Optimization of the gas drying process in the production of hydrogen by training the fuzzy Sugeno model

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Abstract: The article deals with the processes associated with obtaining and drying hydrogen under steam-carbon dioxide conversion of methane. A fuzzy Sugeno model has been created, and with the help of the training this model, a sample of process parameters has been obtained, some of which values worsen the process, and some, on the contrary, are optimal for its flow.

1. Introduction
At the moment, there is a problem of non-renewable natural resources in the world, and there are various ways to solve it, in this particular case, it is hydrogen power. There are many different ways of producing hydrogen: steam methane conversion, steam-carbon dioxide methane conversion, plasma conversion of hydrocarbons, etc. [1]. In the production of hydrogen in some ways, for example by steam-carbon dioxide conversion of methane, there is a problem of dehydration of hydrogen before transportation, or further use in production. This paper is devoted to solving the problem of hydrogen drying by the Sugeno fuzzy modeling method.

2. Research
The task is as follows: to determine the appropriate technological scheme for gas drying and the sampling of the input parameters of the technological process, create a mathematical model on the basis of this scheme and using the software package Matlab determine the values of process parameters and how they influence the flow of this technological process as well as identify the optimal values.

Hydrogen production technologies are definitely energy-intensive and cost-effective, but the physical and chemical properties of hydrogen give undoubted advantages over other types of energy resources, such as oil and natural gas. The advantage of hydrogen over natural gas is its power capacity and density: the natural gas has a power capacity of natural gas is about 40 MJ/kg, and that of hydrogen – 140 MJ/kg, but 1 kg of methane is equal to 1400 liters and 1 kg of hydrogen – 11200 liters; the latest is not a non-renewable natural gas resource [2]. Also, the production and use of hydrogen in the power sector is more environmentally friendly and makes it possible to make the power supply system decentralized.

The idea of using hydrogen in power engineering is not new. In the 80s of the XX century, hydrogen fuel engines were developed [2]. National and international programs for the development of elements of hydrogen power, including renewable energy sources, are being adopted and implemented in the USA, the EEC countries, Japan and China, and an active propaganda campaign is being carried out. In Madrid, Rome, Amsterdam, Stockholm and other European capitals there are buses on hydrogen. An electric car with a hydrogen engine was purchased by the Prime Minister of Japan, and Iceland is almost
completely switched to hydrogen power: hydrogen engines are installed on boats and cars, houses are heated by heat sources on hydrogen.

The desire of Europe and the USA to develop alternative energy is advisable: Europe does not possess its own oil and gas resources, the USA possess those, but in a small amount. The transition to hydrogen power with the use of renewable energy will allow them to cease to depend on the oil and gas suppliers – Russia and the OPEC (Organization of Petroleum Exporting Countries) countries, as well as solve environmental problems.

In this paper, it is proposed to simulate the process of dehydration of hydrogen during steam-carbon dioxide conversion of methane. The flow diagram of the technological process of hydrogen production (Figure 1) in the paper of the author [3] describes the process of steam-carbon dioxide conversion of methane, after which hydrogen-saturated hydrogen vapor with a volume fraction of 2.6% in a mixture with hydrogen leaves.

![Figure 1. Technological scheme of conversion of methane with water steam to produce hydrogen (configuration with upper heating).](image)

In the case of steam-carbon dioxide conversion of methane in the presence of hydrogen [1], the composition of the source gas is close to the methanol synthesis reaction, in the temperature range from 300°C to 340°C, oxide and carbon dioxide in the feed gas, the carbon dioxide reduction reaction proceeds simultaneously with the methanol formation one:

\[
CO + 2H_2 \leftrightarrow CH_3OH \quad \Delta H_{298}^0 = -21.664 \text{ kcal/mole}
\]

\[
CO_2 + H_2 \leftrightarrow CO + H_2O \quad \Delta H_{298}^0 = 9.838 \text{ kcal/mole}
\]

The last reaction under the conditions of synthesis proceeds practically up to chemical equilibrium, and as a result, carbon dioxide can influence the equilibrium concentration of methanol. The degree of influence is determined by the concentrations of the reacting components and the technological parameters of the process. In any case, the participation of carbon dioxide in the side reactions can be neglected due to the small amount of impurities formed, but the carbon dioxide reduction reaction cannot be neglected.

For this process, the structure of the drying process model of the gas in the absorber is shown in Figure 2.
Figure 2. Model structure of the technological process.

Input variables have the following meaning: $X_1$ is gas flow rate; $X_2$ is the amount of diethylene glycol; $X_3$ is drying process temperature; $X_4$ is the drying process pressure.

Output variables: $y_1$ is the drying efficiency. The internal nodes of the neural network correspond to the structural elements of the absorber: 1 - input node, 2 - contact centrifugal elements, 3 - nozzle in the form of rings, 4 - filter, 5 - cartridges, 6 - diethylene glycol feeding unit.

In determining the statistical data obtained on the basis of the experience of the technological flow diagram of the author [4] for the countercurrent dehydration gas, during natural gas drying, the statistical data specified in [5] were obtained. Since the statistical data on the production of hydrogen cannot be obtained, based on the physical properties of hydrogen, statistical data were compiled for hydrogen. In view of the fact that the density of hydrogen is 8 times less than that of natural gas, it means that for 1 m$^3$ for drying, 8 times less diethylene glycol is needed. For the efficiency of drying a coefficient improving the process of drying natural gas (reducing the temperature of the dew point) is taken. When compiling the table, the following data were obtained (Table 1).

Table 1. Drying efficiency for hydrogen.

| Gas flow rate, (H$^2$) | The amount of diethylene glycol | Process temperature $^\circ$C | Process pressure | Drying efficiency of gas |
|------------------------|---------------------------------|-------------------------------|------------------|------------------------|
| m$^3$/h.               | kg/m$^3$.                        |                               |                  |                        |
| 1112                   | 4.3                             | 14                            | 4                | 59.85                  |
| 960                    | 5                               | 13                            | 4.6              | 27.01                  |
| 1040                   | 10.7                            | 15                            | 5.2              | 61.31                  |
| 824                    | 16                              | 15                            | 5                | 78.10                  |
| 864                    | 13.2                            | 15                            | 4.5              | 68.98                  |
| 664                    | 12                              | 15                            | 4.3              | 72.63                  |
| 640                    | 12.3                            | 15                            | 4.3              | 61.68                  |
| 1040                   | 9                               | 13                            | 4.4              | 90.88                  |
| 1064                   | 1.3                             | 12                            | 4.4              | 41.61                  |
3. Results and discussion

3.1. RESULTS 1.

At this stage, the technological process of steam-carbon dioxide conversion of methane was chosen for further consideration and analysis, the technological flow diagram of hydrogen production was selected (Figure 1), a mathematical model was created (Figure 2) and statistical data for further modeling (Table 1) were obtained.

Based on the initial data (Table 1), this article proposes to predict the process of hydrogen dehydration efficiency by creating and teaching a fuzzy Sugeno model containing parameters affecting the drying efficiency.

Forecasting the efficiency of gas drying is a typical task of nonlinear regression analysis. Forecasting the efficiency of gas drying is carried out according to the following process parameters: amount of diethylene glycol, gas flow rate, process temperature, process pressure, drying efficiency.

Data for calculating the efficiency of hydrogen drying were taken from the author’s paper. The efficiency of hydrogen drying $\phi_{H_2}$ is calculated by the formula (1):

$$\phi_{H_2} = \frac{100}{(T_{CH_4(MAX)} - T_{CH_4(MIN)})} \times T_{CH_4(tek)}$$

where $T_{CH_4(MAX)}$, $T_{CH_4(MIN)}$, $T_{CH_4(tek)}$ are temperatures (maximum dew point, minimum dew point, current temperature of natural gas).

Using the Matlab programming environment, the procedure for evaluating the information content of the process parameters on the basis of rough input-output models is described (Figure 3).
Figure 3. Rough input-output models:

amount of diethylene glycol - Q, gas flow - V, process temperature - T, process pressure - P, drying efficiency – E.

3.2. RESULTS 2.
As can be seen from the graph, the most informative sign is the gas flow rate, and the second one is the pressure of the technological process. For gas flow rate, the value of the discrepancy for the training sample is 0.1856, and for the test sample it is 0.2141.

The discrepancies in the test and training samples are of the same order, therefore, one more input variable can be added to the model. It would be logical to select the gas flow rate and pressure to compile the ANFIS model, but this directive approach does not guarantee that the chosen ANFIS model with two inputs will provide the maximum forecast accuracy.

The figure (Figure 4) shows the graph of the procedure for evaluating the information content for the pairs of variables.

Figure 4. Testing of rough models "two inputs - one output"

3.3. RESULTS 3.
The most informative pair of features are gas flow rate and process pressure, for them the discrepancy value for the training sample is 0.0248, and for the test sample it is 0.4732. The difference in the
discrepancies on the training and test samples increases, which signals the effect of the model complication.

The figure (Figure 5) shows a graph of the procedure for evaluating the information content for triples of variables.

![Graph showing discrepancies on training and test samples](image_url)

**Figure 5.** Testing of rough models "three inputs - one output".

### 3.4. RESULTS

The best forecasting is provided by the model with such input variables: gas flow rate, process temperature, process pressure, for them the discrepancy value for the training sample is 0, and for the test sample it is 0.4649.

The minimal discrepancies on the training and test samples did not significantly decrease in comparison with the model "two inputs - one output". Therefore, adding one more input variable to the steam gas flow rate and the process pressure does not greatly increase the accuracy of predicting the efficiency of gas drying. To provide better generalizing properties, it is preferable to use simpler models, so for the further research the model "two inputs - one output" is selected (Figure 4).

The figure (Figure 6) shows the training results of the selected two-input model. In the previous stages, candidate models were trained using the function only during the first iteration of the ANFIS algorithm. This is done to quickly select a suitable set of input variables. When selecting input variables, it can be spend more time for training systems using several iterations.

![Training results of selected two-input model](image_url)

**Figure 6.** Testing of rough models "three inputs - one output".
3.5 RESULTS 5.

The figure (Figure 6) shows the dynamics of training a fuzzy model in the form of the dependence of learning errors (lower curve) and testing (upper curve) on the number of iterations of the algorithm. The minimum of the test error is achieved still by the 1st iteration of the algorithm. Then the test error increases, which indicates the effect of retraining, i.e. the loss of the model generalization properties. The minimum point is marked on the graph by a circle.

The figure (Figure 7) shows several kinds of input and output surfaces for the best two-input ANFIS model, which takes into account the gas flow and process pressure, which is a fuzzy model with a minimum test error.

a)
3.6. RESULTS 6.
For the model depicted in figures (Figure 7 (a, b, c)), the discrepancies in the training and test samples are 0.473 and 0.225, respectively.

The sections of the yellow color of the model show a high efficiency of gas drying, close to 100%, and blue sections show ineffective drying. However, considering the far corner of red color, gives a forecast for improving the efficiency of gas drying, i.e. increasing pressure and diethylene glycol consumption during the hydrogen drying process can significantly improve its dehydration, especially since the drying efficiency was calculated for natural gas based on the dew point temperature. The dew point temperature of hydrogen, based on its physical properties, is much lower than that of natural gas.

The yellow area with the minimum amount of diethylene glycol and process pressure gives an understanding that other factors also affect this technological process, but their effect is much less than the amount of diethylene glycol and pressure during the technological process. Such unexpected behavior is explained by the absence in the training sample of the factor space data in this area.

As a result of training the fuzzy Sugeno system, it was found out that the maximum dehydration of gas in the hydrogen production is more dependent on the pressure and gas flow rate. The system showed a minimum test error for the 1st iteration.

4. Conclusion
For hydrogen dehydration, the countercurrent absorption scheme after steam-carbon dioxide conversion of methane is analyzed in this paper. A mathematical model is created in which the parameters influencing the process of hydrogen drying are gas flow rate, amount of diethylene glycol, drying process temperature, drying process pressure. For these parameters, statistical values are determined when the process passes. Based on these statistics, Sugeno fuzzy modeling is performed, the parameters are determined which values maximize the efficiency of gas drying: there are the gas flow rate and process pressure. The fuzzy model is trained, the optimal influence on the technological process is provided by the 1st iteration of the algorithm. Based on these data, the ANFIS model was obtained and analyzed in the Matlab software package.
As a result of the analysis, it was found out that the discrepancies in the training and test samples are equal to 0.473 and 0.225, respectively. The maximum efficiency of drying is achieved with the maximum increase in the gas flow and the increase in the pressure of the technological process. At maximum process pressure and minimum gas consumption, the gas drying efficiency is minimal.

References
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