# Possibilities of Minimization of Influence of Measurement Errors in Expert System with Fuzzy Control

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*Abstract* - **Investigation of work of expert system with fuzzy control with presence of measurement errors is very important, because measurement errors can cause wrong choice of working regime, which can result with great disturbance of regulated values and incorrect work of the system.**

*Keywords* - **Expert system, Fuzzy control, Measurement errors, Random errors, Working regime**

## I. INTODUCTION

Investigation of work of expert system with fuzzy control with presence of measurement errors is performed on expert system with fuzzy control for dehydrator for raw vegetable mass, which model is developed in Laboratory for Thermal Engineering and Energy in Institute for Nuclear Sciences Vinca. In mentioned expert system regulated values are outlet temperature which should be set by user, fuel flow rate and belt conveyer speed for inserting material in a dryer, which are selected from knowledge base to achieve optimal working regime. Values which are input in system are measured fuel flow rate, measured outlet temperature, measured inlet material moisture which is parameter for choosing working regime, and averaged inlet material layer height, which is not measured, but it is entered as a parameter. In paper three types of error are shown.

1. Systematic error in averaged inlet material layer height
2. Random measurement error of fuel flow rate
3. Random measurement error of inlet material moisture

Examination of measurement error of outlet temperature is not necessary, because this error can cause only a fact that outlet temperature is different from nominal value, although operator on system on a basis of measurement can see that it is equal to nominal value. This error could be detected only with additional measurement system, which has greater accuracy from accuracy of devices in regulation contour. Influence of other types of errors, which could be found in system, is examined by simulation program. Influence of every type of error on system work has been separately examined.

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## II. INVESTIGATION OF INFLUENCE OF SYSTEMATIC ERROR OF AVERAGED INLET MATERIAL LAYER HEIGHT

In investigations is shown that this type of error can cause steady state error, i.e. system keeps outlet temperature on value different from nominal. For that reason new way of fuzzification of deviation of fuel flow rate from nominal value is introduced. If error of averaged inlet material layer height exists, this is possible with combination of different control rules to achieve steady state with outlet temperature different from nominal value. During fuzzification of fuel flow rate which has been defined in the beginning of system configuration, for fuel flow rate disturbance value defined by parameter KFf, linguistic value related to middle disturbance of fuel flow rate had membership rate equals one, and other linguistic values related to disturbance of fuel flow rate had membership rate equals zero. For fuel flow rate deviation value of 2KFf, all linguistic values related to disturbance of fuel flow rate had membership rate equals zero, except linguistic value related to large deviation of fuel flow rate, which had membership rate equals one. Idea is that value of deviation of fuel flow rate, when linguistic value related to large deviation of fuel flow rate obtains membership rate equals one, will not 2KFf, but larger, 5KFf, as it is shown in figure 1.1. This way of fazification in great part decreases possibility that with combining of appropriate control rules system achieves steady state with outlet temperature different from nominal value, with good dynamic preferences achieved with choice of parameter of fuzzification KFf=1.

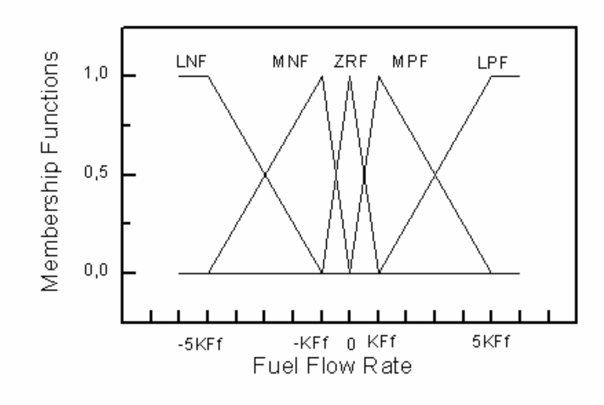


Figure 1.1: Modified way of fuzzification of deviation of fuel flow rate from nominal value

Influence of this error is examined by recording disturbance responses of system with different values of error in layer height. These diagrams are shown in figure 1.2. Disturbance was -0.1 kgw/kgdm, i.e. decreasing of inlet material moisture from 2.6 to 2.5 kgw/kgdm has been simulated. Step responses has been also examined with presence of errors, but from these responses same conclusions could be made as from disturbance responses, and for that reason these results are not shown in further work. In figure 1.2 disturbance response for layer height error of 15mm is shown. From diagram it could be seen that deviation in averaged layer height results with instability, i.e. few oscillations of outlet temperature exist before stabilization. Reasons for that instability are in fuzzy control rules. Due to positive error in layer height, small decreasing of temperature from nominal value will activate appropriate fuzzy control rules, which will cause increasing of fuel flow rate and new positive deviation of temperature. Similar situation occurs with negative deviation of averaged layer height caused by increasing of temperature from nominal value. In any case averaged layer height error does not cause steady state error of outlet temperature. For better and more stabile work of system is desirable that averaged layer height error should be as small as possible, with absolute value less then 10mm, which is not difficult to achieve, even in industrial application. But presence of larger averaged layer height error is not great problem, because disturbance, after few oscillations, attenuated for less then 15 minutes, and maximal deviation of outlet temperature after disturbance does not grow with grow of averaged layer height error.

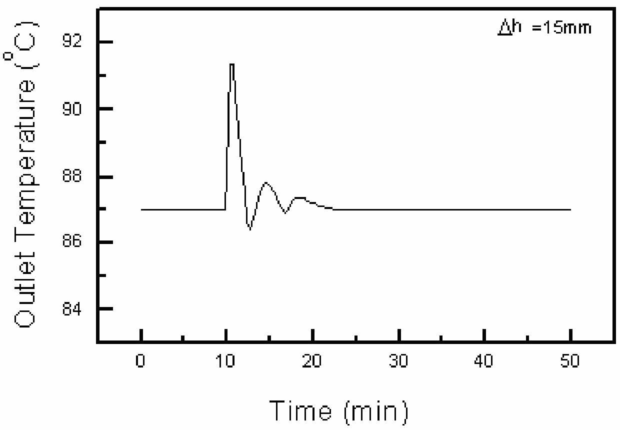


Figure 1.2: Disturbance response of system for averaged layer height error of 15 mm

## III. INVESTIGATION OF INFLUENCE OF RANDOM MEASUREMENT ERROR OF FUEL FLOW RATE

Random measurement error of fuel flow rate can cause great disturbance in process of fuzzy control, and we have to take into account that measurement of fuel flow rate is in control contour. If outlet temperature is equal to nominal value, measurement error of fuel flow rate have not any influence, because on a basis on fuzzy control rules for zero deviation of outlet temperature from nominal value, for every deviation of fuel flow rate, zero output is always generated. But in case of disturbance, measurement error of fuel flow rate can cause great problems. In figure 2.1 disturbance responses with presence of random measurement errors of fuel flow rate are shown. Maximal value of random measurement error of fuel flow rate has been changed, and disturbance responses have been recorded for disturbance of inlet material moisture of -0.1kgw/kgdm. Diagrams are recorded for maximal value of random measurement error of fuel flow rate of 1%, 3% and 5%. As could be seen from figure 2.1, for random error value of 1%, disturbance of outlet temperature attenuated after few oscillations. But for random measurement error of fuel flow rate of 3% and larger, outlet temperature is not attenuated, but continue with oscillations with changeable amplitude, lesser then 1°C. This behavior of system is not correct, and it is necessary to perform detailed examination of system with presence of measurement error of fuel flow rate.

Fuel flow rate is measured by three sensors, by measurement of volume fuel flow rate, fuel temperature and fuel pressure. Value of fuel flow rate is obtained from equation:

$$Gg = (360000 / \Delta t \cdot Pg \cdot 273.16 \cdot \rho f)$$
$$/(273.16 + Tg)$$

(2.1)

In equation 2.1 Δt is time between two pulses of device for measurement volume fuel flow rate, Pg is fuel pressure, ρf is density of fuel which is exactly known, and Tg is fuel temperature which is measured. Equation for relative measurement error of fuel flow rate is:

$$\frac{\Delta Gg}{Gg} = \sqrt{\left(\frac{\Delta(\Delta t)}{\Delta t}\right)^2 + \left(\frac{\Delta Pg}{Pg}\right)^2 + \left(\frac{\Delta Tg}{Tg + 273.16}\right)^2}$$

(2.2)

Largest part of fuel flow rate measurement error is error of interpolation polynom in measurement of fuel pressure. This error is constant for constant values of pressure, and it does not change from iteration to iteration, as it is declared in simulation software. Random measurement errors of fuel flow rate, which changes from iteration to iteration, are small, lesser than 1%. Decreasing of influence of these errors by filtration of measured signal of fuel flow rate is not possible, because this filtration introduces integral effect in control contour, and causes great instability. As a greater part of measurement error is caused by interpolation polynom, it is necessary to examine influence of this error on system behavior. For small changes of fuel pressure it is possible to calculate with constant error of interpolation polynom in measurement of fuel pressure. When in simulation program constant error of fuel flow rate of 1% and 3% is defined, which is maximal value of this error, and after disturbance of inlet material moisture is simulated, responses will be obtained as it is shown in figure 2.2. From these diagrams it could be seen that system for both values of error attenuates after disturbance after about ten minutes, but with increasing of error, deviation of outlet temperature is increasing, and it is very large for error of 3%. Influence of these errors could be minimized with precise calibration and with finding better interpolation polynoms, with lesser interpolation error. But there could be concluded that in fuzzy control system measurement error of fuel flow rate is a large problem, and presence of this error decreases performances of fuzzy controller. This means that system is very sensitive on measurement error of fuel flow rate. Although in this case these errors could be minimized with precise calibration, with finding better interpolation polynoms, and with using better pressure sensor, though it is very interesting to examine any possibility of improvement of fuzzy controller, which will decrease sensitivity of system on measurement error of fuel flow rate.

One possibility for improving performances of fuzzy controller, which could decrease sensitivity of system on measurement error of fuel flow rate, is using differential effect on system output. Idea is that differential effect should be added on system output obtained by fuzzifcation, i.e. difference of output from current and previous iteration, multiplied with appropriate time constant of differential effect, and divided with signal sampling rate. Due to integral effect of executable device, this differential effect could increase system stability. On the basis on fuzzy control rules output fuzzy linguistic variables are generated. After that, defuzzification is performed, and output variable is obtained, which is used as control signal for valve after multiplying with calibration factor and after DA converting. This variable is defined as "output". It is necessary to examine system behavior with differential effect used in output generation described in previous text, i.e. with calculating new output variable which is after multiplying with calibration factor used as input for DA converter. This new variable will be defined as "output2", and will be calculated as it is shown in equation 2.3:

$$output\ 2(n) = output\ (n) + \frac{Td}{ts} \cdot \left(output\ (n) - output\ (n-1)\right) \qquad (2.3)$$

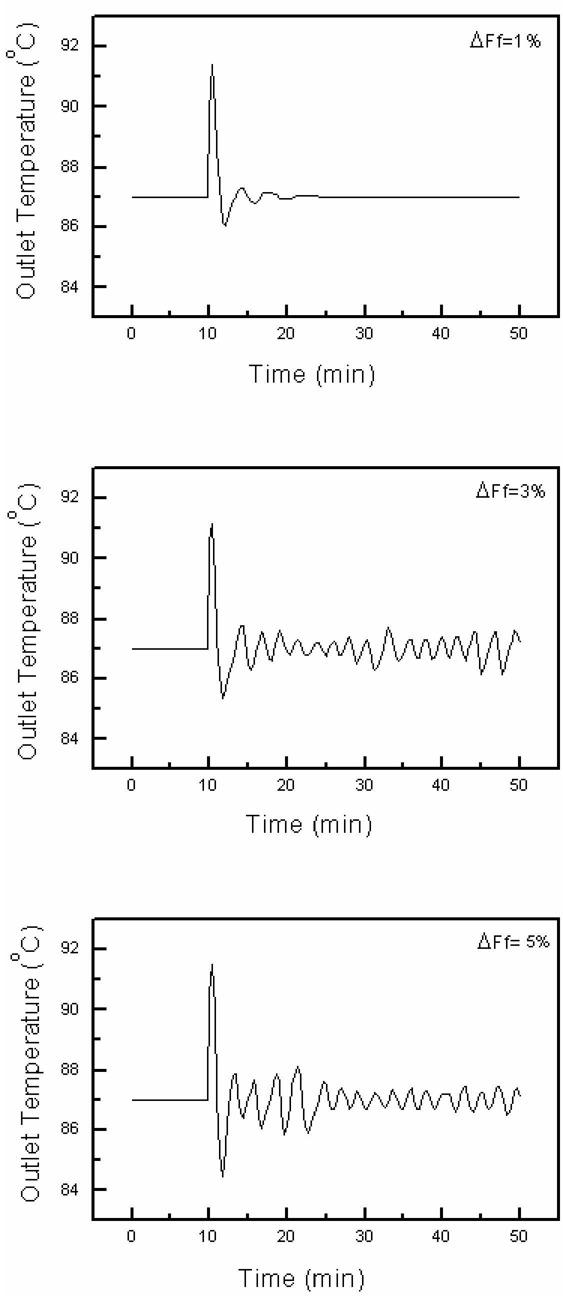


Figure 2.1: Disturbance response of system for different values of random measurement error of fuel flow rate

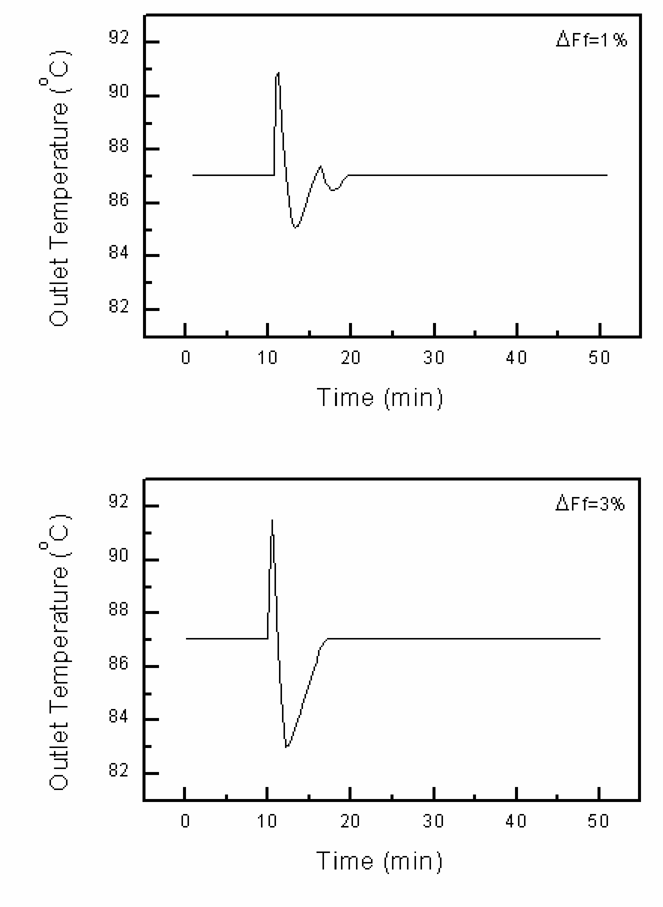


Figure 2.2: Disturbance response of system for different values of random measurement error of fuel flow rate caused by error of interpolation polynom in measurement of fuel pressure

Variable "output2", should be multiplied with calibration factor and should be used as input for DA converter. This variable in current iteration is calculated on the basis of variable "output" in current and previous iteration, obtained by defuzzification, and on the basis on time constant of differentiation Td and of the sampling rate ts, which is period of activation of timer-control for activating one iteration of fuzzy control, and it is equal 4s. Choice of time constant of differentiation is done by simulation of step and disturbance response for different values of this parameter.

Now is possible to examine system behavior with differential effect with presence of random measurement error of fuel flow rate. First examination has been for random measurement error, which changes from iteration to iteration, and disturbance response has been recorded for deviation of -0.1 kgw/kgdm. Difference between responses with and without differentiation is very large, and it is possible to conclude that differential effect in output generation is notably decreasing sensitivity of the system on the random measurement error of fuel flow rate.

Most important thing with differential effect in output generation is, that even with measurement error of fuel flow rate of 5%, there are no permanent oscillations after disturbance, which has existed in system without differential effect. For every value of random measurement error of fuel flow rate up to 5%, system attenuated after disturbance for less then 10 minutes, with maximal deviation of outlet temperature, which is not larger, then deviation without measurement error of fuel flow rate. Results obtained by simulation for fuzzy controller with differential effect are shown in figure 2.4.

It is necessary to examine system behavior with measurement error of fuel flow rate caused by error of interpolation polynom in measurement of fuel pressure, with differential effect in output generation, which is shown in figure 2.3. For small changes of fuel pressure it is possible to calculate with constant error of interpolation polynom in measurement of fuel pressure, and this case also could be used for investigation of sensitivity of fuzzy controller on systematic measurement errors of fuel flow rate. Negative deviation, which occurs after disturbance with this type of error without differential effect, has been almost 5$^{o}$C, and outlet temperature has attenuated after about 10 minutes. Negative deviation in same situation, but with differential effect with time constant Td=15s, is lesser then 2$^{o}$C, a temperature attenuates after about 5 minutes. It is possible to conclude that differential effect in output generation is great improvement in decreasing sensitivity on measurement errors of fuel flow rate.

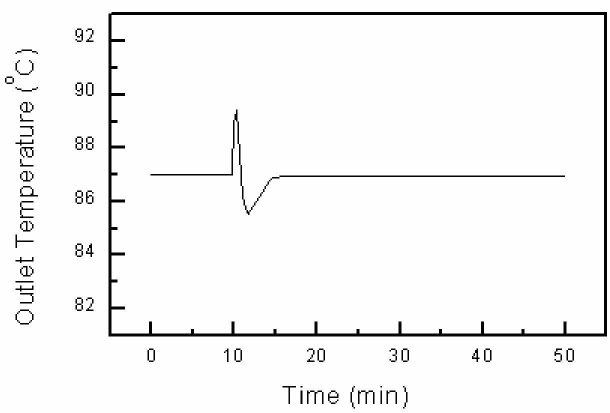


Figure 2.3: Disturbance response of system with random measurement error of fuel flow rate caused by error of interpolation polynom in measurement of fuel pressure of 3%, with differential effect in output generation with time constant Td=15s

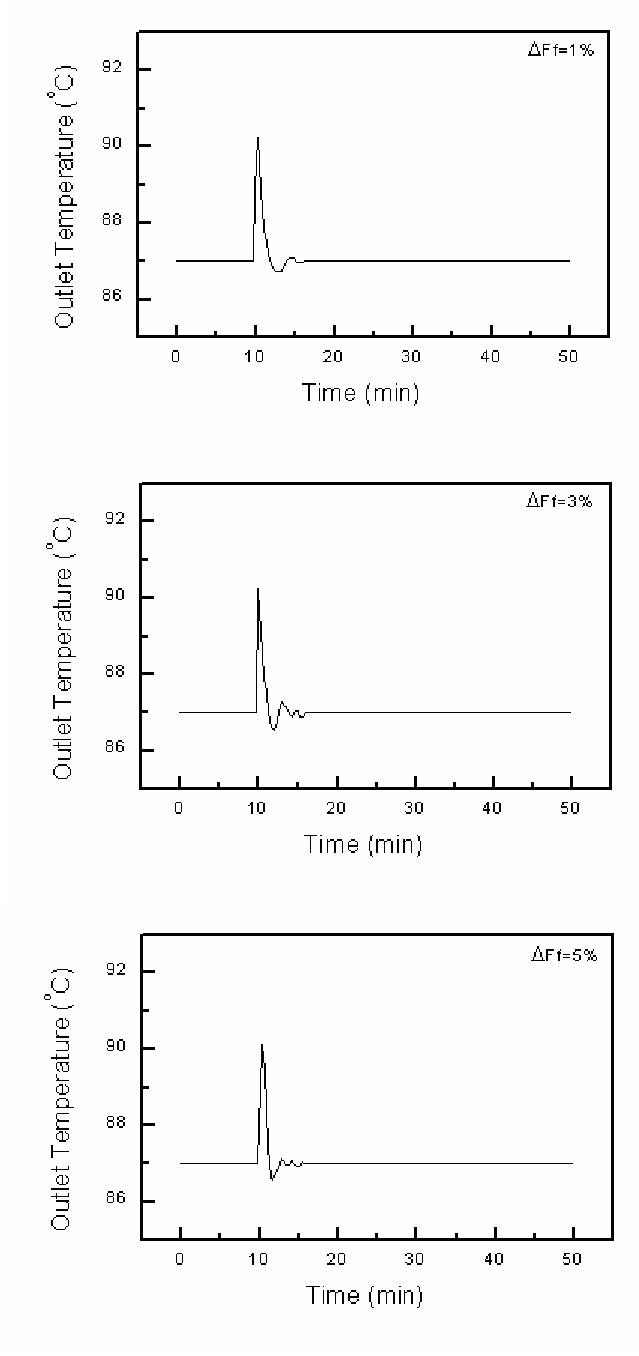


Figure 2.4: Disturbance response of system for different values of random measurement error of fuel flow rate with differential effect in output generation with time constant Td=15s

## IV. INVESTIGATION OF INFLUENCE OF RANDOM MEASUREMENT ERROR OF INLET MATERIAL MOISTURE

Influence of random measurement error of inlet material moisture is a little bit different from influence of random measurement error of fuel flow rate. Unlike from measurement of fuel flow rate, measurement of inlet material moisture is not in control contour, but it is used for choice of working regime. It is necessary to examine influence of frequent changes of working regimes caused by random measurement error of inlet material moisture on system behavior. Especially is unsuitable case where random measurement error of inlet material moisture causes frequent changes of belt conveyer speed. When outlet temperature is equal to nominal value, due to choice of control rules, zero output always will be generated, unaffected by measurement error of inlet material moisture. But if measurement error of inlet material moisture will cause choice of working regime with new belt conveyer speed, that will cause disturbance of temperature, with problematic attenuation for larger values of error. It is interesting to see disturbance response of system with random error of inlet material moisture, without changes of belt conveyer speed. Investigations shows that grow of random measurement error of inlet material moisture introduce instability in system. For error of 5%, system does not attenuate after disturbance, but continue with oscillations with maximal amplitude of 2°C. These results are shown in figure 3.1. It is possible to conclude that maximal random measurement error of inlet material moisture, which could be tolerated, is 3%, if control system will not be changed.

But if working regime is examined, where measurement error of inlet material moisture causes to changes of belt conveyer speed, situation is more unsuitable. This case is shown in figure 3.2. To avoid changes of belt conveyer speed caused by noise, i.e. by inhomogeneity of inlet material moisture, during synthesis of fuzzy controller is decided to change nominal belt conveyer speed in system only if both fuzzy values which describe inlet material moisture and which have membership rate greater then zero, are related to value of nominal belt conveyer speed in knowledge base different from current nominal belt conveyer speed. But if measurement error of inlet material moisture exists, there is possible to have superposition of noise and measurement error, which will cause frequent changes of belt conveyer speed. It is possible to find that in some cases, even a small random measurement error, causes frequent changes of belt conveyer speed. Outlet temperature always has small oscillations caused by noise in a signal of inlet material moisture, i.e. caused by inhomogeneity of inlet material moisture, and this is always present in system where inhomogeneity of inlet material moisture exists. But changes of belt conveyer speed caused by measurement error are not allowed. In order to cause changes of nominal belt conveyer speed, measurement error of inlet material moisture should cause a case that both fuzzy variables related to inlet material moisture, in knowledge base, are related to new value of belt conveyer speed. If nominal belt conveyer speed in system was 62.5 m/h, and real value of inlet material moisture was a little bit larger then 2.45 kgw/kgdm, superposition of noise and measurement error, which will cause inappropriate change of nominal belt conveyer speed to 65m/h, should be a little bit larger then 0.05 kgw/kgdm, according to knowledge base. It is possible to conclude that superposition of noise and error with absolute value larger than 0.05 kgw/kgs can cause oscillations of nominal belt conveyer speed. But if nominal belt conveyer speed is equal to 62.5m/h, and real value of inlet material moisture is a little bit larger than 2.4 kgw/kgdm, minimal noise can cause change of nominal belt conveyer speed to 65m/h. To turn back nominal belt conveyer speed to

62.5 kgw/kgdm in next iteration, measured value of inlet material moisture should be larger than 2.45kgw/kgdm, which means that error with noise which will cause that, should be 0.05 kgw/kgdm. It is possible to imagine more unsuitable case. If nominal belt conveyer speed is 62.5m/h, and real value of inlet material moisture is a little bit larger than 2.425 kgw/kgdm, value of error with noise a little bit larger than 0.025 kgw/kgdm could cause change of nominal belt conveyer speed to 65m/h, and same error with opposite sign, in next iteration, could cause new change of nominal belt conveyer speed to 62.5m/h. These examples from knowledge base are used to illustrate situation, and same things could be concluded for some other values of inlet material moisture and belt conveyer speed. As it noise in system is defined as random value in range from -0.025 to +0.025, which should be added on value of inlet material moisture, that could be seen that theoretically is possible, even without any error, only due to noise, i.e. inhomogeneity of inlet material moisture, to obtain frequent changes of nominal belt conveyer speed.

This problem could be solved with filtration of inlet material moisture according to following equation:

$$Uin(n) = Uin(n-1) + (Uin(n) - Uin(n-1)) \cdot \frac{ts}{Tf} \tag{3.1}$$

In equation 3.1 ts is sampling time, i.e. period of activation of timer-control for activating one iteration of fuzzy control, and it is equal 4s, while Tf is time constant of filtration of measured inlet material moisture.

Measurement of inlet material moisture is not in regulation contour, and this filtration does not introduce instability in system. But large time constant of filtration of inlet material moisture is not good, because disturbance response of system becomes slower, when new working regime should be chosen. It is necessary to find minimal time constant of filtration for known value of random measurement error of inlet material moisture, to avoid changes of nominal belt conveyer speed with noise. In every iteration, measured inlet material moisture is multiplied with filter factor ts/Tf. It is necessary to choose time constant, which will decrease eventual measurement error enlarged with noise, and multiplied with filter factor, to be less than value, which could cause frequent changes of belt conveyer speed, less than 0.025 kgw/kgdm.

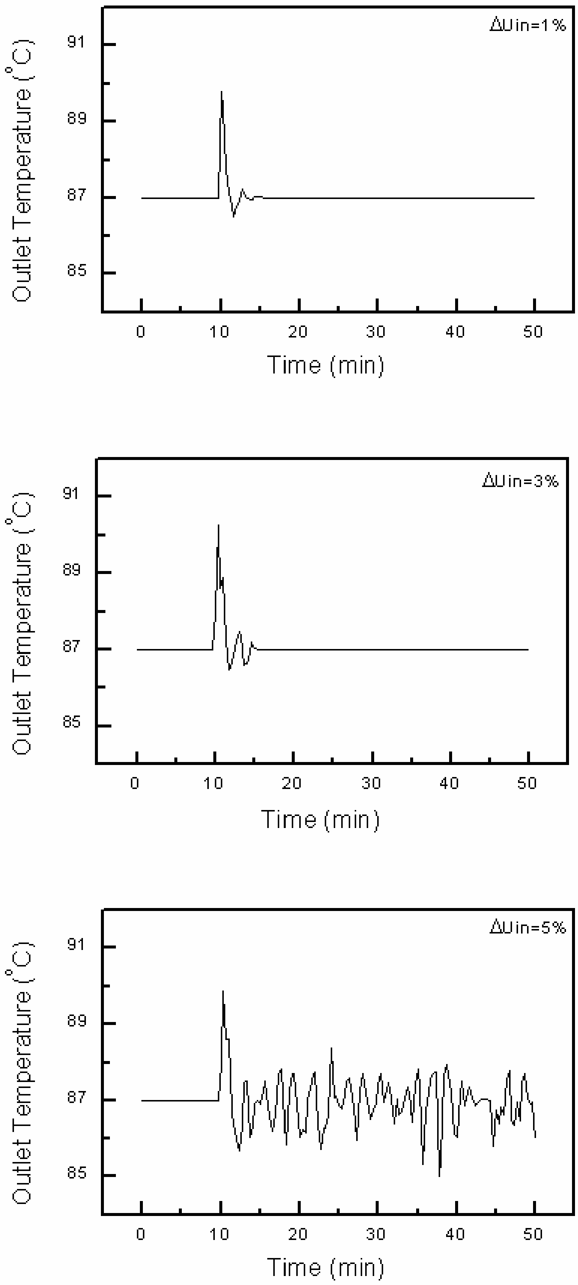


Figure 3.1: Disturbance response of system with different values of random measurement error of inlet material moisture

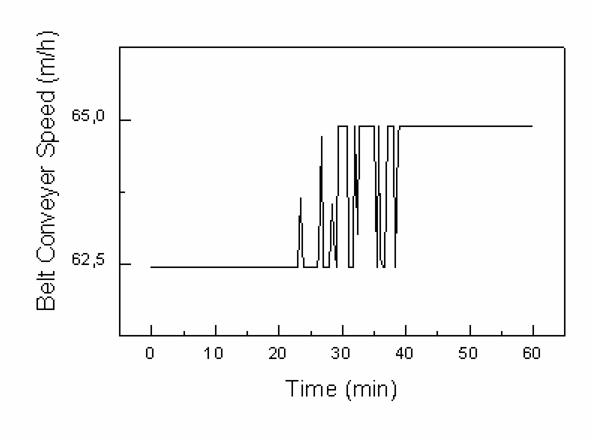


Figure 3.2: Changes of belt conveyer speed caused by the sinusoidal change of inlet material moisture with amplitude of 0.1kgw/kgdm and period of 300 minutes, with random measurement error of inlet material moisture of 1%

When accumulation of error is taken into account, maximal allowed measurement error enlarged with noise and multiplied with filter factor should be less than half of this value, i.e. should be less than 0.0125 kgw/kgdm. With this criterion, for different values of random measurement error of inlet material moisture, necessary time constants of filtration are calculated, and inserted in table 3.1.

| ΔUin (%) | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| ΔUin+noise (kgw/kgdm) | 0.06 | 0.095 | 0.52 | 0.66 | 0.80 |
| Tf (s) | 20 | 35 | 45 | 60 | 70 |

Table 3.1: Necessary time constants of filtration of measured inlet material moisture depending on maximal random measurement error of inlet material moisture

Now it is necessary to examine disturbance response of system with presence of measurement error of inlet material moisture again, with filtration of measured inlet material moisture. For every value of maximal relative error of inlet material moisture, appropriate time constant of filtration is used. Investigations show that even for maximal relative measurement error of inlet material moisture of 5%, there are not permanent oscillations of outlet temperature. This means that even this value of error could be tolerated in system, if filtration of measured inlet material moisture with appropriate time constant is used. But with grow of time constant of filtration of measured inlet material moisture, system has slower disturbance response, and maximal deviation of outlet temperature after disturbance grows. For that reason maximal random measurement error of inlet material moisture should be as small as possible, and known in the system, for reason to find appropriate time constant of filtration of inlet material moisture. These results are shown in figure 3.2.

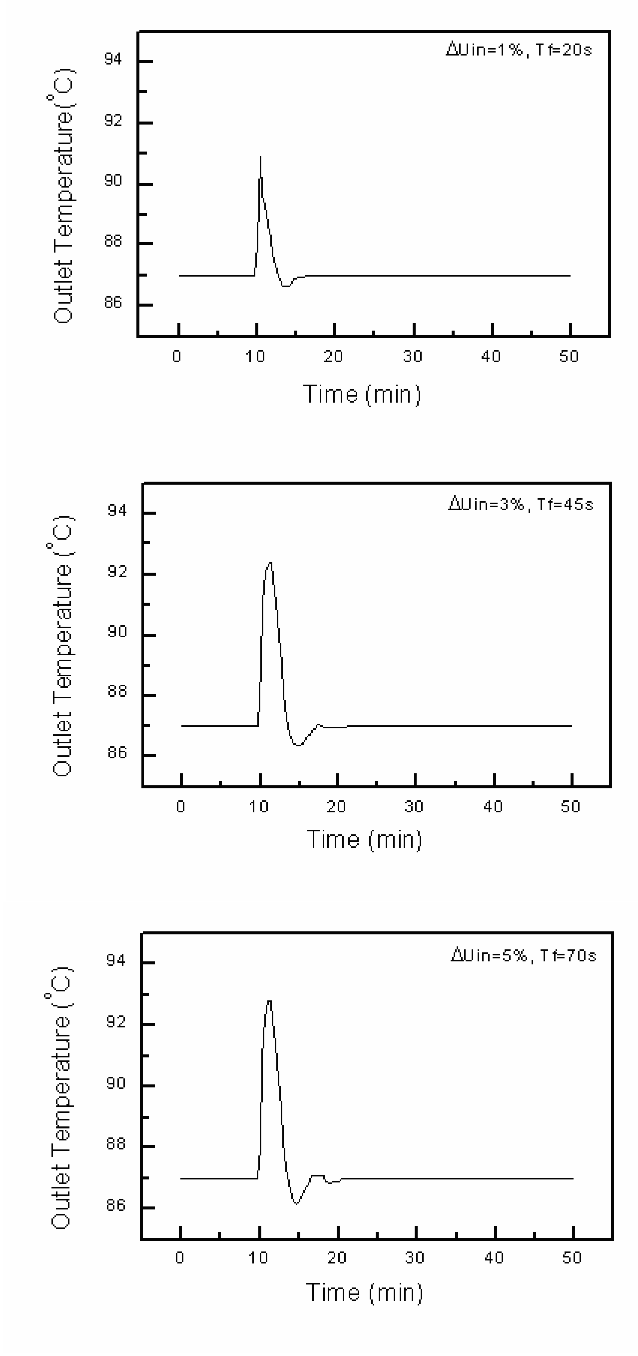


Figure 3.3: Disturbance response of system for different values of random measurement error of inlet material moisture with appropriate time constants of filtration of measured inlet material moisture

Filtration of measured inlet material moisture is necessary in the system, even if there are not other reasons except noise, and minimal value of time constants of filtration should be 20s, because measurement error of inlet material moisture less than 1% is very difficult to achieve in industrial application.

From described investigation there is possible to conclude that fuzzy control system could be applied in situation where measurement errors of fuel flow rate and inlet material moisture are present, both random and systematic. For increasing fuzzy controller performances, differential effect in output generation is introduced, which decreases sensitivity on measurement errors of fuel flow rate. Filtration of measured inlet material moisture decreases sensitivity on random measurement error of inlet material moisture and noise, i.e. inhomogeneity of inlet material moisture, but large time constant of filtration causes that system has slower disturbance response. For that reason maximal random measurement error of inlet material moisture should be as small as possible, and known in the system.

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