Improved climate control for potato stores by fuzzy controllers

Klaus Gottschalk a,*, László Nagy b, István Farkas b

a Institut für Agrartechnik Bornim e.V. ATB, Max-Eyth-Allee 100, D-14469 Potsdam, Germany
b Faculty of Agricultural Engineering, Department of Physics and Process Control, Szent István University, Gödöllő, Pater K.u.1. H-2103, Hungary

Abstract

The main tasks for climate controllers in potato bulk stores are to keep the storage climate in an appropriate condition for quality conservation. To avoid extra energy costs by using cooling systems the internal climate of potato bulk stores is controlled with outdoor air. A conventionally designed controller is difficult to adapt for an optimal climate control to reduce quality loss. However, a controller designed with fuzzy logic is found as advantageous for adapting control parameters to improve the control process. A test stand is built to ventilate and to control two samples of potato bulks simultaneously with the same outdoor weather conditions for comparisons. Several experiments were carried out to compare climate controllers with different control algorithms, i.e. conventional to a different conventional and conventional to fuzzy.

© 2003 Elsevier Science B.V. All rights reserved.

Keywords: Potato store; Fuzzy control; Genetic algorithm; Parameter adapting

1. Introduction

The most important quality factors for potatoes are freshness (low mass/water loss), health (keep dry storage) and absences of germs (keep cool storage). Bulk stores for potatoes are mostly ventilated by outdoor air (Fig. 1). To reduce energy costs, cooling and heating systems are used in some storage facilities temporarily when needed. Some cooling systems are mobile. When not using such systems, the...
store climate is controlled by outdoor climate only. Harvesting time and storing time for potatoes is in September to October (Johannson, 1989). In this time mostly there are cool nights and some cool days for using fresh cool air to ventilate the potato bulk directly.

Under Mid-European climatic conditions, the following objectives are to be fulfilled ('rules' to control the climate):

- dry the potato surfaces if necessary
- cool down the potatoes as fast as possible after laid in
- keep potato bulk cool during the whole storage time at constant temperature
- avoid wet surface i.e. avoid water condensation on the potatoes to prevent foulness
- warm up the potatoes as fast as possible after storage time
- minimize mass loss during the whole storage time
- minimize energy consumption during the whole storage time

To achieve these aims, a well adapted control algorithm is to be implemented in the control equipment. Conventionally, the climate controller controls the fan and the damper openings to get inlet air flow to the potato bulk. The controller uses the current outdoor climate, i.e. outdoor temperature. If available in practical stores the outdoor air humidity also can be taken into account. The controller takes also into account the (average) potato temperature, the inlet air temperature, the inlet air humidity (if available in practical stores) and outlet air temperature and finally outlet air humidity (if available in practical stores). The outlet air may be mixed with recirculated air to obtain the most suitable inlet air condition.

The basic control ‘rules’ for cooling and storing potatoes are defined as:

\[\begin{align*}
\text{if} & \quad \text{cooling air is needed} \\
\text{and} & \\
\text{if} & \quad \text{cool air is available}
\end{align*}\]
then 
ventilate (open dampers and switch on fans)
else 
do not ventilate (close dampers and switch off fans)

Additional rules are to define and to obtain the most appropriate air conditions, i.e. to reach appropriate inlet air temperature into the bulk and, for more extended control, best suited inlet air humidity for reducing mass loss.

This is achieved by additional control of dampers, for outdoor and recirculated air. Therefore fresh outdoor air can be mixed with recirculated air to obtain the appropriate air temperature, and—if needed and applicable—also to obtain high relative humidity to ventilate the bulk.

2. Conventional control approach

The climate controller controls the damper positions (open–partially open–closed positions) and the fan (on–off). The ‘rules’ to control the climate are forming a complex set of dependencies which are difficult to implement, to maintain and to test when using a conventional control algorithm. A good and comprehensible aid to define the appropriate algorithms is to use so-called ‘state diagrams’. The state diagram for fan control is shown in Fig. 2, for example. More diagrams are defined for damper control, humidity control, etc. (Fig. 3a and b).

On these diagrams, the rules, set up ‘intuitively’, can be defined. It can be directly seen how to act for cooling a storeroom (Maltry and Gottschalk, 1993). The diagram area is separated into different areas corresponding to different actions. A change of the ‘state’ of the controller corresponds to a ‘moving’ of the actual state point (e.g. \( \{ \theta_p, \theta_A \} \)) within its corresponding area. The state point can change to the neighbor area and invoke an ‘action’, for example ‘switch on fan’. The border lines between the areas denote the ‘shift’ of state. For example, if the outdoor temperature (\( \theta_A \)) is below the potato temperature (\( \theta_p \)), the state point lies in the area above the diagonal.

![State diagram of conventional fan control for cooling.](image-url)
In this corresponding area the control fan action is defined to switch ON. When the potato temperature approaches the line, it means that the temperature approaches the storage control set point temperature. When the state point is close to the line or exceeds the line, the fan action is to switch OFF, etc.

For the conventional programming technique it is difficult to implement and change the rules because the rules are complex (Fig. 4).

### 3. Use of fuzzy control

Regarding these circumstances gave the idea to use a fuzzy control algorithm to benefit from the ability to implement the ‘rules’ directly into the rulebase of a fuzzy controller. A storekeeper may define a rule like this, for example: ‘IF Potato Temperature = high AND Air Temperature = low THEN Fan = ON’, and so on. A fuzzy controller comes therefore close to the intuitive manner of defining rules and measures.

The input values of the fuzzy controller are:

- temperature difference between potatoes and inlet air, i.e. $\theta_{pot} - \theta_{air}$ (with linguistic variable denoted ‘DT’; range: ‘LZ’ = less than zero, ‘Z’ = zero, ‘M’ = medium, ‘GZ’ = greater than zero)
- potato temperature (average value or from a sensor placed in approximately 1 m depth from bulk surface) $\theta_{pot}$ (linguistic variable ‘TP’; range: ‘VL’ = very low, ‘L’ = low, ‘M’ = medium, ‘H’ = high)
- outdoor air humidity (if humidity measurements equipped in store)
- inlet air humidity; probably mixed with outlet air, (if humidity measurements equipped in store).

The output value (control value) is controlling the ventilation rate (either continuously or discretely, i.e. ‘ON/OFF’-positions only). The ventilation rate is a...
result from the answer of the fuzzy-controller with respect to the input values and the ‘climate control rules’. To better obtain the ‘optimization goal’, the fan revolution speed is controlled by a frequency converter to set defined ventilation rates continuously. The respond function of the fuzzy-control algorithm for the ventilation rate, dependent on the temperature difference and the potato temperature, reflects the rules (Fig. 5). The variables for the input values, e.g. of the temperature differences and the potato temperature are defined as linguistic variables DT and TP. For each of these linguistic variables, four fuzzy sets are defined. The definition of these four fuzzy sets is shown for fan control. The ‘state point’ to switch the fan is approximately \( \pm 0 \) K for the temperature difference and about 4 °C for the potato temperature (the optimal storage temperature). If the fan is controlled continuously by using a frequency converter, the ventilation rate can

```
if (Tair<Tpot) AND
    NOT(Tinlet<Tsetpoint+Hyst) then begin

    if Tpot<5 then GOTO M1;
    if Tpot<Tair+Hyst then GOTO M1;
    if FAN=ON then GOTO M3;
    if Tpot<5.5 then GOTO M2;
    if Tpot<Tair+Hyst then GOTO M2;
    FAN:=ON;
    if Tair < freezingPoint then
        Damper=CLOSE
    else Damper=OPEN;

M3: if Tinlet<1.0 then
    Damper=CLOSE
else
    if Tpot>Tinlet+7 then
        Damper=CloseOneStep
    else
        if Tpot<Tinlet+5 then
            Damper=OpenOneStep
    GOTO M_END;

M1: FAN=OFF;
M2: if Tpot>Tair then
    if Tpot>5.5 then begin
        DAMPER=OPEN; GOTO M_END
    end;

M4: if Tpot<Tair-1 then
    DAMPER=CLOSE
end;
M_END:
```

Fig. 4. Conventional fan and damper control algorithm for cooling and long term storage.
adapted to obtain a ‘smooth’ cooling process. This means for example that the ventilation rate should be reduced, when the potato temperature reaches its optimal storage temperature and when the temperature difference is approximately 0 K. To reduce the mass loss, additional rules are implemented as an option to make use of a high inlet air humidity (and outdoor air humidity if available). In this case, a higher ventilation rate is allowed if the relative humidity of the inlet air is high (approximately above 80%). When the inlet air is too dry, then the drying effect on the lower layers of the bulk must be reduced to decrease mass loss. In this manner, the rule base of the fuzzy system is derived directly from the state diagrams.

4. Parameter for fuzzy control

The variables for the input values, e.g. of the temperature difference and the potato temperature are defined as linguistic variables DT and TP. For each of this linguistic variables, four fuzzy sets are defined. The set point range to control the ventilation rate is about ±0 K for the temperature difference and about 4 °C for the potato temperature (the assumed optimal storage temperature). This means for example that the ventilation rate should be reduced, when the potato temperature reaches its optimal storage temperature or when the difference temperature is about 0 K. To reduce the mass loss, additional rules are implemented to make use of a high inlet air humidity (and outdoor air humidity, if available). In this case, a higher ventilation rate is allowed. When the inlet air is too dry then the ventilation rate must be reduced to avoid too much mass loss due to the drying effect on the lower layers of the bulk.

The most useful shape for the member function of a fuzzy set (with linguistic terms as DT, TP and so on) is the normalized trapezoidal function $\mu(x)$ with the parameters $m_1$, $m_2$, $a$ and $b$ (Fig. 6).
For all fuzzy sets, the parameters $m_1$, $m_2$, $a$ and $b$ are defined as the relevant parameters to adapt. The objective is to use an adaptive algorithm to fit these parameters to the criteria to minimize the total storing cost, for example. The Genetic algorithm (GA) search procedure is a good technique to solve this problem.

5. Use of genetic algorithm to adapt fuzzy control

For each fuzzy set a number of members are chosen (e.g. 10 members), constituting a population. For the first member of each population, the parameters of the concerned fuzzy set are fixed heuristically. All further members of each population are derived from the first member and their parameters are varied randomly. Thus, on start of the optimization procedure the parameters are all different among the population members. The algorithm starts its calculation with the first member of each population using the heat and mass transfer model to calculate the change of potato temperatures, air temperature, air humidity, potato mass loss, total energy consumption and total cost, taking into account actual cost factors.

![Diagram](image)

**Fig. 6.** Member function of trapezoidal shape with parameters.

**Fig. 7.** Example of the variation of the fuzzy sets for DT before and after an optimization process.
During the following steps of the optimizing procedure (Fig. 8, Fig. 9), for each population a pair of members are selected randomly to act as ‘parents’ to generate a ‘child’ for the next generation. The parameters of the child are a combination (crossover) of the parameters of the parents. The child ‘inherits’ the characteristics of the parents. The part of the characteristics (the parameters) of each parent is randomly selected (Table 1). In the next step the parameters of the child are mutated with a low probability to avoid the genetic procedure to stagnate. The probability to select parents with ‘good’ characteristics rises with their ‘goodness’, but parents with ‘worse’ characteristics are also selectable with a low probability. For the reproduced

![Fig. 8. Genetic algorithm (principle).](image)

![Fig. 9. Genetic algorithm.](image)

Table 1
Crossover code for the fuzzy set parameters; ‘0’ means: change not the parameter from parent 1 but from parent 2, ‘1’ means: change the parameter from parent 1 but not from parent 2

<table>
<thead>
<tr>
<th>$m_1$</th>
<th>$m_2$</th>
<th>$a$</th>
<th>$b$</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>7</td>
</tr>
</tbody>
</table>
and (probably) mutated child, the calculation is made again, with the new parameters (Fig. 6, Table 1). The calculated total cost is regarded as a ‘fitness’ value for the child. The child replaces the member with the ‘worst’ characteristics within the population. The procedure continues like this until a (sub-) optimum is found (Fig. 10).

Comparisons of simulation runs (Gottschalk, 1996; Gottschalk 1997) show the well known physical effect that dry air is cooling the lower layers of the bulk even below to the inlet air temperature (Maltry and Gottschalk, 1993; Boyd, 1992). This effect occurs due to the evaporation process of the water diffusing from inside the potato to the ambient air. The latent heat is dissipated from the potato reducing its temperature and humidity. This effect is less distinct when using air with higher humidity. The evaporation effect can be advantageous to accelerate the cooling process that reduces cooling time and ventilation energy. On the other hand, air with high humidity can reduce mass loss but longer ventilation time and ventilation energy is needed. An algorithm taking into account these contrary circumstances can adapt the parameters to gain the objective to find an optimum between these two distinct effects, thus, to minimize the total cost function

\[
\text{Cost} = \sum_{\Delta} (k_{\text{TotalEnergy}} \cdot \text{Energy}_{\Delta'} \cdot \Delta t) + k_{\text{MassLoss}} \cdot \text{relative Mass Loss}_{\Delta'} \\
\cdot \text{Mass}_{\text{TotalPotatoInStore}}
\]
with the time step $\Delta t$ and the coefficients $k_i$ fixed for each optimization procedure. The mass loss is evaluated as a 'monetary' factor, rather than a quality factor. On the other hand the mass loss is a quality factor. When disregarding energy costs, the optimizing procedure has the objective to minimize mass loss. The coefficient $k_{\text{TotalEnergy}}$ has to be set to zero in that case. Starting the optimization process with $k_{\text{TotalEnergy}} = 0$ finds the optimal parameter set for minimal mass loss.

The optimizing criteria may be:

- minimize energy consumption
- minimize mass loss
- minimize total cost.

The energy consumption is the consumption of electrical energy of the fans. The fan motor energy consumption is proportional to the third power of the ventilation rate. Reducing the ventilation rate means to reduce energy consumption and to reduce mass loss but to rise storage time during cooling, which means an increase in the total energy consumption. Hence, an optimal storage time with an optimal controlled ventilation rate is expected.

In this simulation example, a total cost function 'cost' (see above) is defined as the validation criteria to be minimized (with constants $k_{\text{TotalEnergy}}$, $k_{\text{MassLoss}}$ and fan-switch-on time-intervals $\Delta t$; the energy is a function of the ventilation rate). The results show that the total mass loss is reduced during the optimizing procedure, accompanied by a slight rise of energy consumption, while the (average) total cost is monotonously decreasing (Fig. 10).

The effect of the optimization process on the parameters of the fuzzy set can exemplary be seen for the linguistic variable DT in Fig. 7. The parameters $m_1$, $m_2$, $a$ and $b$ are modified for each fuzzy set by the GA in a manner that the optimization goal—e.g. minimize total cost during ventilation of the potato bulk—is reached.

6. Experiments

In this paragraph the layout of the test stand and the experimental results will be introduced and discussed.

6.1. Test stand

A test stand was constructed to demonstrate climate control (Figs. 11 and 12). The equipment represents a real potato bulk storage facility. The potato samples were stored in two separate sections which can be independently controlled. The two tests run concurrently with almost the same ambient conditions. With this configuration comparisons can be made between effects on different samples, or different control strategies, or different control algorithms, etc.
Sensors are installed to measure temperature and relative humidity in the inlet air and the outlet air duct separately for each section. Up to 30 temperature sensors were placed into the boxes to acquire bulk temperatures in several heights within the bulk. At the outlet ducts and in front of the mixing chambers dampers are installed to control air flow mixing and recirculation. The fan motor revolutions can be
remote controlled by frequency converters to control the air rate. An industrial PC is controlling the equipment and logging the data automatically.

6.2. Experimental results

Test runs were made with several potato samples. In each section one box was placed which contained approximately 190 kg potatoes in 19 bags, each of approximately 10 kg. The box dimensions are: height = 1.4 m and squared ground area = 0.218 m². The bags where weighted before and after each test to obtain mass loss for the test period. Five controlled cooling processes were tested (test #1 to #5; Table 1).

The first test (test #1) was run with conventional control on both sections (1) and (2), the other tests (test #2 to test #5) with fuzzy control on section (1), the other section (2) conventional controlled. Section (1) was always run with lower air rate (air velocity) than section (2). This shows lower temperature decrease rates (°C/h) for section (1) than for section (2). Test #2 and #3 were run with fuzzy control on section (1) without optimization. Test #4 and #5 were run with fuzzy control on section (1) with optimizations made after parameter adapting with GA.

In these tests, the air velocity values were also decreased, but kept even lower for the fuzzy system than for the conventional system. In these tests (test #4 and #5) the temperature decrease rates (°C/h) were higher with the ‘optimized’ fuzzy system compared to the conventional system. This phenomena was reverse to the other tests (#1 to #3). Also, on these tests, the energy consumption for fan motors were significantly lower with the fuzzy system, due to the lower average air velocities through the bulks. The reason is the significant dependency of the air flow pressure drop when flowing through porous bulk material (distributed resistance). Anyway, the temperature decrease rates for the fuzzy control system are still high enough to cool the bulk quickly. During the experiments, the potatoes started to germ, which caused a higher mass loss during test #3 to #5.

7. Conclusions

When cooling potato bulks with outdoor air, it is difficult to maintain exact conditions in two separate sections for comparative experiments. Meanwhile there were no significant differences between the mass losses for the experiments (even compared to a non-ventilated control bag). However the effects on the cooling rate, the air velocity, and the fan motor energy consumption show significant differences. The air rate is an important factor for energy saving optimization procedures. Also, the air rate influences the mass loss and the temperature decrease rate. It is possible to lower the air rate and consequently the energy cost by using a frequency converter for fan motor revolution control with fuzzy logic. Due to the short test times, compared to long storage time in real stores, significant dependencies of the mass loss on some optimization procedures cannot be seen. The reason for this is that mass loss optimization procedures in simulations showed that a mass loss may be
reduced by approximately 1.0–1.5% during a long-term storage period over 6 months. Such a result cannot be verified by experiments for a short test run period on small potato samples over 24 h, for example. Anyway, in these tests it can be seen that the test with fuzzy control and optimized with GA lowered the all over energy consumption for the test period (test #5, Table 2).

Acknowledgements

This work has been sponsored by the MÖB-DAAD project No. 12/2002–2003.

References

