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Abstract

This paper treats the subject of analysis, design and development of the control system for a solar panel based milk pasteurization system to be used in small villages in Tanzania. The analysis deals with the demands for an acceptable pasteurization, the varying energy supply and the low cost, low complexity, simple user interface and high reliability demands. Based on these demands a concept for the pasteurization system is established and a control system is developed.

A solar panel has been constructed and the energy absorption has been tested in Tanzania. Based on the test, the pasteurization system is dimensioned. A functional prototype of the pasteurization facility with a capacity of 200 l milk/hour has been developed and tested. The system is prepared for solar panels as the main energy source and is ready for a test in Tanzania.

1. Introduction.

Improving the general standard of health in developing countries unadulterated beverages is an important issue. A well known process to prevent the growth of bacteria is proper pasteurization. Major problems in pasteurization is to obtain a constant temperature during start up, normal production conditions and the closing down of the system, in addition an effective cleaning process must be implemented.

The power supply in many small villages in Africa is a generator and at the same time fuel is expensive and in short supply, consequently it has been decided to base the energy supply for the pasteurization on solar panels. The strongly time varying energy absorption in solar panels imply a time varying energy supply causing the need of an effective control system.

The aim of the project is to develop a low-technological solution mainly to be produced by local engine shops. The project described includes the pasteurization unit containing a heat exchanger, two pumps, a holding tube and electronic equipment for control. To obtain a complete pasteurization system a solar panel, tanks for milk and a 12 V car battery must be connected. The milk path must be cleaned and disinfected using acids and bases demanding acid-proof equipment. The electronic equipment is constructed as a single changeable module.

The electronic module contains a single board computer for pasteurization control, modules for the pump driving and a simple display and keyboard. A short introduction make it possible to operate the system.

2. Demands for the pasteurization system.

The pasteurization system is meant to have a capacity making it well suited for small villages or larger farms, additionally working conditions to be met in Tanzania must be taking into account. Therefore the capacity must be at least 1000 l milk/day. Assuming app. 5 hours effective sunshine a day, the throughput must be 200 l milk/hour. The solar panel must provide an effect of approximately 10 kW. To prepare for solar cells the electrical energy supply is 12 V DC. Solar panel must be the pasteurization energy source.

3. The milk pasteurization concept.

The low pressure solar panel gives a maximum temperature of the water in the heat exchanger on 100 ^{o}C , while it is chosen to use HTST pasteurization. A schematic diagram of the process is shown on figure 1.

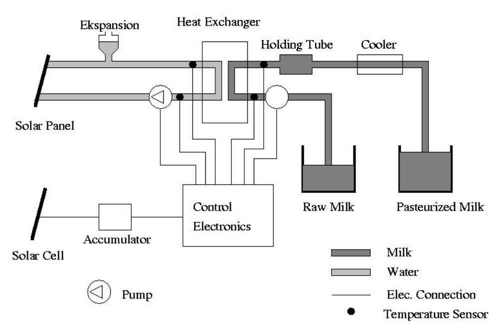

Figure 1: The pasteurization process

The system consists of a water path and a milk path. In the water path the energy is transferred from solar energy to the water in the solar panels. A pump placed at the solar panel input circulates the water through the solar panel and the heat exchanger. Due to the possibility of a very high pressure an expansion tube is inserted in the water path. In the milk path is placed a pump, the heat exchanger and a holding tube. To avoid over pasteurization a cooling system must be inserted after the holding tube. To obtain a complete pasteurization a solar panel of min. 10 kW must be connected in the water path. In the milk path a tank for unpasteurized (raw) milk, a cooling system and a tank for pasteurized milk is connected. For cleaning purposes tanks for water/acids may be connected to the milk path.

The solar energy transferred to the system is varying during the day as the absorbed energy depends on the angel between the solar panel and the sun, in addition weather conditions may influence the energy absorption. The energy can be accumulated neither in the solar panel nor in the pasteurizer meaning that the milk has to absorb the solar panel energy. The varying energy transferred to the milk necessitates a controlled flow of milk to fulfill the pasteurization. At 99.6 % pasteurization the following relationship between pasteurization time, t_p, and pasteurization temperature, T_{mo}, may be fitted to [A.J.F Joergensen]

$$t_p = 5 \cdot 10^{14} \cdot e^{-0.4353 \cdot T_{mo}}$$

Assuming a constant raw-milk temperature, the total solar effect is transferred to the milk. The pasteurization system gives no possibility for energy accumulation, meaning that the milk flow must vary according to the solar effect. Feed forward control of the milk flow based on a solar effect may be problematic due to difficulties in measuring the solar effect. Furthermore a good control strategy takes milk measurements into account.

At situations with very high solar energy the milk pump even at it's maximum capability is unable to deliver a sufficient milk flow for energy consumption resulting in an alarm. Another alarm situation arises when no or low solar effect is present. A lack of energy implies a low water temperature making pasteurization impossible.

4. Dynamic and steady state modeling of the pasteurization system.

The aim of a steady-state investigation of the pasteurization system is to calculate the operating range. The water outlet temperature of the heat exchanger gives demands for the necessary pump temperature data.

The water inlet temperature to the heat exchanger gives the limit of the operating area as temperatures above 100 ^{o}C resulting in evaporation in the water path is unwanted. Evaporation of water may appear at a certain milk flow under pasteurization assumptions giving the maximum milk flow. From the steady state model it will be possible to dimension a reasonable holding volume.

A dynamic model may be used for a stability analysis of the pasteurization feedback loop. Furthermore it can be used to calculate the dynamic pasteurization error appearing when a milk particle change velocity in the holding tube.

Steady state model

The steady state model consists of three components the solar panel, the heat exchanger and the holding tube.

The solar panel in use is given by the equation:

$$\eta = 0.74 - 3.17\left(\frac{T_{wi} + T_{wo}}{2} - Ta\right) / E$$

η is the is the efficiency, T_a ambient temperature, E is the solar effect/m^2 , T_{wi} is the water inlet temperature, T_{wo} is the water outlet temperature. The heat exchanger is given by :

$$T_{wo} = T_{wi} + (T_{mi} - T_{wi})\frac{1 - \varepsilon_w}{R - \varepsilon_w}$$

$$\varepsilon_w = e^{\left(\frac{kA}{m_w c_w} - \frac{kA}{m_m c_m}\right)}$$

$$R = \frac{m_w c_w}{m_m c_m}$$

$$T_{mo} = T_{mi} + (T_{wi} - T_{mi})\frac{1 - \varepsilon_m}{\frac{1}{R} - \varepsilon_m}$$

$$\varepsilon_m = e^{\left(\frac{kA}{m_m c_m} - \frac{kA}{m_w c_w}\right)}$$

T_{mo} is the milk outlet temperature, T_{mi} is the milk inlet temperature, m_w is the water flow, m_m is the milk flow, k is the heat transfer coefficient and A is the heat transfer area. The holding tube is given by:

$$t_p = \frac{V_h \cdot \rho_m}{m_m}$$

V_h is the holding volume and ρ_m is the milk density.

Using the above mentioned equations with a fixed water flow m_w and a fixed milk inlet temperature T_{mi} the graphs illustrated in figure 2 and 3 are calculated.

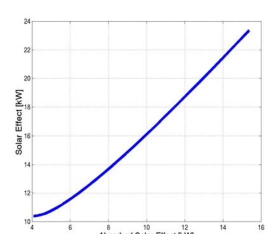

Figure 2: Solar effect to panel versus absorbed effect.

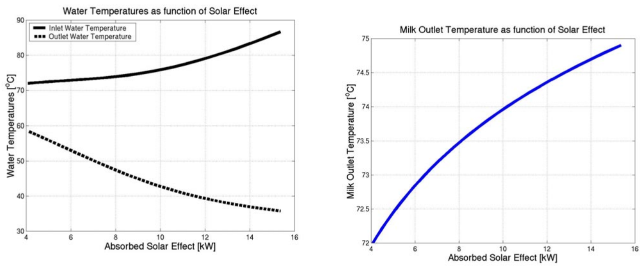

Figure 3: In- and outlet water temperatures versus absorbed effect (left) and milk outlet temperature versus absorbed effect (right).

To meet the above mentioned system demands the over all water temperature must not exceed 100 ^{o}C. As seen from figure 3(left) this phenomena does not appear for absorbed solar effect below 16 kW. The 65 ^{o}C water temperature demand to the water pump is not violated as the outlet water temperature from the heat exchanger does not exceed 65 ^{o}C. In figure 3 (right) it is illustrated that a realistic temperature variation is between 72 ^{o}C and 75 ^{o}C corresponding to a milk flow range of 85 l/hour to 310 l/hour.

Dynamic model

A controller from the measured outlet milk temperature $T_{mo\ mes}$ to m_m is given by

$$m_m = \frac{V_h \cdot \rho_m \cdot e^{0.4353 \cdot T_{momes}}}{5 \cdot 10^{14}}$$

The purpose of this controller is to guarantee pasteurization. This gives a closed loop system where the controller small signal gain increases with T_{mo}.

To investigate the stability in the feedback loop a dynamic model to describe the heat exchanger relation between m_m and T_{mo} is constructed. The model is based on distributed parameter and is simulated in the closed loop with a first order linear model of the temperature sensor and the controller. Simulation results show no instability the same results are obtained by system experiments.

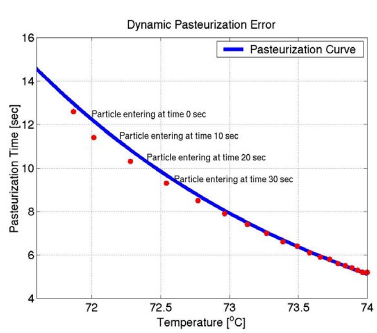

Figure 4: Pasteurization error caused by milk flow variations.

The correct pasteurization time is obtained in the holding tube. The solar effect variations imply milk flow variations causing errors in the milk particles pasteurization time. To analyze the phenomena a dynamic model of the heat exchanger is used giving the results shown in figure 4.

As seen in figure 4 a realistic variation in the solar effect only causes a small error in the pasteurization.

5. The control system

The control system for the pasteurization process must be able to handle the normal working conditions, the starting up and closing down procedure as well as the situations given by solar effect outside the defined working range for the process. Additionally a controlled cleaning process is important.

In the normal operating area a control structure as shown in figure 5 is implemented. The control system is a feedback loop from the milk outlet temperature T_{mo} to the milk pump, additionally two feed forwards from the milk inlet temperature T_{mi} and water inlet temperature T_{wi} are used.

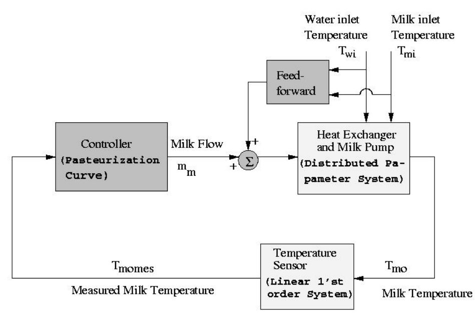

Figure 5: The control structure for the pasteurization system.

System experiments have shown that a simple and efficient start up procedure for the pasteurization is to start the water pump and measure the water inlet temperature to the heat exchanger. When this temperature reaches 74 ^{o}C a 22 sec waiting timer is started to secure a proper heating of the heat exchanger. After this delay the milk pump starts with a fixed flow. When T_{mo} reaches 72 ^{o}C the automatic control system is started. The time delay and the temperatures are based on experiments on the actual heat exchanger starting from an ambient temperature at 25 ^{o}C.

The milk pump control signal indicate the amount of solar effect, when the control system causes the maximum possible milk flow an alarm is set. The alarm tells the operator that the solar panel absorbs to much solar energy, a solution could be e.g. to cover a part of the solar panel. A lack of solar energy is indicated by a minimum flow signal to the milk pump. In this situation it is impossible to obtain a proper pasteurization and the system is closed down.

The cleaning process is based on a rinse of the milk path by cleaning liquid. In this process a fixed flow at 400 l/hour is used for the water path and a cleaning liquid flow at 420 l/hour for the milk path as given by the heat exchanger specifications. Subsequently the heat exchanger is rinsed by water to avoid cleaning liquid in the system.

6. Results

The pasteurization system has been tested in the laboratory pasteurizing water. In the test the solar panel is replaced with a water tank containing a 10 kW electrical heater making it possible to simulate the said panel. The system performance for variations in the inlet water temperature was measured as shown in figure 7 where the left graph shows the water inlet temperature T_{wi} , the water outlet temperature T_{wo} and the "milk" outlet temperature T_{mo} . T_{wi} is nearly constant 78 ^{o}C to time 80 sec reduced to 74 ^{o}C in the interval from 80 sec to 250 sec and increased to 82 ^{o}C in the interval from 250 sec to 300 sec. As seen in figure 3 a variation of 8 ^{o}C corresponds to a large variation in the solar effect in a short time interval meaning that this is a worst case test.

In the upper right graph in figure 7 the pasteurization curve is shown as well as the milk particles. The lower right graph in shows the pasteurization in pct. and as seen in the first time interval with nearly constant inlet temperature the pasteurization is in the interval 95% to 105%. In the second time interval where the inlet temperature is decreased rapidly a 125 % pasteurization appears temporary and in the last time interval under pasteurization (80%) as expected temporary appears. The test shows that under normal conditions a pasteurization from 95 % to 105 % may be expected and under large and rapidly solar effect changes the pasteurization in the interval from 80% to 125 % may be expected.

6. Conclusions

In this paper a prototype solar panel based pasteurization system is presented. The system is based on low technology components and a single board computer module for control purposes. The system has been tested in the laboratory using a simulated solar panel and pasteurizing water showing satisfactory results. Major problems have been the development of a control system and selection of appropriate system components. A start up procedure is tested and considerations concerning to high and to low energy supply has been made.

To minimize the energy consumption a heat exchanger based cooling system extension will be appropriate. Using the raw milk as the secondary flow in the cooling heat exchanger, the milk will be preheated for pasteurization implying that the solar panel effect demands can be reduced. A cooling system extension will cause an increasing production because an additionally heat exchanger is expensive and it will typically not be produced by the local smith as the solar panel can be.

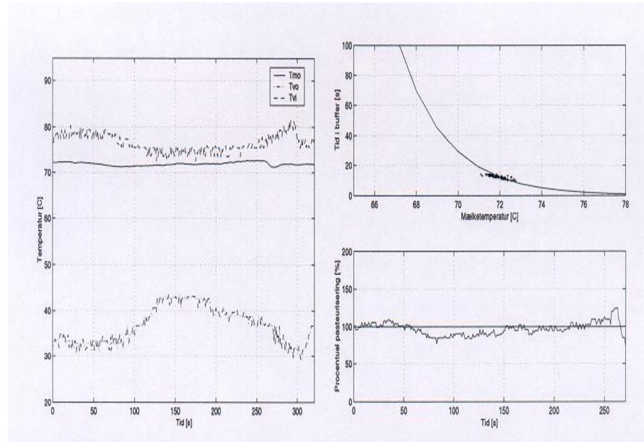

Figure 7: Test results in controlling T_{mo}, T_{wo} and T_{wi} (right) and the pasteurization error (left)

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