Performance Testing of Refrigerators Using Fuzzy Inference Methodology under LabVIEW®

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Abstract The purpose of this paper is to present the use of fuzzy inference methodologies in the performance testing of refrigerators, as an efficient alternative to the classical time-consuming and relatively complex techniques. The basic elements that are used to optimize the performance of a refrigerator are fuzzified and then used in fuzzy inference models to represent the intelligent behavior of a human tester. These models are simulated and the results are compared with the ones obtained by classical algorithms. Further, conclusive comments are provided regarding the effectiveness of the introduced models and the avenues that need to be explored in order to make them increasingly efficient and fully automated.

1. Introduction

Performance testing and evaluation of refrigerators is an important stage in the pipeline of refrigerator production, which includes the gas charging. The main purpose of the testing is to find the amount of gas needed to attain the smallest possible temperature in as small a time period as possible. This is done by repeatedly adding a specific gas amount and monitoring the temperature change as a function of time. Every time an amount of gas is added, the minimum attained stable temperature should be detected in as small duration as possible.

Due to the trend of temperature change with time (see Figure1), the shorter the time period over which this change in observed as it starts to become insignificant, the risk of detecting a larger temperature than the one that can be achieved becomes higher. This problem can be dealt with by devising some sort of a compromise that makes the observation interval fairly sufficient relative to temperature change. This is done to allow for the detection of the lowest, or close to the lowest, temperature while minimizing time to finish the testing process.

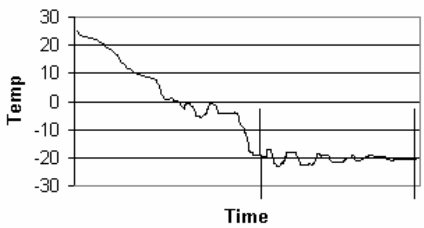

Fig. 1. The Change in Temperature versus Time.

Given the above noted problem and the devised solution, it appears that an approximate reasoning or a humanistic type of a testing procedure needs to be implemented. Usually, a human expert does the refrigerator performance testing and evaluation. But, this has limitations including cost and effort.

In order to automate the testing process, a classical software solution has been developed to monitor the change in temperature until it is stabilized. When the temperature change becomes confined within a specific minimum crisp limit over a relatively large time duration, a reading of this temperature is taken and another gas amount is added. Also, an improved classical solution i.e. a solution closer to human testing has been developed (Section 3).

The purpose of this paper is to introduce an automated procedure to control the process of refrigerator performance testing using fuzzy logic and inference systems, and also to compare with the developed classical solutions. The derived fuzzy model represents the manner by which a human expert performs the testing procedure. This is compatible with the basic objective of fuzzy logic, which consists of dealing with the analysis and design of humanistic systems by employing the principles of approximate reasoning [1-3].

Furthermore, it is clear from the problem statement and suggested solution that fuzziness is embedded in the basic nature of the problem. In addition to the approximate type of reasoning involved, the words: insignificant, fairly sufficient, and close to the lowest are fuzzy terms that can be represented by fuzzy sets. Fuzzy inference rules, which can be used in the fuzzy model solution to this problem, can be of the form:

- If temperature change is large and observation time is insufficient, then testing continues.
- If temperature change is very small and observation time is fairly sufficient, then testing stops.

(1)

The fuzzy model is facilitated by graphical programming for instrumentation that is embedded in LabVIEW® and its fuzzy logic toolkit [4]. With graphical programming as embodied in LabVIEW and the Fuzzy Logic for G Toolkit, one can design a fuzzy logic controller and implement the controller in the G applications.

2. Fuzzy Inference

A fuzzy controller or fuzzy inference system contains a fuzzifier, a defuzzifier and a set of inference rules. Fuzzification is the assignment of a number of fuzzy sets that describe the different fuzzy states of the system input and output variables. The inference rules, usually expressed in the form of IF-THEN rules, provide the necessary connection between the system input and output fuzzy sets. Defuzzification is a process which converts each fuzzy output, obtained as a result of implementing the inference rules and in response to a particular crisp input, into a crisp output so that it can be used for practical purposes [5-7]. The implementation of the inference rules is done through the use of Zadeh's Compositional Rule of Inference (CRI) [2]. Let an N-rule, two-input, one-output fuzzy system be such that the jth rule, $1 \le j \le N$, is expressed as follows:

R_j : IF x is A_j AND y is B_j , THEN z is C_j

A_j, B_j and C_j are fuzzy sets assigned over x,y and z which are respectively the input and output variables of the system. The fuzzy output C_o obtained through the CRI and corresponding to the crisp input pair (x_0, y_0). is:

$$\mu_{Co}(z) = \max_{1 \le j \le N} [\mu_{Aj}(x_o) \wedge \mu_{Bj}(y_o) \wedge \mu_{Cj}(z_o)] \qquad (2)$$

The maximum, minimum and minimum are respectively used for "OR", "AND" and "THEN" operators.

3. Classical Solutions

Considering Fig.1, which shows the trend of temperature change with time, a classical software has been developed. Its basic operation is shown in Fig.2.The scanning stops when Dtemp less than or equal 0.5C^o for a time duration greater than or equal to 30 minutes. This time duration is chosen to leave no doubt about reaching the stability stage and thus recording the smallest temperature that can be achieved for specific amount of gas. When the scanning stops, another gas amount is added and the process is repeated.

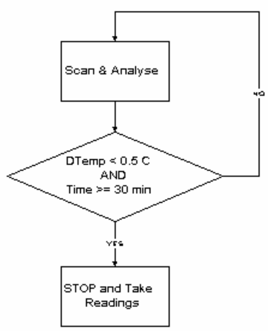

Fig. 2.The Algorithm Used in the 1st Crisp Controller.

In Fig.3 a chart is drawn showing the gas amount versus the minimum temperature. Thus, the gas amount needed to attain the smallest possible temperature can be found. But this is not in as small a time period as possible.

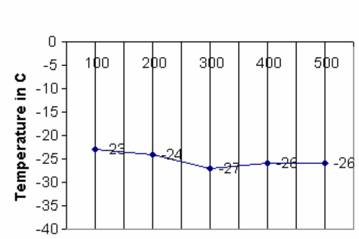

Fig. 3. Gas Amount versus Minimum Temperature.

An improvement to the solution in Fig.2 to make it closer to the manner a human expert performs the testing can be done. The solution in Fig.4 considers, in addition, the state of having Dtemp less than or equal to 0.35 as stable if the time elapsed is equal to or greater than 25 minutes. The state of having Dtemp less than or equal to 0.25 is also considered stable if the time elapsed is equal to or greater than 20 minutes. Actually, this enhanced controller is one based on classical inference and it requires a very complex code and a good programming effort, especially, if the number of bounds on Dtemp and their corresponding time intervals is increased. A timer for each different bound on Dtemp is also needed. The use of fuzzy logic and inference provides a better representation of human expertise and requires the use of a simple controller.

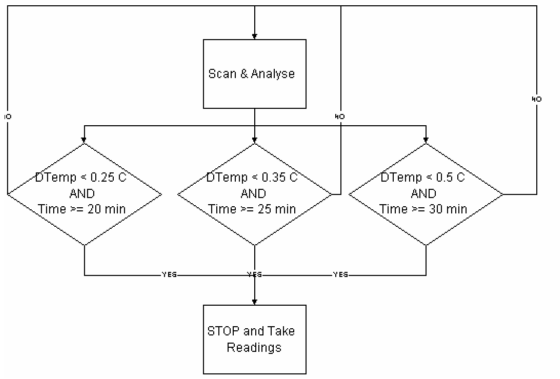

Fig. 4. Enhanced Crisp Controller.

4. The Fuzzy Inference Model Solution

In this section the fuzzy model that is formed by inference rules of the sort listed in Equation (1) is constructed and used in an automated testing system. The whole monitoring process will be computerized using the data acquisition tools: PCI-MIO-16E-4, SCXI-1300, and SCXI-1000. The software package is coded using graphical programming for instrumentation LabVIEW© and its fuzzy toolkit. The algorithm of the automated testing system is shown in Fig.5. The main fuzzy controller has two inputs Dtemp and Time representing the change in temperature and the observation of this change over some period of time. The membership functions (MFs) of these two variables and the rules relating them are assigned based on expert knowledge. Tuning has also been done to improve the system to give satisfactory results. Dtemp has 4 fuzzy terms: Very Small, Small, Medium, and Large with MFs as shown in Fig.6. The noted terms, as they relate to the problem description (See Section 1), can also be interpreted as insignificant, fairly insignificant, significant, and highly significant respectively. The Range of the variable "Dtemp" is between 0 and 5 C^o.

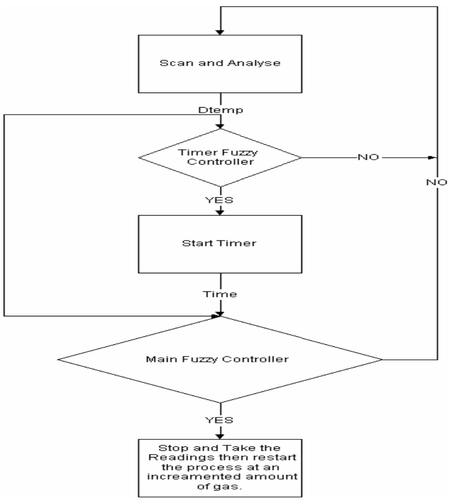

Fig.5. Algorithm With a Fuzzy-based Controller.

The second variable "Time" has 5 fuzzy terms: "Very Early", "Early", "Right", "Late", and "Very Late" (Fig.7). These terms can also be interpreted as insufficient, fairly insufficient, sufficient, fairly sufficient, and highly sufficient as they relate to the time required to stop the evaluation process. The Third variable denoted " Output" represents the output variable of the fuzzy controller. It controls the start and stop of the monitoring process. It has 2 singleton terms named: "Stop" and "Continue". The first term "Stop" is a singleton at 0. The second term "Continue" is a singleton at 1.

The Timer fuzzy controller, controlling the start and stop of the timer, has two variables: "Dtemp" and "Output". They have the same MFs as those in the main fuzzy controller. But, the output singletons are named: "Stop" and "Start".

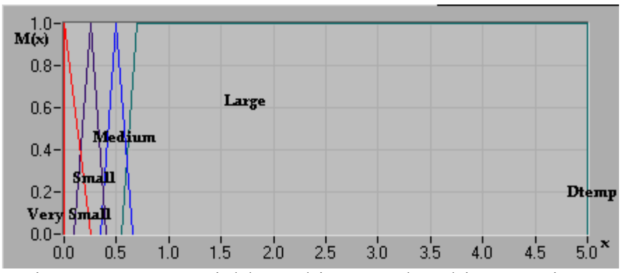

Fig. 6. Dtemp Variable and its Membership Functions.

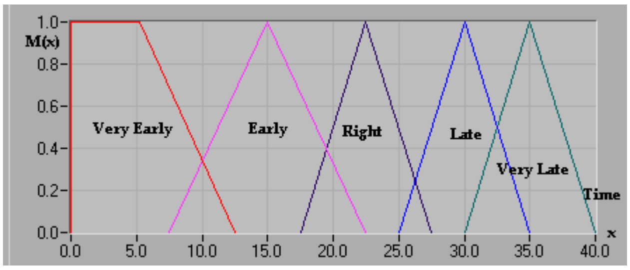

Fig. 7. Time Variable and its Membership Functions.

The timer controller has the following inference rules:

RULE1: **if** (Dtemp is Very Small) **then** (Output is Start).
RULE2: **if** (Dtemp is Small) **then** (Output is Start).
RULE3: **if** (Dtemp is Medium) **then** (Output is Start).
RULE4: **if** (Dtemp is Large) **then** (Output is Stop). } (3)

The main fuzzy controller, that performs the decision-making based on the change in temperature and the timer, uses the 20 inference rules in Table1:

Time / DTemp	**Very Early**	**Early**	**Right**	**Late**	**Very Late**
Very Small	Continue	Stop	Stop	Stop	Stop
Small	Continue	Continue	Stop	Stop	Stop
Medium	Continue	Continue	Continue	Stop	Stop
Large	Continue	Continue	Continue	Continue	Continue

Table. 1. Inference rules used in the main controller.

The previous algorithm (Fig.5) is the main part of a large monitoring system designed using the LabVIEW® and its graphical programming tools for instrumentation. This programming tool controls a complete hardware interfacing and measurement system. This monitoring system, used for performance testing and evaluation of refrigerators, also contains two software parts: "The Scanner" and "The Analyzer". The scanner is designed to acquire the temperature readings from the thermocouples connected to the hardware interfacing cards. It stores these readings in special purpose files are for later retrieve and processing by the analyzer. Different controls are supported to control the acquiring speed, output files, and delay time. The analyzer is designed to process the data in the files (created by the scanner) and to monitor the change in temperature readings for the use by the fuzzy controllers.

5. Results and Analysis

Based on the MFs in Fig.6, and the inference rules given in Equation (3), Fig.8 shows the behavior of the output of timer fuzzy controller as Dtemp changes. Setting a threshold value somewhere between 0.5C° and 0.75C° to start the timer shows the ability of being able to modify the start time in accordance with the manner the human operator regards the relationship between Dtemp and time for reaching stability. The range of Dtemp threshold can be modified as well by varying the rules in Equation (3). For example, making the output of rule 3 equal to stop rather than start causes a shift in the range to the left. So the change in Dtemp at which the timer needs to start can be set in accordance with the expertise of the human. This could be exploited to reduce the risk of detecting a temperature much higher than the one that can be achieved (Fig.1).

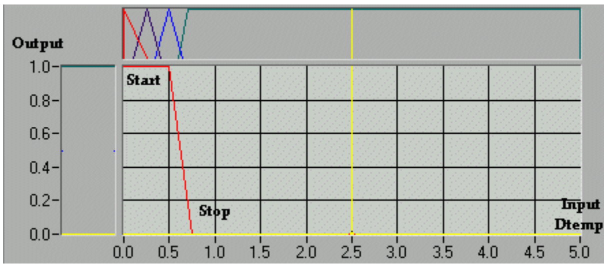

Fig.8. Behavior of the output of the Timer fuzzy controller with the change in temperature (Dtemp).

Based on the MFs in Fig.6 and Fig.7 and the rules in Table1, Fig.9.a shows the behavior of the main controller output with the change in time for any Dtemp in the range between [0 C°, 0.15C°]. Thus, if Dtemp takes values only in the noted range after the start time, then the controller is able to stop the test after only 12 minutes of detecting stabilization. This has a major effect on the whole time of the performance testing. Now, if the change in Dtemp confined between (0.15 C°, 0.37C°] (See Fig.9.b.), then the controller stops the testing after 20 minutes. For Dtemp in (0.37 C°, 0.58 C°], the controller waits more time to stop the test (27 minutes). Moreover, if the value of Dtemp is between (0.58 C°, 5 C°], then the controller will keep the test running.

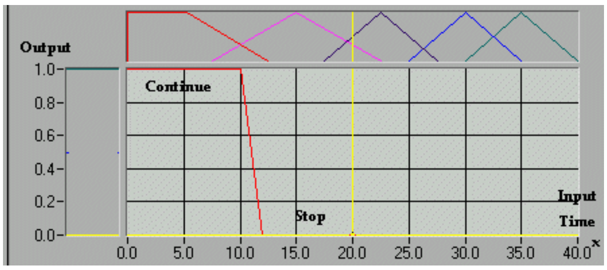

Fig.9.a. Values of Dtemp between [0°C, 0.15°C]

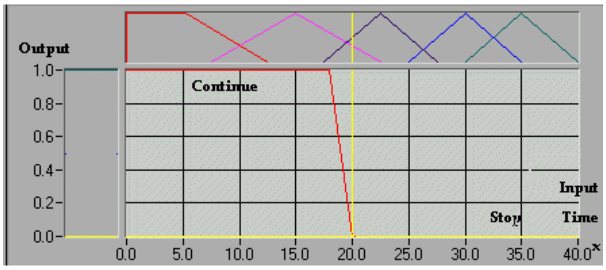

Fig.9.b. Values of Dtemp between [0.15°C, 0.37°C]

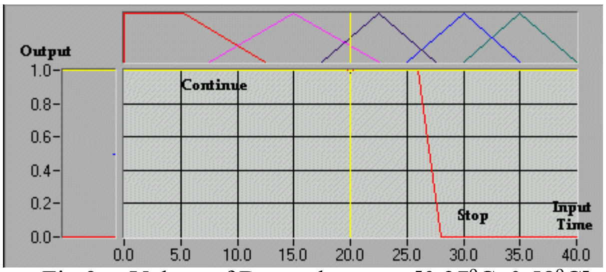

Fig.9.c. Values of Dtemp between [0.37°C, 0.58°C]

Fig.9. The output (Stop/Continue) versus Time input for different Dtemp values.

The plot of the main controller output versus Dtemp and Time is shown in Fig.10. It is clear from this figure that when the testing time becomes long, then the controller allows for the test to stop at Dtemp values that are relatively larger than those at which the test stops when the testing time is short. It needs also to be mentioned here that the 12, 20 and 27 minutes are not the only time values at which testing can stop. When the timer starts, Dtemp values could for example be in the range (0.37 C°, 0.58 C°]. Then, as the time progresses these values of Dtemp could decrease and become in the range (0.15 C°, 0.37 C°] and then in [0 C°, 0.15 C°]. When this happens, the time could have reached any value between 12 and 20 minutes at which the testing stops. Also the passage of Dtemp values from the first range to the second could occur at any time between 20 and 27 minutes. The testing would then stop at this time value. Consequently, the stoppage time of the test can be at any value in the continuum range between 12 and 27 minutes depending on the behavior of the change in temperature as a function of time. This is different from the classical solutions in figures 2 and 4 and closer to human reasoning.

In addition to the humanistic aspect provided by the fuzzy models in the performance testing and evaluation of refrigerators, these models can also give time saving and reduced complexity. Tables 2 and 3 show some comparisons between the crisp and the fuzzy controllers. The listed time savings in Table 2 are the smallest that can be obtained through the use of the fuzzy approach.

6. Conclusion

Fuzzy logic and inference methodologies, which have been applied in various interesting areas, such as the control of complex and imprecisely defined processes, have been used in this study to develop a fuzzy controller algorithm to test and evaluate the performance of refrigerators at the manufacturing stage. The fuzzy models turned out to be a simple, and gave time saving as compared to the classical approaches. They also provided a good representation of the human expertise in terms of the use of linguistic terms and fuzzy rules and also making available a continuum of decisions.

Future research should deal with the tuning and improvement of the fuzzy model to guarantee a real competition and possibly superiority over the human experts in terms of the achievement of the smallest possible temperature and the time needed for the achievement. In addition, automating the gas charging using automatic valves could be made by introducing new variables to the fuzzy controller to control the gas amount charged into the refrigerator.

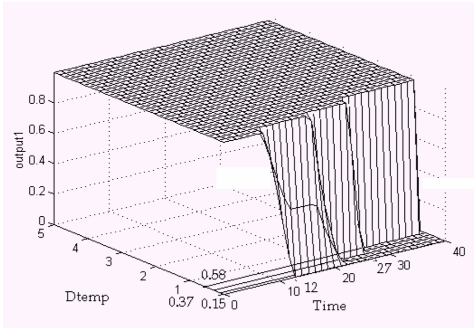

Fig.10. Main Controller Output versus Dtemp and Time.

Change in Temperature	Crisp Controller *Figure 2*	Crisp Controller *Figure 4.*	Fuzzy Controller *Figure 5.*
$0.4 \leq$ Dtemp ≤ 0.5	30 min.	30 min.	27 min.
Time Saving in Percent	**0 %**	**0 %**	**10 %**
$0.35 \leq$ Dtemp ≤ 0.4	30 min.	30 min.	[25 min, 27 min]
Time Saving in Percent	**0 %**	**0 %**	**[10%, 13%]**
$0.25 \leq$ Dtemp ≤ 0.3	30 min.	25 min	20 min
Time Saving in Percent	**0 %**	**16.7%**	**33.3%**
$0 \leq$ Dtemp ≤ 0.25	30 min.	20 min	[12 min, 20 min]
Time Saving in Percent	**0 %**	**33%**	**[33.3%, 60%]**

Table 2. Stop time estimation at different values of Dtemp with the saving of the fuzzy over the crisp controllers.

	Crisp Controller *Figure 2.*	Crisp Controller *Figure 4.*	Fuzzy Controller *Figure 5.*
Software Complexity	Simple	Complex	Simple
Development	Complex	Complex	Easy to develop and tune.
Compatibility with the human operator's behavior	Covers a single decision	Covers multi-decisions but limited	Compatible and covers many decisions

Table 3. Comparison of crisp and fuzzy controllers .

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