Evaluation of the dual digestion system
Part 4: Simulation of the temperature profile in the batch fed aerobic reactor

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Abstract

An algorithm is presented which enables the profile of the reactor sludge temperature vs. time in the batch fed aerobic reactor of the dual digestion system to be simulated by solving the unsteady state heat balance. From the algorithm a computer model is developed which calculates and plots the sludge temperature vs. time profile in a reactor which is oxygenated either by air, oxygen enriched air or by pure oxygen. The model is shown to accurately predict the temperature/time profiles in the pure oxygen aerobic reactor of the Milnerton dual digestion system for a wide range of different operating conditions.

Nomenclature and abbreviations

(For symbols not in this list see **Parts 2** (Messenger et al., 1993) and **3** (Messenger and Ekama, 1993a)

ATASIM = Autothermal thermophilic aerobic reactor simulation computer program.
f_b = batch fraction, i.e. fraction of the full operating volume transferred per batch cycle (= V_b/V_p).
H_s = enthalpy (heat content) of the reactor sludge (MJ). Subscripts t and t+Δt denote H_s at times t and t+Δt respectively.
T_{se} = reactor sludge temperature (°C). Subscripts 1, 2 and 3 denote T_{se} at the end of phases 1, 2 and 3 of the batch cycle respectively (Fig. 1). Subscripts t and t+Δt denote T_{se} at times t and t+Δt respectively
T_{ref} = reference temperature for reactor sludge enthalpy (° C).
t = batch phase time (h). Subscripts tpr, fpr, D and c denote transfer, feeding, heating and total cycle times respectively.
V_p = reactor volume (m^3). Subscripts t and t+Δt denote V_p at times t and t+Δt respectively.
ΔH_s = change in H over time interval Δt.
Δt = integration step length time interval (h).

Introduction

In **Part 3** of this series (Messenger and Ekama, 1993), considerations in, and a procedure for, the design of the aerobic reactor in the dual digestion system were presented. These were developed from principles observed in the results of the research on the Milnerton pure oxygen and Athlone air oxygenated aerobic reactors (Messenger et al., 1990;1992;1993; Pitt, 1990; Pitt and Ekama, 1993). In the interests of simplicity, the design procedure was based on the steady state heat balance which in effect accepts that the sludge flow through the digester is continuous. This approach allowed a constant temperature for the aerobic reactor to be calculated by balancing the heat sources and heat sinks. However, the aerobic reactor is required to be operated under batch draw-and-fill conditions so that the pasteurised effluent sludge is not contaminated by raw feed sludge. This causes a moment-by-moment imbalance between the heat sources and heat sinks and results in a continually changing reactor sludge temperature with time which takes the form of a distinctive saw-tooth profile (Fig. 1). In this paper, an algorithm is presented capable of simulating this reactor sludge temperature vs. time profile.

The algorithm presented is completely general and may be

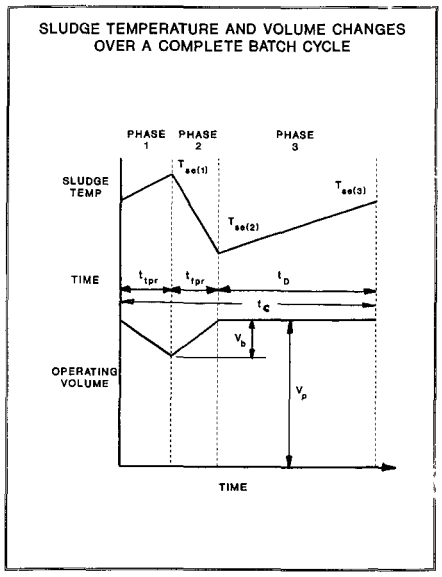

Figure 1
Reactor sludge temperature (top) and operating volume (bottom) versus time profile of the batch fed aerobic reactor in dual digestion showing the 3 phases over the batch cycle: (1) transfer (of duration t_{tpr}), (2) feeding (of duration t_{fpr}) and (3) heating (of duration t_D). The volume of sludge transferred i.e. the batch volume V_b, as a ratio of the full operating volume V_p, is called the batch fraction (f_b)

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applied to the aerobic reactor of any dual digestion system provided that the reactor is continuously mixed and oxygenated with air, oxygen enriched air or pure oxygen and the reactor is batch fed using a draw-and-fill system. Hence, biological and mechanical heating are continuous and constant throughout the 3 phases of the batch cycle. The algorithm has been codified into a computer program to simplify the calculations. This program, called ATASIM, is briefly discussed at the end of this paper (Continuously fed reactors can be simulated by reducing the heating cycle to a very small proportion of the batch cycle time and imposing frequent alternate transfer and feeding phases of equal duration).

The batch cycle

The batch cycle illustrated in Fig. 1 comprises 3 phases, viz: transfer, feeding and heating. Due to the moment-by-moment imbalance between the heat sources and heat sinks caused by the system of batch feeding, steady state can only be defined in terms corresponding times in successive batch cycles; if the temperature at corresponding times, (such as T_{se} in Fig. 1) is the same, then the reactor is at steady state.

The batch fraction f_b is the ratio of the batch feed volume and the full operating volume of the reactor. The amount by which the reactor sludge temperature, T_{se}, decreases during the feeding phase is proportional to f_b and the difference between the influent and effluent sludge temperatures (T_{si} and $T_{se(1)}$ respectively). The temperature after feeding $T_{se(2)}$ should not fall below the minimum specified for pasteurisation.

The cycle time, t_c, is equal to the duration of a complete batch cycle and it determines the duration of the heating phase of the batch cycle (Fig. 1). Because of the danger of sludge flow short circuiting, pasteurisation is generally considered to be effective only if the sludge is maintained above a specified temperature for a specified undisturbed detention time t_D. This undisturbed detention time is not the reactor retention time R_H but the duration of the heating phase. Hence the cycle time duration must be sufficiently long so as to ensure that the heating phase is at least as long as the minimum required pasteurisation time, t_D. Thus:

$$t_c = t_{tpr} + t_{fpr} + t_D \text{ (h)} \qquad (1)$$

The number of batch feeds in a day and the volume of each of these batches which are functions of t_c and f_b respectively, define the daily sludge flow (Q_s), and hence the reactor retention time R_H as follows:

$$\begin{aligned} R_H &= V_p/Q_s = V_p/\{(24/t_c) \cdot (f_b V_p)\} \\ &= t_c/(24 f_b) \\ &= (t_{tpr} + t_{fpr} + t_D)/(24 f_b) \qquad \text{(d)} \end{aligned} \qquad (2)$$

At Milnerton, where pasteurisation conditions were accepted to be :$\geq$55°C for, $\geq$2 h, meant that $T_{se(2)} > 55$°C and $t_D > 2$ h. The batch fraction, f_b, is then calculated so that these conditions are achieved at the minimum design retention time R_H. For Milnerton, the minimum R_H was accepted to be around 1 d and because the transfer and feeding phases were only 3 and 4 min respectively, f_b was set to 2/(24.1) = 1/12th which gave the batch volume $V_b = 45/12 = 3{,}75$ m^3. With f_b = 1/12th and t_c = 2 h + 3 min + 4 min = 2,12 h, the actual minimum R_H is 1,06 d. However, a 1 d retention time could not be maintained throughout the year because sufficient biological heat could not be generated. At 1,25 d which could be maintained, the batch cycle was 2,5 h and the detention time t_D 2,38 h, sufficiently long in terms of the pasteurisation conditions set.

The procedure for simulating the temperature-time profile of the reactor sludge

The change in reactor sludge temperature with time is caused by changes in the enthalpy of the sludge. By constructing an unsteady state heat balance across the reactor, these enthalpy changes can be calculated over a small, arbitrary time interval Δt, allowing the sludge temperature change over this time interval to be determined. The algorithm to do this, which comprises 4 calculation steps, is as follows:

- Step 1: The enthalpy, $H_{s(t)}$, of a defined operating volume of sludge, $V_{p(t)}$ is calculated at time t by assuming a reactor sludge temperature, $T_{se(t)}$.
- Step 2: An unsteady state heat balance is constructed across the reactor at time t over a small time interval Δt, accepting that the reactor volume and sludge temperature at time t, $V_{p(t)}$ and $T_{se(t)}$, remain constant. From the heat balance over Δt, it is found that the heat sources and heat sinks are not equal and differ by an amount ΔH_s [Note that in the 3 earlier papers, the symbol $\dot{H}$ denoted the flow of heat (MJ/h). In this paper, the same convention applies except in the case of the symbols ΔH_s, $H_{s(t)}$ and $H_{s(t+\Delta t)}$, which now denote amount of heat (MJ)]. The ΔH_s amount of heat represents the change in sludge enthalpy over the time interval Δt.
- Step 3: At time (t+Δt), the new operating volume, $V_{p(t+\Delta t)}$, and the new reactor sludge enthalpy, $H_{s(t+\Delta t)}$, are calculated where $H_{s(t+\Delta t)}$ is obtained by adding ΔH_s from step (2) to $H_{s(t)}$ from step (1).
- Step 4: The reactor sludge temperature at time (t+Δt), $T_{se(t+\Delta t)}$, is calculated from the new reactor sludge enthalpy, $H_{s(t+\Delta t)}$, and the new operating volume, $V_{p(t+\Delta t)}$.

Commencing at Step (1) with two initial condition inputs, i.e. an assumed or estimated starting value for T_{se} and specified sludge volume V_p, and repeating steps (2) to (4) over a large number of successive small time intervals (Δt), the profile of the reactor sludge temperature vs. time is obtained. For continuity after each iteration of Steps 2 to 4, the values of $T_{se(t+\Delta t)}$, $V_{p(t+\Delta)}$ and $H_{s(t+\Delta t)}$ at the end of one time step are substituted for $T_{se(t)}$, $V_{p(t)}$ and $H_{s(t)}$ respectively, to be the initial conditions for the next time step.

To give greater insight into this algorithm of the program ATASIM, the calculations at the various steps in the algorithm are briefly discussed below, commencing with Step (1).

Step 1: The reactor sludge enthalpy at time t, $H_{s(t)}$

The enthalpy of the sludge in the aerobic reactor is a function of the operating volume, V_p, and the temperature, T_{se}, of the sludge. It is not an absolute measure of energy but is calculated relative to an arbitrary reference temperature, T_{ref}. The enthalpy of the reactor sludge relative to T_{ref} at time t is:

$$H_{s(t)} = V_{p(t)} \rho_s C_{ps} (T_{se(t)} - T_{ref}) \qquad \text{(MJ)} \qquad (3)$$

Step 2: The change in the reactor sludge enthalpy over the time interval Δt, ΔH_s

The reactor sludge enthalpy changes as the reactor loses heat to 4

sinks (i.e. H_{se}, H_{ge}, H_{ve} and H_{we}) or gains heat from 4 sources (i.e. H_{bi}, H_{mi}, H_{gi} and H_{si}). The change in reactor sludge enthalpy, ΔH_s, over a time interval, Δt, is calculated as the difference between the 4 heat sources and heat sinks across the reactor during this interval. Hence:

$$\Delta H_s = \sum_{t}^{t+\Delta t} \text{heat sources} - \sum_{t}^{t+\Delta t} \text{heat sinks} \quad (MJ) \quad (4)$$

Equation (4) is solved with the aid of the unsteady state heat balance over the time interval Δt, i.e.:

$$\Delta H_s = \Delta t\,(H_{bi} + H_{mi} + H_{gi} + H_{si} - H_{se} - H_{ge} - H_{ve} - H_{we}) \quad (5)$$

Although some important considerations in connection with the heat balance terms H_{bi}, H_{mi}, H_{gi}, H_{si}, H_{se}, H_{ge}, H_{ve} and H_{we} in Eq. (5) are discussed below, the equations required to calculate these terms are not presented in this paper: Details are given by Messenger et al. (1992) and Messenger and Ekama, 1993. In conformity with the convention in this series of papers, these equations yield values for the heat balance terms in MJ/h. The terms are multiplied by the time interval Δt, to give ΔH_s as the net heat difference in MJ which increases or decreases the reactor sludge enthalpy over the time interval Δt. Additionally the following also should be noted with regard to Eq. (5) (see Fig. 1);

- H_{se} is zero, except in phase 1 when sludge is transferred from the reactor.
- H_{si} is zero, except in phase 2 when sludge is pumped into the reactor.
- H_{bi}, H_{mi}, H_{si}, H_{gi} are assumed to remain constant for a specified set of plant operating conditions i.e. their value does not change in successive Δt intervals; they change only when the input conditions defining the reactor operation change.
- H_{se}, H_{ge}, H_{ve}, and H_{we} are functions of the reactor sludge temperature, T_{se} and change in successive Δt intervals as T_{se} changes with time.

The biological heat generation rate, H_{bi}

At Milnerton H_{bi} was found to be proportional to the oxygen transfer rate (OTR) of the oxygenation system, with the constant of proportionality being the specific heat yield Y_H. This proportionality was found to hold for OTR values up to the sludge oxygen consumption rate (OCR_{bio}). Furthermore, it was found that Y_H was proportional to the degree of oxygen limitation in the sludge and could be represented by:

$$Y_H = 14{,}245 - 1{,}648\,\left(\frac{OTR}{OCR_{bio}}\right) \quad (MJ/kgO) \quad (6)$$

where:

OCR_{bio} = 0,38 kgO/(m^3·h) for Milnerton sludge which was a mixture of primary and humus tank sludges.

The mechanical heat input rate, H_{mi}

The nature and means by which mechanical heat enters the reactor sludge will vary depending upon the reactor mixing/oxygenation design. This makes it difficult to develop a general equation for predicting H_{mi}. Accordingly, for ATASIM an appropriate value for H_{mi} needs to be selected which is accepted to remain constant over the batch cycle. A constant H_{mi} not only simplifies calculations but also is reasonable for most mixing/oxygenation applications.

The wall heat loss rate, H_{we}

Theoretically, H_{we} changes during the 3 phases due to the change in the reactor sludge temperature T_{se} with time. Practically however, not only is H_{we} itself very small relative to the other heat sinks, but also the changes in it (due to the 2 to 5°C changes in T_{se}) are very small. This, together with the fact that H_{we} depends on the reactor geometry, weather conditions and the degree of reactor lagging, led to accepting for ATASIM that H_{we} is constant at some estimated rate.

The vent gas heat loss rate, H'_{ve}

The vent gas heat loss rate, H'_{ve} is the sum of the rates of vent gas water vapour heat loss (H_{ve}) and sensible heat loss ($H'_{ge} = H_{ge} - H_{gi}$) and may be calculated with the aid of the Eq. (14) in Messenger and Ekama (1993). This equation applies to a vent gas stream which is saturated with water vapour, a condition that was found to exist in the Milnerton pure oxygen and Athlone air oxygenated aerobic reactors. Should it be necessary to simulate reactors which produce undersaturated vent gas streams, this can be accommodated by specifying an appropriately larger temperature difference between the vent gas and the reactor sludge (T_{diff}), with the magnitude of T_{diff} dependent on the degree of undersaturation expected. For a reactor which is continuously oxygenated, the equation for H'_{ve} applies over the complete batch cycle.

The sensible heat loss/gain due to sludge leaving/entering the reactor, H_{se}, H_{si}

The volume of sludge leaving and entering the reactor during the transfer and feeding phases is equal to the batch volume, V_b. The loss and the gain in sensible heat due to this sludge flow may be calculated with the following equations:

$$H_{se} = \frac{V_b}{t_{tpr}}\,\rho_s\,C_{ps}\,(T_{se} - T_{ref}) \quad (MJ/h) \quad (7)$$

$$H_{si} = \frac{V_b}{t_{fpr}}\,\rho_s\,C_{ps}\,(T_{si} - T_{ref}) \quad (MJ/h) \quad (8)$$

In Eqs. (7) and (8) like in Eq. (3) ρ_s and C_{ps} are accepted to be equal to that of water (Messenger et al., 1992). Also the influent and effluent batch volume (V_b) remains constant; justification for this for oxygen and air oxygenated reactors is given by Messenger and Ekama (1993) (see Eq. 1).

Step 3: The reactor sludge enthalpy at time t+Δt, $H_{s(t+\Delta t)}$

The enthalpy in the reactor at time t, $H_{s(t)}$, (Eq. 3) increases after the interval of time, Δt, by ΔH_s i.e.

$$H_{s(t+\Delta t)} = H_{s(t)} + \Delta H_s \quad (MJ) \quad (9)$$

Step 4: The reactor sludge temperature at time t+Δt, $T_{se(t+\Delta t)}$

By rearranging Eq. (3), the reactor sludge temperature at time t+Δt, $T_{se(t+\Delta t)}$ is given by:

$$T_{se(t+\Delta t)} = \frac{H_{s(t+\Delta t)}}{V_{p(t+\Delta t)}\,\rho_s\,C_{ps}} + T_{ref}\ (°C) \qquad (10)$$

To use Eq. (10), the sludge operating volume at time t+Δt $V_{p(t+\Delta t)}$ needs to be known. The operating volume V_p only changes during transfer and feeding phases. During the heating phase V_p remains constant (Fig. 1). Hence the rate of change in V_p in the transfer, feeding and heating phases are generalised with the following equations:

Phase 1: $\Delta V_p/\Delta t = -f_b(V_p/t_{tpr})$ (m^3/h) (11a)
Phase 2: $\Delta V_p/\Delta t = f_b(V_p/t_{tpr})$ (m^3/h) (11b)
Phase 3: $\Delta V_p/\Delta t = 0$ (m^3/h) (11c)

Thus V_p at time t+Δt is given by:

$$V_{p(t+\Delta t)} = V_{p(t)} + (\Delta V_p/\Delta t)\Delta t \quad (m^3) \qquad (12)$$

Performing the 4 calculation steps

In order to proceed with the calculations in Steps 1 to 4 above, values for $T_{se(t)}$ and $V_{p(t)}$ in Step 1 at some starting time t and the iteration time interval Δt, need to be defined. Furthermore, to solve the heat balance equations in Step 2, information regarding the design and operating conditions of the reactor is required and accordingly, the values of 16 input variables need to be specified.

The initial values of T_{se}, starting time t, and V_p

At the start of the simulation, the precise value of T_{se} at any given time is not known and therefore a value which serves as a reasonable starting point needs to be selected. While any value in the thermophilic range is adequate, a value which closely approximates the final maximum temperature of the dynamic steady state temperature-time profile will reduce the number of iterations required to achieve dynamic steady state. To facilitate initial T_{se} selection, the ATASIM incorporates the steady state heat balance solution procedure (from Messenger and Ekama, 1993) which calculates the steady state sludge temperature T_{se} from the specified input design and operating conditions. Examination of the temperature predicted by the steady state heat balance indicated that this temperature was slightly lower than the measured temperature reached at the end of the heating cycle ($T_{se(3)}$ Fig. 1). Consequently the starting time and temperature for ATASIM were selected to be the start of the transfer cycle and the steady state heat balance temperature estimate respectively. If the user requests ATASIM not to calculate the steady state heat balance temperature to start the dynamic simulation, a default value of 58° C is assumed for $T_{se(3)}$.

Unlike the sludge temperature, T_{se}, the operating volume, V_p, during the 3 phases of the batch cycle is completely defined by the input design and operation conditions. The starting value for $V_{p(t)}$ required by ATASIM is the volume at the starting time, t, i.e. the volume of the reactor at the beginning of the transfer phase, which is equal to the full operating volume of the reactor.

The length of the iteration time interval, Δt

The value of the time interval Δt need not be the same in each of the 3 phases of the batch cycle. In ATASIM, the value of Δt in a particular phase is 1/10 of the duration of the phase. Therefore 30 iterations, 10 per phase, of Steps 2 to 4 above, will generate 30 values of T_{se} per batch cycle from which the temperature-time profile for the batch cycle is constructed.

The step length of 1/10 of the duration of the phase was chosen as a compromise between speed of calculation and accuracy; too short a step length results in tediously long calculation times per batch cycle and too long step lengths may result in inaccurate temperature estimates. The latter occurs because with long step lengths, large temperature changes over the time interval occur with the result that the heat loss estimates via vent gas water vapour and sensible heat (which are dependent on reactor sludge temperature) become inaccurate. However, because these heat losses constitute less than 10% of the total heat loss for oxygen aerated reactors, the step length can be quite long before significant errors arise. For air systems the vent gas heat losses are a much larger proportion of the total, and therefore the step length for these reactors needs to be shorter than for oxygen reactors. The step length of 1/10 of each phase duration is sufficiently accurate for both air and oxygen reactors. On modern fast 386 PC computers, shorter step lengths of 1/100 can be implemented and still obtain very rapid results.

The reference temperature, T_{ref}

A convenient value for T_{ref} is 0° C as this simplifies Eqs. (7) and (8). With T_{ref} at 0° C, the enthalpy of the sludge is 0 MJ when T_{se} is equal to 0°C.

The variables defining the design specifications and operating conditions

To solve the unsteady state heat balance (Eq. 5), 16 input variables need to be specified which define the design specifications and operating conditions of the reactor. The 16 variables are: Q_s, R_H or V_p, T_{si}, H_{mi}, H_{we}, OTE, OTR, f_b, t_c, t_{tpr}, t_{fpr}, T_{diff}, T_{gi}, P_T, V_p, OCR_{bio}.

It should be noted that H_{we} and H_{mi} are not calculated by ATASIM and need to be calculated separately and entered as MJ/h values. Also, ATASIM requires the OCR_{bio} to define the maximum rate at which oxygen can be consumed by the sludge and to calculate Y_H with Eq. (6). With OCR_{bio} defined, ATASIM ensures that the OTR of the oxygenation system does not exceed the specified OCR_{bio}, and, should this happen, warns the user of this problem with the input data. Also with OCR_{bio} defined, Y_H is fixed and hence also the maximum biological heat generation rate H_{bimax}.

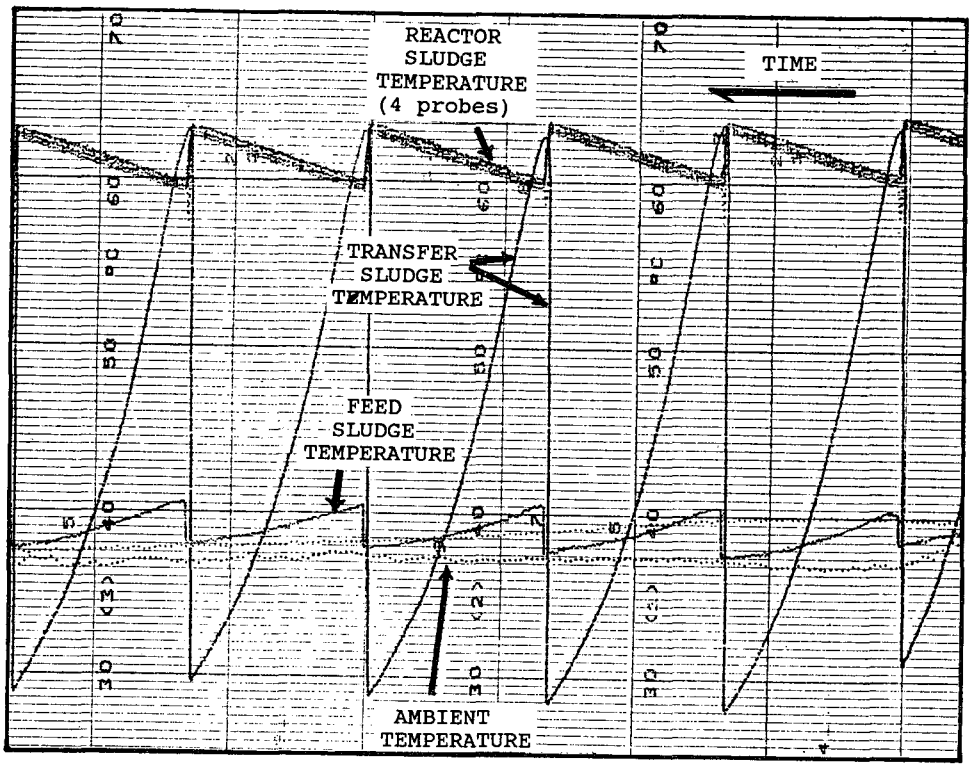
Features and predictive power of the simulation program ATASIM

ATASIM (Autothermal Thermophilic Aerobic Simulation) which is based on the algorithm outlined above, was written in Turbo Pascal 4,0 and designed to calculate and plot the reactor sludge temperature vs. time profile. Its features, where to obtain it and how to use it are given in **Appendix 1.**

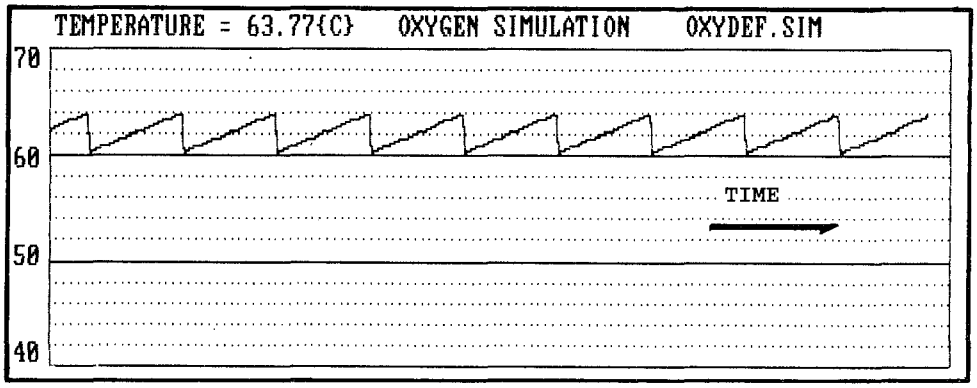
The accuracy with which ATASIM predicts reactor sludge temperatures is demonstrated in Table 1 and Figs. 2(a) and (b) where the temperatures measured at Milnerton are compared

TABLE 1
PREDICTED VS. ACTUAL REACTOR TEMPERATURES

Retention RH (days)	O_2 supply (kg/h)	$\%O_2$ consumed	Feed temp T_{si} (°C)	Actual T_{se} (°C)	Predicted T_{se}(°C)
1,25	24,3	69,2	17,9	61,0	60,1
1.25	22,0	77,9	19,0	60,5	60,8
1,25	18,5	83,5	18,3	57,1	56,8
1,5	18,5	84,4	19,7	65,8	66,6
1,5	16,5	85,4	20,8	62,4	62,0
1,25	14,5	92,6	18,8	53,0	54,0
3,0	6,3	100,0	20,8	67,8	67,0



(a)



(b)

Figure 2
Measured (Fig. 2a top, reading right to left) and simulated (Fig. 2b, bottom, reading left to right) reactor sludge temperature versus time profiles for the batch fed aerobic reactor at 1,25 d retention time, and batch fraction and cycle time of 1/12th and 2,5 h respectively

with those predicted by the model under the same operating conditions. The temperatures quoted in Table 1 are those measured at the end of the transfer phase of the batch cycle i.e. the maximum temperature of the cycle [$T_{se(1)}$ in Fig.1] . In Figs. 2(a) and (b) the measured and simulated temperature - time profiles of dynamic steady state reactor operation are compared. Clearly, the model accurately predicts the temperature profile - to within about 1,0°C - throughout the batch cycle for retention times of 1,25 and 3 d. Pitt (1990) found ATASIM also to accurately predict the reactor sludge temperature of the Athlone air oxygenated reactor.

Closure

From the dual digestion research conducted at Milnerton, Cape, an algorithm and computer program ATASIM were developed which allows the sludge temperature versus time profile in the batch fed aerobic reactor to be graphically simulated for specified input conditions. Although based on research conducted on a pure oxygen oxygenated reactor, ATASIM is general and can simulate reactors oxygenated with pure oxygen, air or oxygen enriched air; it has been found to accurately predict reactor sludge temperatures of the Milnerton (pure oxygen) and Athlone (air) dual digestion systems (Pitt, 1990; Pitt and Ekama, 1993).

Acknowledgements

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[For all references cited, see **Part 1** (Messenger et al., 1993)]

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MESSENGER, JR and EKAMA, GA (1993) Evaluation of the dual digestion system – Part 3: Considerations in the process design of the aerobic reactor. *Water SA* **19**(3) 201-208.

Appendix 1

ATASIM - a computer program for the design and operation of the batch fed autothermal thermophilic aerobic reactor in dual digestion

ATASIM is the joint property of the Water Research Commission, University of Cape Town and Afrox and copyright is vested in them. Copies of the program may be obtained from either Prof GA Ekama, Department of Civil Engineering, University of Cape Town, Rondebosch 7700, Cape, South Africa, Dr D Ossin, Market Development, Afrox, P O Box 4100, Germiston South 1411, South Africa, or Dr O Hart, Water Research Commission, P O Box 824, Pretoria 0001, South Africa.

The program consists of 3 sections, i.e. a preliminary data input and steady state design section; a detailed data input section; and a simulation section. With the first section the user can perform a preliminary steady state design of the reactor at a fixed temperature of 60°C. The first 7 operating parameters listed in the paper (see the variables defining the design specifications and operating conditions) appear in a screen window and their values represent the reactor at steady state at 60°C. One or more of these parameters may be changed as required and with a change in one, other dependent parameters of the 7 will change in conformity with maintaining steady state at 60° C. In this way a preliminary design is done yielding principally information on the oxygen or air requirements at the chosen retention time. A help menu is provided upon request defining the operating parameters required for input and explaining how to use the preliminary design section.

Upon completing the preliminary design, the program proceeds to the second section, i.e. the detailed data input window. At the user's request, the data generated in the preliminary design are transferred to this window for either a pure oxygen, air- or oxygen-enriched air simulation. If preliminary data transfer is not required, then a default data file provides data to the data window. The data window allows the design data to be more precisely specified for the simulation by requesting the remaining 9 operating parameters listed in the paper. A key menu lists the various functions that can be performed such as data modification, quick simulation, full simulation, help and file manipulation - the last mentioned for storing the full input data to a disk file.

Two parameters cannot be entered as data to the program, i.e. the maximum specific heat yield Y_H (at zero oxygen transfer) and the respiration quotient Y_{CO_2}. These values are fixed at 14,2 MJ/kgO and 0,70 respectively, values found to give good predictions at both Milnerton with pure oxygen (Messenger et al. 1992;1993) and Athlone with air (Pitt, 1990; Pitt and Ekama, 1993).

Once input data refinement is complete, the program allows a quick or a full simulation to be performed. The purpose of the former is to establish an accurate starting temperature to reduce dynamic simulation time and also gives another opportunity to check the now more refined design. If the quick simulation is bypassed, a default starting temperature of 58° C is assumed.

At the instruction of the user, the dynamic simulation section commences and the program graphically plots the temperature-time profile on the screen as temperature values are calculated. As the simulation proceeds, the unsteady state heat balance results are given below the graph at the time of feed phase

commencement (i.e. at maximum temperature, $T_{se(1)}$), Fig. 1. At each feed phase commencement time the unsteady state heat balance data are updated from the previous batch cycle results. If the heat sources and heat sinks of these results do not balance then the reactor has not yet reached dynamic steady state and the simulation should be allowed to continue.

At any stage of the simulation, irrespective of whether or not dynamic steady state has been achieved, the calculation and plotting may be interrupted in order to change any of the operating parameters. This allows the user to examine the effect of a change in operating conditions in the temperature-time profile. The input parameters can be scrolled through and changed as desired and the simulation restarted. When restarted, the simulation proceeds from where it was interrupted. Should the operating change be anticipated to cause a large change in reactor temperature, an accelerated simulation (non graphical) option is available. Once the temperature closely approximates the new dynamic steady temperature, the graphical output is resumed automatically. A menu summarising 11 options for program control and output management is displayed below the simulation plot. These options allow:

- making a hard copy of (1) the graphical profile or (2) simulation data;
- (3) displaying and changing the operating parameters;
- continuing the simulation with changed operating parameters (4) graphically or (5) first quickly finding a new approximate sludge temperature and then continuing graphically;
- (6) interruption of simulation and await further instruction;
- display (7) sludge mass, (8) oxygen mass or (9) heat balances in right hand screen window;
- (10) fetch a different data file from disk for simulation, and
- (11) exit the ATASIM program and return to DOS.

Additional features incorporated in the program facilitating its use are:

1) **Start:** Insert the floppy disk you receive in drive A and Type ATASIM. Press Return.
2) **Help:** Help routines are available in the steady state design and data input sections (Sections 1 and 2) and may be activated by Ctrl-H. These routines give supporting information about the parameters displayed in the windows.
3) **File Operations:** Files may be saved and retrieved from the data input (Section 2) and simulation (Section 3) windows. From the data window, the program automatically retrieves 2 default files OXYDEF.SIM and AIRDEF.SIM for oxygen and air/oxygen enriched air simulations respectively. These default files can be altered with the program or with another standard file editor. During file operations, unless otherwise specified, the default file path and drive are those from which the program was started.
4) **Graphics capability:** The program employs graphics routines from Borland's Turbo Graphix Toolbox Ver 4.0. The program runs only on PCs with Hercules graphics cards.
5) **Printer capability:** The printing routines operate only on Epson or compatible printers.
6) **Exiting ATASIM:** From the design and data windows the program may be exited with Ctrl-Break.

From the above features, in particular (4), it can be seen that the program is somewhat outmoded with regard to the hardware it requires and therefore somewhat restricted as to the PCs it can run on. This is because the program evolved during the research project which did not have modern computer facilities at its disposal. At this stage, the perceived demand for the program is deemed too low to justify the cost of rewriting the program to improve and modernise its software and hardware features.

Important note to users and disclaimer

The computer program ATASIM is the codification of research results obtained on the Milnerton and Athlone full-scale dual digestion facilities. This research has been outlined in this series of 4 papers and by Pitt (1990) and Pitt and Ekama (1933) The program was designed to be user-friendly and contains various help routines to assist with the selection of input data. Accordingly, only a rudimentary knowledge of biological heat generation and heat balances in autothermal thermophilic aerobic reactors is required to accomplish the design and simulation of the aerobic reactor of a dual digestion system with the aid of the program. However, for potential users without considerable knowledge and experience of the underlying principles of the process design and operation of autothermal thermophilic aerobic reactors, **the ATASIM program should not be regarded as replacement for the lack of knowledge and experience**: ATASIM does not design aerobic reactors; it merely takes the tedium out of the calculations required from which an experienced engineer/operator can make a sound engineering judgment. It is strongly recommended that before ATASIM is used, the user hold a sound working knowledge and familiarity with the principals and research embodied in ATASIM by careful study of the relevant papers and reports. Only with such knowledge does the user have the insight and critical ability to determine the reasonableness of the output for a particular application and so ensure that ATASIM is being responsibly used and its output meaningfully interpreted. Also, while it is believed that ATASIM is based on the best available knowledge and that significant effort has been expended in eliminating errors, users are warned that use of the program and application of the results obtained, is the sole responsibility of the user.