	M	M	M	S	VH	VH	H	L	0.765
3	H	M	M	M	S	S	S	M	M	M
4	0.950	2.500	1.070	1.150	1.000	0.025	90.00	4.500	170.0	0.704

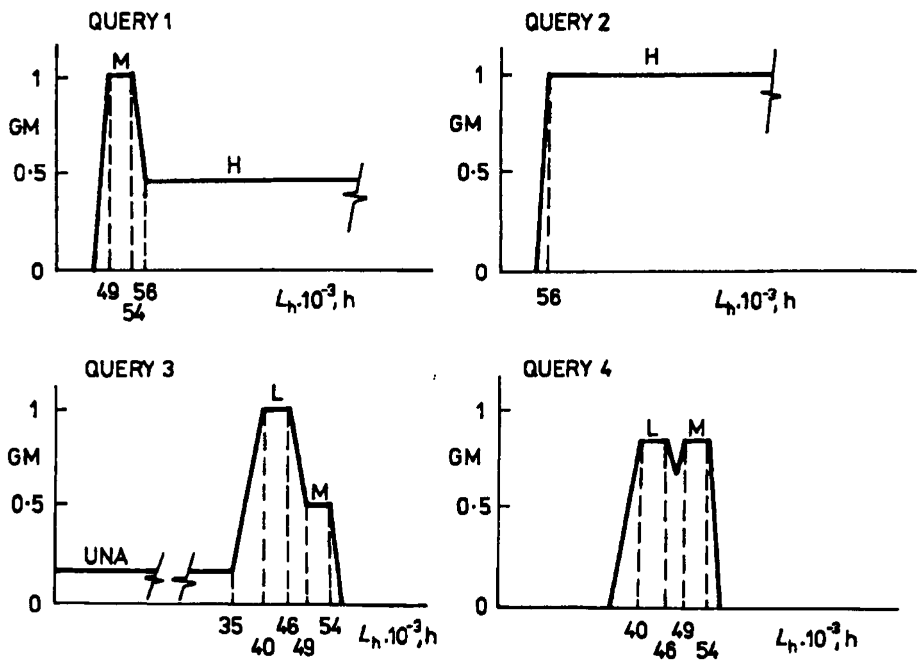

FIG. 3
Graphical interpretation of the example results (tube service life)

representative of the fuzzy set usually the value having the highest grade of membership is selected.

The fuzzy expert system[2] enables an operative modification of the knowledge base and an exchange of dependent and independent variables. In case of the steam reforming a situation can take place for instance when it is necessary to foresee the amount of fuel gas in order to obtain a certain methane conversion into carbon dioxide and monoxide. Then the conversion (x) becomes an independent variable quantity and the burner input ($\dot{V}_{tp}$) a dependent variable quantity. In this case a quick estimate of quantity required reveals advantageous. The simulation model[1] is conceived so that the quantity $\dot{V}_{tp}$ is always an independent variable and the quantity x always a dependent variable. An estimate of fuel gas amount necessary for obtaining the conversion required is only possible by evaluating several variants, whereby function dependence of conversion on the amount of fuel gas can be obtained. If we take into account the duration of the simulation calculation we can find out that is a considerably time-consuming operation. Also a combined utilization of the fuzzy expert system and the mathematical model in case of simulation is possible. By means of the expert system a fuzzy

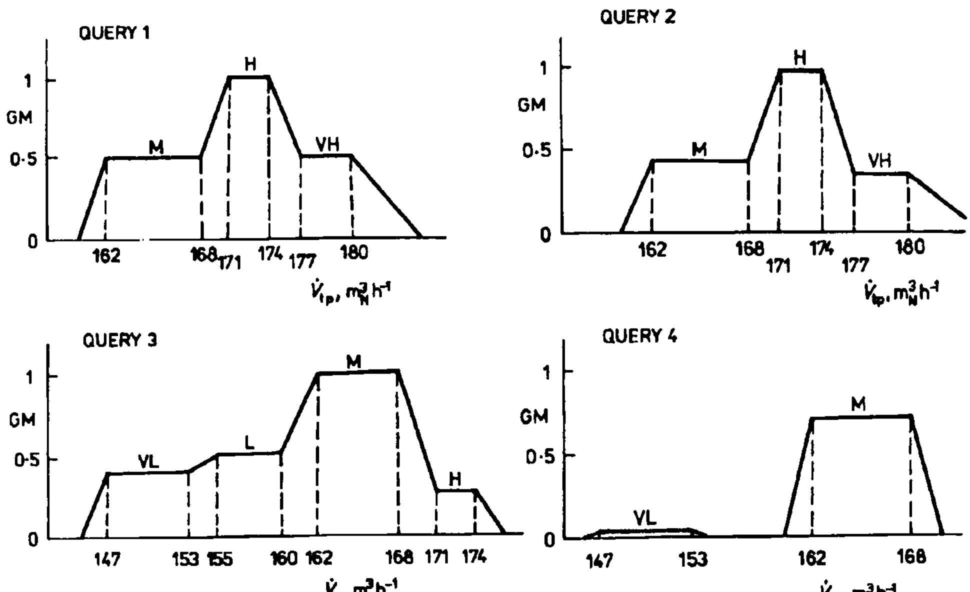

FIG. 4
Graphical interpretation of the example results (burner input)

set for the quantity $\dot{V}_{tp}$ can be obtained. The grade of membership GM specifies in detail the range of $\dot{V}_{tp}$ values taken into consideration. Then a small number of simulation calculations is sufficient since the interval of burner input values necessary to obtain the conversion required is exactly limited. The input data in case that $\dot{V}_{tp}$ expresses a dependent variable and x an independent variable are similar to the foregoing examples, the only difference being that instead of the variable No. 9 ($\dot{V}_{tp}$) the variable 9′ (x) is used together with the combination of the linguistic and numerical input data in query No. 2. A graphical illustration can be seen in Fig. 4.

SYMBOLS

ABSUNA	absolutely unacceptable
E	activation energy, kJ mol^{-1}
GM	grade of membership
H	high
H_2O/C	water vapour to hydrocarbons rate
L	low (small)
L_h	reaction tube service life, h
L_p	burner flame length, m
LG	long
LIM	limit
M	medium
$\dot{Q}_{sp}$	heat flux liberated during fuel combustion, MW
$\dot{Q}_z$	heat losses, % $\dot{Q}_{sp}$
r_{01}	catalyst activity, mol kg^{-1} s^{-1}
S	standard
SH	short
UNA	unacceptable
UNRE	unreal
$\dot{V}_{tp}$	fuel gas amount, m_N^3 h^{-1}
VH	very high
VL	very low (very small)
x	methane conversion
ε_t	emissivity of reaction tube surface
$\lambda^{(1)}$	inlet excess air
$\lambda^{(2)}$	outlet excess air

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