Energy-effective Predictive Temperature Control for Soy Mash Fermentation Based on Compartmental Pharmacokinetic Modelling

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Abstract

Compartment modelling has been successfully used in pharmacokinetics to describe the kinetics of drug distribution in body tissues. In this study, the technique is adopted to describe the dynamics of temperature response and energy exchange in a soy mash fermentation system. The objective is to provide a precise temperature-controlled atmosphere for effective fermentation with the premise of energy saving. In analogy to pharmacokinetics, water and mash tanks are treated as compartments, energy flow as drug delivery, and the temperature as the drug concentration in a specific compartment. The model allows us to estimate the time of injecting a certain amount of energy to a specific tank (compartment) in a cost-effective way. Thus, model-based temperature control and energy management can be possible.

Keywords: soy mash fermentation, temperature, predictive control, energy-effective, compartment model

1. Introduction

Soy sauce was invented by the Chinese about 3500 years ago, and the modern producing technology was developed by the Japanese about 500 years ago. The production consists of solid-state fermentation, mash fermentation, and flavouring. The quality and cost of a soy sauce product are mainly determined by the mash fermentation stage. In tradition, soy mash is placed in a pottery tank which is exposed to sunshine for 4~12 months. The duration of exposure under the sun is season-dependent as the enzyme and the microbes in the mash are sensible to temperature variations [1-4].

Despite the cost raised by a longer fermentation time and more manpower, traditional soy sauces still deserve of popularity as their special flavours are superior to cheap, chemical ones. Because the mash fermentation is manipulated outdoors, the processes of fermentation are easily affected by the climate, and the mash is vulnerable to alien contamination [5]. This may lead to a produce with unstable quality and alien contamination. To overcome this problem, we moved the fermentation from outdoors to indoors and controlled the fermentation climate [5], as shown in Fig. 1. In the system, the pottery containing soy mash is bathed in a water tank and the temperature of the batching water is regulated to meet the requirements of various fermentation stages [5-6]. It has been demonstrated that a controlled fermentation climate can create a well environment for the enzymes and microbes participating in mash fermentation [7-8]. Thus, the produce can arrive at a better quality in a shorter time in comparison with the traditional approach [9].

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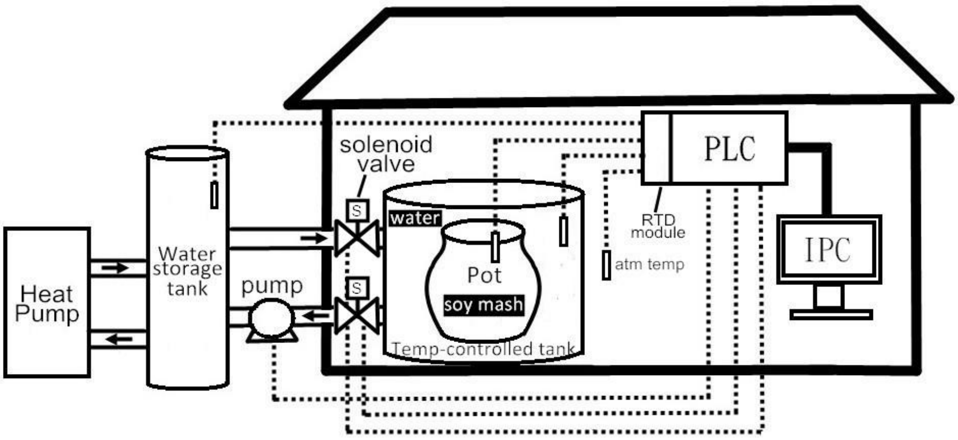
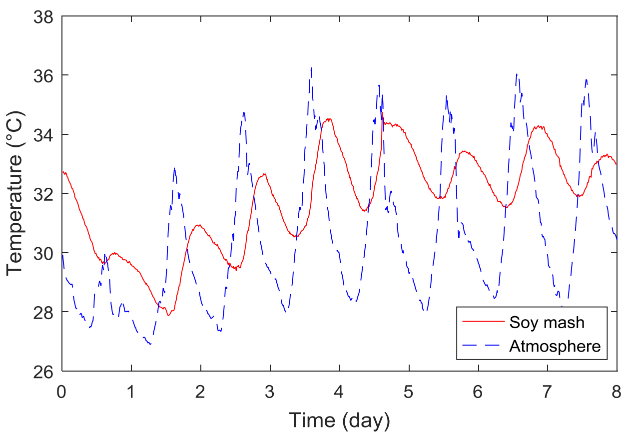
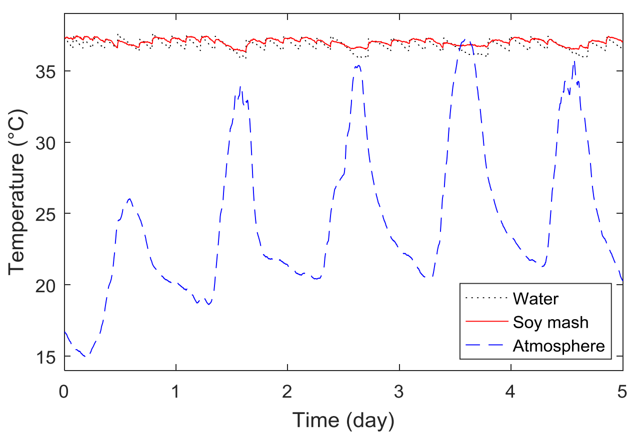


Fig. 1 Setup of the energy-saving soy sauce fermentation system [5].

As Fig. 1 illustrates, the system consists of a heat pump which supplies hot water circulation for regulating the fermenter with desired temperature settings. The system is controlled with a programmable logic controller (PLC) and supervised with an industrial personal computer (IPC). The current principle of operation is to let the heat pump work at noontime for the benefit of a better operational efficiency and the hot water produce is stored in a storage tank for later use, usually in night time. The PLC manipulates the solenoid valves and the circulation pump once the temperature of the mash is below a certain level. These two solenoid valves assure correct water flow directions. Hot water will circulate for 3 min for adequate heat injection into the soy mash. The duration was determined through experimental studies via trial-and-error. Fig. 2 demonstrates the temperature profiles of the soy mash, the atmosphere, and the circulation water. Clearly, the mash can ferment at an environment with a more stable temperature regardless of a varying atmospheric climate. Though, the temperature variation in the fermenter has been improved to be within 1°C, much improved regardless of varying climate, it still fluctuates as a result of simple ON/OFF control using solenoid valves.



(a) Temperature responses of the traditional procedure



(b) Temperature responses of ON/OFF control

Fig. 2 The temperature profiles of the soy mash, the atmosphere, and the water in the bathing tank

The price of electricity is different between peak and off-peak times. The heat pump has a maximum efficiency at noontime. However, the demand of hot water circulation is usually in night time, several hours after the hot water preparation. The stored hot water will inevitably lose some heat to the space before being consumed. There should be an optimum time of operating the heat pump in term of electricity cost [10-12]. It would be possible to operate the heat pump at a most cost-effective way if we can determine when hot water circulation is demanded.

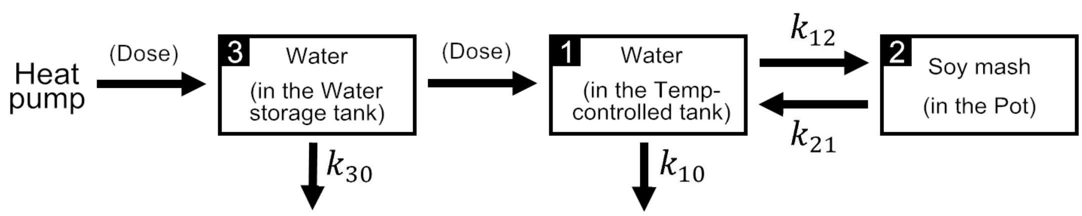
The objective of this study is to develop a temperature and energy prediction model using the compartment modelling technique which has been successfully used in pharmacology for drug administration [13]. As the system described in Fig. 1, we can partition the system into several unique compartments and describe mathematically the energy exchanges among the compartments. In analogy to pharmacokinetics, the water storage tanks and the fermentation tanks are treated as compartments, energy exchange among tanks and the atmosphere as drug delivery, the temperature as drug concentration, electrical energy injected into the heat pump can be treated as a dose input. We can estimate energy flows, temperatures responses, and hence, electricity consumption. Based on this, we can determine the best time of heat pump operation and control the time and duration of hot water circulation using simple and cheap solenoid valves. Hence, the profit can be promoted as a result of better and efficient fermentation without too much of energy consumption and therefore, secured environmental affect. Accordingly, a compromise can be arrived at among economy, ecology, and energy (3E).

2. Materials and Methods

2.1. Compartment modelling

Fig. 3 illustrates the proposed compartment model. The heat pump is identified as an energy supply to the hot water circulation system. The soy mash pot (Compartment 2) is bathed in hot water (Compartment 1). There is heat exchange in between. Compartment 1 will inevitably loss heat to the atmosphere. Compartment 3 stores hot water produce from the heat pump. Heat energy is supplied from Compartment 3 to Compartment 1 via water circulation. Cooled water is to be circulated back to Compartment 3 from Compartment 1. Compartment 1 is equipped with a well-designed stirrer that mixes incoming hot water and the existing cool water efficiently. In other word, energy is injected into Compartment 1 as a dose bolus rather than via heat transfer. Thus, there is no k_{31} and k_{13} correlation in between. To simplify the problem, the storage tank (Compartment 3) is treated as an infinite tank comparing to Compartment 1. Since the hot water storage tank is well insulated, no-heat-loss is assumed, ie. $k_{30} = 0$. Eq. (1) describes the dynamics of energy transfer based on the compartmental model; where T_1 is the temperature of Compartment 1, T_2 is the temperature of Compartment 2, and $r(t)$ is the injected energy dose:

$$\begin{cases} \dfrac{dT_1}{dx} = r(t) - (k_{10} + k_{12}) \cdot T_1 + k_{21} \cdot T_2 \\ \dfrac{dT_2}{dx} = k_{12} \cdot T_1 - k_{21} \cdot T_2 \end{cases} \tag{1}$$

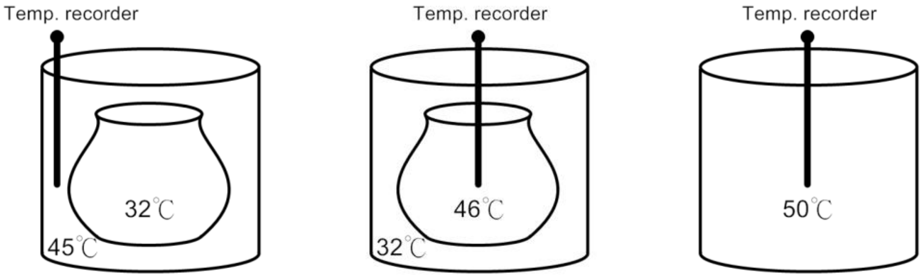


k_{12} : The transfer constant of heat in circulation water transfer to soy mash (s^{-1})
k_{21} : The transfer constant of heat in soy mash transfer to circulation water (s^{-1})
k_{10} : The transfer constant of heat in circulation water dissipate into the air (s^{-1})
k_{30} : The transfer constant of heat in storage water dissipate into the air (s^{-1})

Fig. 3 The proposed compartment model

2.2. Determination of system parameters

Fig. 4 shows the experimental setup for determining the k coefficients. Tanks were filled with water of different temperatures and hence, energy flowed from high temperature to low temperature sites. Temperature responses were recorded every 10 min till thermodynamic equilibrium. Acquired data were fitted to first-order equations using the MATLAB curve fitting toolbox.



(a) for k_{12} (b) for k_{21} (c) for k_{10}

Fig. 4 Experimental setups for determining the k coefficients

Other parameters to be determined are the volume of the circulation water, the volume of the soy mash and the hot water circulation time.

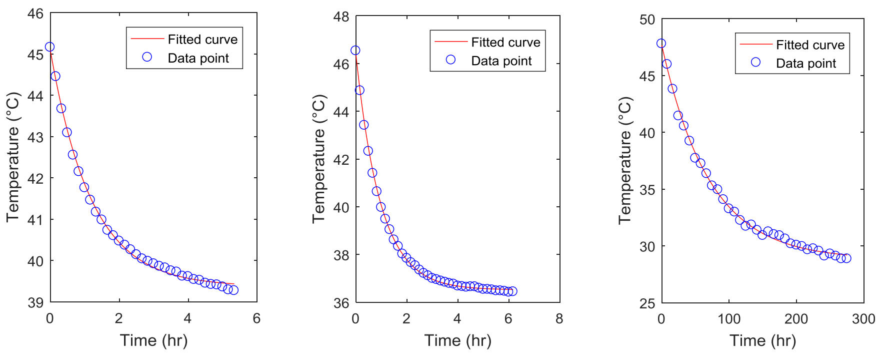
2.3. Energy consumption cost function

The heat pump extracts energy from the air to heat up water. The ambient temperature is the key factor that influences the efficiency of heat pump operation [11]. The higher the ambient temperature is, the higher the heat pump efficiency. Hence to operate the heat pump at noontime will have the maximum operational efficiency. However, the noontime is categorized as a peak time in electricity pricing, ie. the price of electricity is higher than other times. The mash fermentation tank will have a lower temperature at night time and therefore, the hot water prepared at noontime is not used for several hours. In other word, the hot water produced by the heat pump at noontime will loss a big amount of energy to the atmosphere. Thus, it may be more profitable by operating the heat pump away from noontime as a compromise among electricity price, heat pump efficiency, and energy loss. Accordingly, an energy consumption cost function is to be developed to account for the efficiency of the heat pump, the electricity pricing policy, and the heat loss of the hot water storage tank.

3. Results and Discussion

3.1. System parameters

Temperature responses were acquired with a sampling period of 10 min for 6 h which is long enough for the system to reach thermodynamic equilibrium. The acquired data are fitted to a first-order equation using the MATLAB curve fitting toolbox. Fig. 5 shows the temperature responses.



(a) for k_{12} (b) for k_{21} (c) for k_{10}

Fig. 5 Temperature responses for determining the compartment-model coefficients

Fig. 5(a) is the temperature profile for k_{12} and can be described as:

$$T = 5.727e^{-t/7.143} + 39.37\ °\text{C} \tag{2}$$

with a time resolution of 10 min (600 s). The time constant is $7.143 \times 600 = 4285.8$ s and its reciprocal gives $k_{12} = 2.33 \times 10^{-4}\ s^{-1}$.

Fig. 5(b) is the temperature profile for k_{21} and can be described as:

$$T = 9.86e^{-t/5.821} + 36.52\ °\mathrm{C} \tag{3}$$

The time constant is $5.821 \times 600 = 3492.6$ s and its reciprocal gives $k_{12} = 2.86 \times 10^{-4}\ s^{-1}$.

Fig. 5(c) is the temperature profile for k_{10}. The bathing tank is cladded with a good insulation material. Hence as the profile shows, this is a very slow heat transfer system. It took 11 days to reach thermodynamic equilibrium and resulted in 1716 recordings. These data are down-sampled with a factor of 50. The profile can be described with first-order dynamics, as:

$$T = 18.85e^{-t/8.523} + 28.81\ °\mathrm{C} \tag{4}$$

The new sampling period is $60 \times 10 \times 50 = 3 \times 10^4$ s, the time constant is $8.523 \times 30000 = 255690$ s, and the coefficient is $k_{10} = 3.91 \times 10^{-6}\ s^{-1}$.

3.1.1. Other constants

Compartment 1 has a space of 220 litres for circulation water and Compartment 2 accommodates 160 litres of soy mash.

3.1.2. Thermodynamics of the circulation water

The purpose of water circulation control is to regulate the temperature of the soy mash in Compartment 2 through controlling the heat injected into Compartment 1. Fig. 6 illustrates the conceptual thermodynamics of the two compartments. Compartment 1 has a water distributor designed to mix the incoming water with the existing one in an effective way. Hence the two media are assumed to mix instantaneously. The first law of thermodynamics describes the heat balance of the thermodynamic system, as:

$$Q_{in} + Q_{origin} - Q_{out} = Q_{final} \tag{5}$$

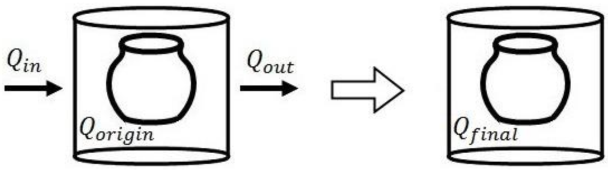


Fig. 6 Heat balance in the batching tank

Substituting $Q = m \times h_f$ to Eq. (4) and discretizing give,

$$\dot{m}_h \times \Delta t \times h_f(T_h) + m_b \times h_f(T_{b,k-1}) - \dot{m}_h \times \Delta t \times h_f(T_{b,k-1}) = m_b \times h_f(T_{b,k}) \tag{6}$$

with $\dot{m}_h$ the circulating water flow rate, h_f the enthalpy of water at a specific temperature, m_b the mass of the bathing water, T_h the temperature of the incoming hot water, T_b the temperature of the bathing water, Δt the heating duration, and k the time stamp.

The enthalpy can be approximated with the specific heat, ie. $h_f \cong C_p \times T$, hence Eq. (6) can be rewritten as:

$$\dot{m}_h \times \Delta t \times C_p \times T_h + m_b \times C_p \times T_{b,k-1} - \dot{m}_h \times \Delta t \times C_p \times T_{b,k-1} = m_b \times C_p \times T_{b,k} \tag{7}$$

Rearranging the above gives the temperature response:

$$T_{b,k} - T_{b,k-1} = \Delta T_b = \frac{\dot{m}_h \times \Delta t}{m_b}\left(T_h - T_{b,k-1}\right) \tag{8}$$

The following values are used for simulation validation: $\dot{m}_h = 10\mathrm{kg/min}$, $\Delta t = 3$ min, $m_b = 220$ kg, $T_h = 47℃$. The water storage tank (Compartment 3) has a capacity of 1500 litres and only 30 litres are demanded for the circulation.

Hence it is reasonable to assume a constant T_h. The initial temperature of the bathing water $T_{b,k-1}$ is assumed as 36.8°C. Substituting the above values into Eq. (8) results in $\Delta T_b = 1.39$°C, ie. a 3-min heat injection heats up the bathing water by 1.39°C. This information will be used in compartment modelling.

3.1.3. Validation

The compartment model of Fig. 3 was validated using the MATLAB SimBiology toolbox using the parameters identified in Section 3. Fig. 7 shows simulation and actual responses. There is a strong degree of coherence in between. This promising result indicates that the proposed compartment model can effectively describes the energy flows of the fermentation system.

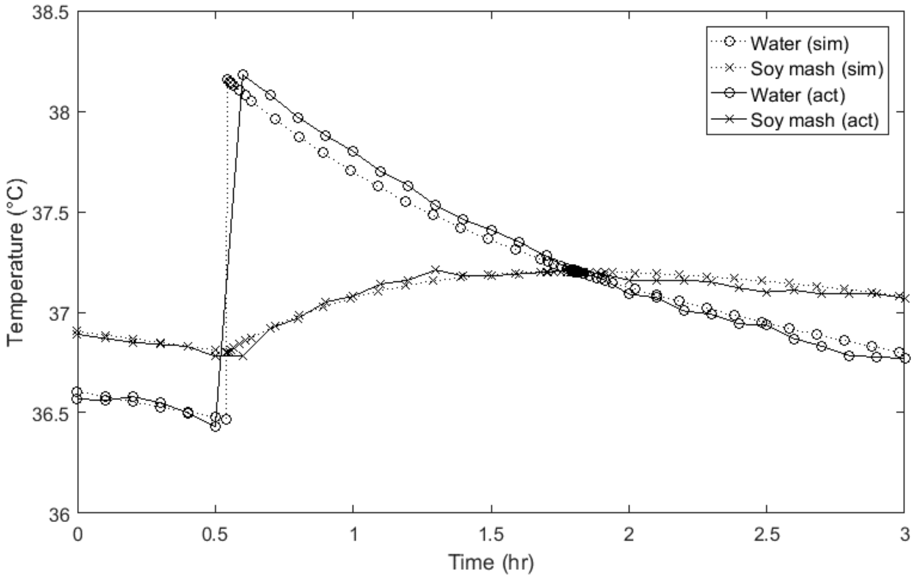


Fig. 7 Simulation and actual responses

It is clear that the timing of operating the heat pump is the key issue of saving energy cost for the fermentation system. The timing should account for the operational efficiency, electricity pricing, and heat losses from tanks. Thus, the above three factors are transcribed as an energy cost function: minimising the function for the least energy bill.

In this study, the heat pump was set to produce hot water at 47℃. The energy for 1 litre of hot water produce is:

$$Q = m \times C_p \times \Delta T = 1 \times 4.2 \times (47 - T_t) = 197.4 - 4.2\,T_t \tag{9}$$

with T_t the temperature of the water in the storage tank, which can be estimated using the compartment model .

The performance of a heat pump is described with the so-called Coefficient of Performance (COP). It is a ratio of the heat generated, Q, by the heat pump to the energy consumed, W, by the heat pump [14], as:

$$COP = \frac{Q}{W} \tag{10}$$

The work done by the heat-pump compressor is:

$$W = \frac{Q}{COP} = \frac{197.4 - 4.2\,T_t}{COP}\,kJ \tag{11}$$

The COP coefficient is sensitive to the ambient temperature T_a. Table 1 lists the COPs of the heat pump (CHP-80Y, SUN TECH, Taiwan). The hotter the ambient is, the larger the COP.

Table 1 COPs of the heat pump at different ambient temperatures

Ambient (°m)	-20	-15	-10	-5	0	2	7	10	16	20	25	30	35	43
COP	2.2	2.4	2.6	2.5	2.6	2.8	3.7	4.0	4.2	4.3	4.4	4.5	4.4	4.3

The compressor of the heat pump is assumed to have an efficiency η=0.9. The work demanded by the heat pump to produce 1 litre of hot water is:

$$W_i = \frac{W}{\eta} = \frac{197.4 - 4.2\, T_t}{COP} \div 0.9 = \frac{219.33 - 4.67\, T_t}{COP} \text{ kJ} \tag{12}$$

or in KWH, as:

$$W_i = \frac{219.33 - 4.67\, T_t}{COP} \div (3.6 \times 10^3) = \frac{0.060925 - 0.001297\, T_t}{COP}\, KWH \tag{13}$$

The cost C, in NTD, that the heat pump take to produce 1 litre of hot water is:

$$C = \frac{E}{COP}(0.060925 - 0.001297\, T_t) \tag{14}$$

where E is the price of unit KWH in NTD/KWH, a value varies at peak and off-peak times. Table 2 shows the pricing policy of Taiwan Power Company (TPC). The above cost function is a function of the time of heat pump operation (transcribed as COP and E) and heat losses from the storage tanks (transcribed as T_t).

Table 2 Pricing policy of Taiwan Power Company

			summertime	non-summertime
Mon~Fri	peak time	07:30~22:30	3.24	3.18
	off-peak time	00:00~07:30 22:30~24:00	1.39	1.33
Sat	half-peak time	07:30~22:30	2.14	2.06
	off-peak time	00:00~07:30 22:30~24:00	1.39	1.33
Sun and off-peak day	off-peak time	all day	1.39	1.33

4. Conclusions

We have built a compartment model for describing temperature response, heat exchange, and energy demand of a soy mash fermentation system. There is a strong coherence between simulation and actual results. Simulation results show that the model can accurately predict the trend of temperature response. Thus, our next work is to implement model-based predictive temperature control based on the developed compartment model. This will give a more precise temperature control. The model also describes the heat exchange, or energy flow, between tanks (compartments). This feature allows us to estimate the optimum time of running the heat pump. Hence we can arrive at a promising temperature control with an economic electricity bill.

Acknowledgements

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