Evaluation of the dual digestion system:
Part 2: Operation and performance of the pure oxygen aerobic reactor

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Abstract

In a comprehensive study of the performance of a full-scale (45 m³) pure oxygen autothermal thermophilic aerobic reactor of a sewage sludge dual digestion system, it was found that: Biological heat generation rate was directly proportional to the biological oxygen consumption rate at 13,1 MJ/kgO; respiration quotient (mol CO_2 generated per mol O_2 consumed) was 0,66; vent gas was saturated with water vapour even at the high vent gas flow rates; COD and/or VS removal rates were poor parameters for quantifying the biological heat generation rate and controlling the reactor temperature. Increases in reactor temperature could be completely and virtually instantaneously controlled by means of the oxygen supply rate (OSR) for as long as the reactor was oxygen limited. The rapidity of response and close correlation between the oxygen transfer rate (OTR) and the biological heat generation rate make the OTR and the OSR pivotal parameters in the operation, control, design and simulation of oxygen limited autothermal thermophilic aerobic reactors in dual digestion.

Nomenclature and abbreviations

ATAD = autothermal thermophilic aerobic digestion.

C_p = specific heat at constant pressure [MJ/(t·°C)]. Additional subscripts s and g refer to sludge liquid and vent gas respectively.

COD = chemical oxygen demand.

f_{mech} = mechanical heat generated per power utilised ratio of recirculation pump.

H = general term for heat flow (MJ/h). Last subscripts i and e denote heat sources (influent) and sinks (effluent). First subscripts b, m, v and w refer to biological, mechanical, vent gas and wall respectively.

OCR = oxygen consumption rate.

O_c = mass OCR by the sludge mass (kgO/h).

OCR_{sys} = volume specific OCR by the sludge [kgO/(m³·h)] (equals O_c/V_p).

OCR_{bio} = volume specific OCR capability of the sludge [kgO/(m³·h)].

O_s = mass OSR by the oxygenation system (kgO/h).

OSR = volume specific oxygen supply rate by the oxygenation system [kgO/(m³·h)] (equals O_s/V_p).

OTR = volume specific oxygen transfer rate to the liquid phase by the oxygenation system [kgO/(m³·h)].

OTE = oxygen transfer efficiency of the oxygenation system (equal to O_c/O_s or OTR/OSR).

Note: Under oxygen limiting conditions OTR < OCR_{bio} and the sludge OCR_{sys} is limited by oxygenation system OTR i.e. OCR_{sys} = OTR. Under oxygen sufficiency conditions OTR > OCR_{bio} and the sludge OCR_{sys} is limited by OCR_{bio} i.e. OCR_{sys} = OCR_{bio}. The number of terms pertaining to oxygen supply and consumption may seem excessive, but this is necessary to distinguish between the oxygen transfer characteristics of the oxygenation system from the oxygen consumption by the sludge.

R_H = hydraulic retention time (d).

U_{oa} = overall wall and pipework heat transfer coefficient [MJ/(m²·h·°C)] .

V = general term for volume (m³). Subscripts p and b denote reactor operating and batch volumes respectively.

T = general term for temperature (°C). Subscripts s and g refer to sludge liquid and vent gas respectively. Subscripts i and e denote heat sources (influent) and sinks (effluent) respectively. Subscript amb refers to ambient atmospheric air temperature.

TS,VS = Total and volatile solids concentrations (g/ℓ) respectively where sludge samples are dried without prior dewatering.

Y_{CO_2} = respiration quotient on a molar basis - mol CO_2 produced per mol O_2 consumed.

Y_H = biological specific heat yield (MJ/kgO consumed).

ρ_s = density of sludge mixed liquor (t/m³).

Introduction

In **Part 1** of this series of 4 papers, the justification and objectives of the Milnerton dual digestion project were set out, together with a general overview of the results (Messenger et al., 1993). In this paper, attention is focused on the operation, performance and control of the Milnerton pure oxygen aerobic reactor. In the subsequent 2 papers, the design and simulation of pure oxygen or air oxygenated aerobic reactors are considered (Messenger and Ekama 1993a; b).

Heat and oxygen mass balances around the aerobic reactor

In order to meet the objectives of the aerobic reactor investigation, accurate simultaneous heat and oxygen mass balances were required to be made across the aerobic reactor. Two types of heat balance can be made, a steady state and an

TEMPERATURE PROFILES OF A BATCH CYCLE WITH IDEAL AND NON-IDEAL MIXING

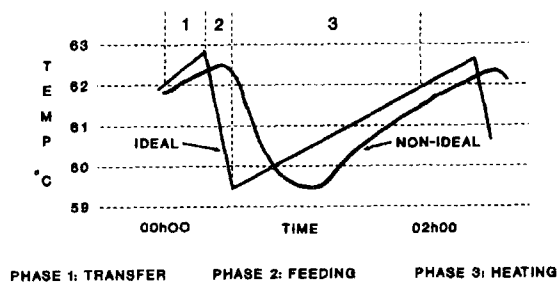PHASE 1: TRANSFER   PHASE 2: FEEDING   PHASE 3: HEATING

Figure 1

Profiles of reactor sludge temperature (T_{se}) versus time, illustrating ideal and non-ideal mixing via the responses of 2 temperature probes. With ideal mixing the response of the probe to change in sludge temperature is rapid and the points of change defining the different phases are clearly defined. With non-ideal mixing the probe response lags behind the changes in sludge temperature with poorly defined points of change

unsteady state. The steady state heat balance applies to a reactor which is fed continuously and under these conditions the sums of the input heat sources and output heat sinks are equal, leading to a constant reactor sludge temperature. However, in practice, aerobic reactors in dual digestion are batch-fed on a draw-and-fill basis to avoid short circuiting and contamination of the pasteurised effluent sludge by the feed sludge. This causes a continuous imbalance between the input heat sources and output heat sinks resulting in a fluctuating reactor sludge temperature profile in the shape of a sawtooth with 3 phases viz. a transfer (4 min), a feeding (3 min) and a heating phase (2 to 6 h) (Fig. 1). Because of the imbalance between the heat sources and heat sinks, only an unsteady heat balance can be made over the reactor.

The heating phase is the most convenient for applying the unsteady state heat balance because the sludge liquid volume is constant due to an absence of transfer and feeding, and a negligible water loss due to water vaporisation. The use of pure oxygen resulted in very low vent gas volumetric flow rates and hence, even at water vapour saturation, very low water loss rates by vaporisation were observed - the highest was 3,35 kg/h (see **Degree of water vapour saturation** below) which out of a flow of 36 m³/d, constitutes a water loss of only 0,01%. From a measurement point of view, the constancy of sludge volume results in 2 advantages, viz. the heat gained by the sludge is directly proportional to the sludge temperature increase; and the vent gas volumetric flow rate and composition are not disturbed by changing sludge volumes.

During the heating phase, the unsteady state heat balance is given by:

$$H_{net} = \Sigma \text{ input heat sources} - \Sigma \text{ output heat sinks (MJ/h)}$$
$$= H_{bi} + H_{mi} - H_{ve} - H_{we} \tag{1a}$$

where:

$$H_{net} = \text{rate of change in sludge enthalpy (MJ/h)}$$
$$= V_p \, \rho_s \, C_{ps} \, dT_{se}/dt \text{ (MJ/h)} \tag{1b}$$

With pure oxygen oxygenation, the heat loss resulting from the difference between the influent and vent gas sensible heats can be ignored because it is negligible (i.e. < 0,1% of the heat sources H_{bi} and H_{mi}) which is the reason these 2 terms have been omitted from Eq. (1); for air oxygenation this would not be the case and these 2 terms would need to be included in the heat balance. Also for sewage sludge, the density ρ_s and specific heat C_{ps} can be accepted as equal to that of water [i.e. 1,00 t/m³ and 4,18 MJ/(t·°C) respectively (Messenger et al., 1992)] .

Setting Eqs. (1a) and (b) equal, yields the unsteady state heat balance for constant reactor volume. All of the terms in the heat balance can be measured except H_{bi}, the biological heat balance can be measured except H_{bi}, the biological heat generation rate. Hence, by measuring H_{mi}, H_{ve}, H_{we} and dT_{se}/dt, during the heating phase, H_{bi} can be determined.

The mass OCR by the sludge (O_c) was obtained from the oxygen mass balance measured over the same heating period during which the unsteady heat balance was conducted; O_c is given by the difference between the mass OSR (O_s) and the oxygen mass flow rate in the vent gas. Knowing H_{bi} and O_c, the specific heat yield Y_H is found from $Y_H = H_{bi}/O_c$ (MJ/kgO).

Operation and monitoring of the aerobic reactor that enabled determination of the various parameters in the heat and oxygen mass balances are outlined below.

Aerobic reactor operation and monitoring

Aerobic reactor layout, operation and monitoring

For batch operation of the aerobic reactor, which was lagged with 50 mm polyurethane foam for insulation, a centrifugal pump first transferred a fixed batch volume (3,75 m³) from the aerobic reactor to the anaerobic digester and then a macerator feed pump refilled the reactor to its operating volume of 45 m³ with thickened (to ≈ 3,5%) feed sludge which was a mixture of primary and humus sludge drawn from the base of the sludge thickener. The time interval between feeding was varied between 2 and 6 h to achieve different retention times between 1 and 3 d. A specially designed sludge level control system controlled the sludge transfer and feeding operations. This system also provided an accurate means for sludge flow measurement obviating the need for (invariably temperamental) sludge flow meters.

The reactor was oxygenated with pure oxygen by means of a Vitox™ system installed on a continuously operating pumped sludge recirculation loop. The pump was a torque flow centrifugal one producing a flow of about 150 m³/h giving a reactor sludge turnover time of about 20 min. It had a relatively high power consumption (~ 20 kW), but this was not wasted because about 90% of the power consumed contributed directly to heating the sludge (H_{mi}) (see below).

Good mixing in the reactor was achieved by trial and error positioning of the recirculation flow discharge nozzle. Initially, even at the very high power density of 450 W/m³ (20 kW in 45 m³) mixing was poor which was reflected in disparate temperature traces from 3 reactor temperature probes (Fig. 1). Good mixing, as reflected by identical temperature traces, was achieved once the right discharge nozzle and position was found.

The O_s was controlled and measured on accurately calibrated rotameters fitted with needle valves. Vent gas flow was measured with a calibrated Parkinson-Cowan positive displacement town gas meter, which, to give accurate readings, required the vent gas to be dehumidified. The total vent gas flow was collected, cooled to 20° C in a double jacket water cooled condenser fitted with

water traps to condense the water vapour, reheated about 10°C to ensure dryness, and passed through the gas meter. The temperature, pressure and percentage oxygen (by volume) of the vent gas was measured at the gas meter, the last by means of the Orsat apparatus. Ideal gas laws were applied to calculate the vent gas oxygen and carbon dioxide molar or mass flow rates, accepting that the dry vent gas contained only oxygen and carbon dioxide; this was checked periodically with some of the Orsat tests - no gas remained after carbon dioxide and oxygen absorption. From the vent gas oxygen and carbon dioxide mass flow rates and O_s, not only could O_c be determined but also, the respiration quotient Y_{CO_2} (i.e. moles CO_2 produced per mole O_2 consumed) and OTE of the oxygenation system (OTE = O_c/O_s).

Temperatures were measured and recorded by 10 PT100 resistance thermometers coupled to a Honeywell strip chart recorder. On the aerobic stage, temperatures were measured at 7 points i.e. 3 in the reactor, and one each in the feed sludge, transfer sludge, recirculation sludge and the vent gas at the point of exit from the reactor head space (see Messenger et al., 1993, Fig. 1). The last mentioned was positioned so that any condensate formed upstream drained back into the reactor and any formed downstream accumulated in the water traps. This facility enabled not only the vent gas water vapour heat loss rate (H_{ve}) to be determined but also the degree of water vapour saturation of the vent gas at the point of exit from the reactor.

The operation and monitoring described above provided all the information for the heat and oxygen mass balances except 2 terms i.e. the mechanical heat input rate (H_{mi}) and the wall and pipework heat loss rate (H_{we}). These two terms were measured twice each. For H_{mi}, accepting the power factor for the pump motor to be 0,80, the mechanical heat generated per power consumed (f_{mech}) was measured to be 0,92 on both occasions and therefore a f_{mech} value of 0,92 was used in all the heat balance calculations. Of the heat sources H_{mi} contributed between 20 and 45% depending on the retention time (20% at 1,25 d and 45% at 3,0 d); the balance was generated biologically. When H_{we} was measured, once in summer and once in winter, it was found to be 9,4 and 24,8 MJ/h respectively. From this the wall and pipework overall heat transfer coefficient (U_{oa}) was estimated to be 0,0073 MJ/(m²·h·°C) which was used for all the heat balance calculations. Of the total losses H_{we} was less than 8%.

The data collected during a typical heat and oxygen mass balance test, conveniently called a specific heat yield test, are listed in Table 1. Details of the calculations with this data are given by Messenger et al. (1992).

Chemical testing

Sampling: The nature of sewage sludge, especially with primary sludge, makes sampling vulnerable to many sources of variability. Composite samples were collected to minimise variability as much as possible. During the 4 min sludge transfer phase, regular short bursts of sludge were collected from a tap in the transfer line into a 25 ℓ bucket. A 1,5 ℓ sample from the bucket was collected in a second bucket. In this way 1,5 ℓ samples from each batch interval were composited from 08:00 to 24:00, the period when shift operators were on duty. Daily, after thorough mixing, a 1,5 ℓ sample was taken from the composite sample bucket for laboratory analysis. The composite feed sample was collected in the same way.

Laboratory analysis: Samples of feed and transfer (reactor)

sludge were analysed for *inter alia* COD, TS, VS, conductivity and pH. The COD method was checked against standards. Some of the COD, TS and VS results were cross-checked by testing the same samples in the laboratory of the DWT of the CSIR.

Experimental results and discussion

Specific heat yield Y_H

Altogether over a period of 8 months, 116 specific heat yield tests were done, covering a range of O_s from 5,9 to 24,3 kgO/h, retention times R_H from 1,2 to 3,0 d, reactor sludge temperature T_{se} from 54 to 69°C and ambient temperature 8 to 30°C. The number of tests conducted at each T_{se}, O_s and R_H are given in Table 2.

The 116 biological heat generation rates H_{bi} are plotted versus O_c in Fig. 2. The 116 data clearly show a linear relationship between H_{bi} and O_c (correlation coefficient $R^2 = 0,98$), and the slope of the line gives a Y_H value of 12,8 MJ/h. For the 116 data Y_H ranged from 11,4 to 14,6 MJ/kgO, with a median value of 13,1 MJ/kgO. However, the small intercept on the H_{bi} axis indicates that the Hbi is closely but not exactly, proportional to O_c (see **Dependence of Y_H on reactor operating conditions** below).

Comparison between Milnerton Y_H with values reported in the literature

The literature contains a number of determinations of the specific heat yield Y_H in terms of MJ/kgO consumed. The field of human physiology provides some of the earliest determinations (Atwater and Benedict, 1903; Benedict and Milner, 1907; Gephart and Du Bois, 1915), typically ranging from 13,8 to 16,1 MJ/kgO; Consolazio et al. (1963) recommend a value of 14,0 MJ/kgO. From thermodynamic data reported by McCarty (1972) an average heat of oxidation of 14,4 MJ/kgO can be deduced for a wide range of organics. Kambhu (1971) determined the mean ratio of the heats of combustion and CODs of thermophilic organisms grown on glucose to be 5 860 BTU/lb (13,6 MJ/kg COD) while Wright (1975) and Kite (1985) observed that this ratio for organic materials ranged from 12,6 to 16,7 MJ/kg COD. The Milnerton average value of 13,1 MJ/kgO compares favourably with the 4 sets of data cited. The fact that heat of combustion values tend to be higher than the Milnerton values is expected because the Y_H value measured in a biomass cannot be higher (provided no exothermic reactions occur without the transfer of electrons) than the heat of combustion, because a portion of the energy is retained in biomass synthesised.

Less favourable agreement is found with Y_H values measured experimentally by microbiologists or deduced from ATAD research data. Values for yeast reported by Cooney et al. (1968) range from 11,4 to 18,6, although the average of 14,4 MJ/kgO is close to the Milnerton value. Values for *E. coli* reported by Rothbaum and Stone (1961) range from 16,3 to 26,7 MJ/kgO. From work published on ATAD by Trim (1984) and Wolinski (1985) both low and high values can be deduced; from Trim's data Y_H ranges from 5,3 to 11,7 MJ/kgO and Wolinski's data yield a value of 21 MJ/kgO. However, in a comment on Wolinski's value, Kite (1985) suggests that 13,4 MJ/kgO is a more realistic value.

TABLE 1
SAMPLE SPECIFIC HEAT YIELD TEST DATA

Date: 12 September 1988			Weather: Sunny and clear		
Ambient 13,5°C			**Feed temp** 18,3°C	**Amps** 45	**Oxygen** 18,5 kg/h

Time	Reactor sludge T_{se} Temp 1	Temp 2	Vent temp T_{ge}	Gas meter temp	Gas meter reading
9:20	53,8	54,2	51,6	25,5	3618,5
30	54,0	54,4	51,8	26,0	3620,2
40	54,3	54,6	52,0	26,5	3621,8
50	54,5	54,8	52,2	26,5	3623,4
10:00	54,8	55,0	52,4	27,0	3625,0
10	55,0	55,3	52,6	27,0	3626,7
20	55,2	55,5	52,8	27,0	3628,5
30	55,3	55,8	53,1	27,0	3630,2
40	55,6	56,0	53,3	27,5	3631,9
50	55,9	56,2	53,5	27,5	3633,7
11:00	56,0	56,4	53,7	27,0	3636,4
10	56,3	56,6	53,9	28,0	3637,3
20	56,5	56,8	54,2	27,5	
30	56,7	57,1	54,4		
ΔT_{se}	2,9	2,9	**Data summary**		

Gas meter @ 11:15 3638,0
Gas meter @ 9:15 <u>3617,6</u>
   (m³)   20,4

Condensate collected from
9:20 to 11:20 = 1,74 ℓ

Orsat analysis
   @ 11:10 : 23% O_2
   @ 11:18 : 23% O_2

V_{gm}	:	10,2 m³/h
T_{gm}	:	27°C
fo_2	:	0,23
O_s	:	18,5 kgO/h
M_{wc}	:	0,87 kg/h
T_{ge} (avg)	:	53°C
$\Delta T_{se}/\Delta t$	:	1,338 °C/h
I	:	45 amps
T_{amb}	:	13,5 °C

TABLE 2
RANGES OF AEROBIC REACTOR OPERATING CONDITIONS

T_{se} (°C)	54	55	56	57	58	59	60	61
Tests	4	2	9	6	7	17	9	13
T_{se} (°C)	62	63	64	65	66	67	68	69
Tests	12	9	7	6	1	5	5	4

O_s (kg/h)	5,9-8,1		14,5		16,0-16,5		18,5	
Tests	13		7		29		15	

O_s (kg/h)	19,4		22		24,3			
Tests	13		28		11			

R_h (days)	1,2		1,25		1,5		3	
Tests	25		47		31		13	

Dependence of Y_H on reactor operating condition

Because of the slight deviation from proportionality between H_{bi} and O_c (Fig. 2), the Y_H data were examined to check whether or not they showed a dependence on reactor operating conditions such as temperature T_{se}, O_c or retention time R_H. Statistically, there was no significant dependence of Y_H on T_{se}. However, a significant dependence of Y_H on O_c was evident. This dependence is shown in Fig. 3. Clearly Y_H shows a decrease as O_c increases. Decreasing values of O_c arose from the need to reduce O_s as R_H increased and made the system more oxygen limited. The dependence of Y_H on O_c therefore is indirect - it is rather a dependence on oxygen limitation; the greater the oxygen limitation, the higher the Y_H. In terms of bioenergetics, an increase in Y_H results from a decrease in the efficiency of energy capture into biomass (synthesis) which arises from an increase in organism maintenance energy requirements. It seems reasonable that increasing oxygen limitation increases the organism maintenance energy requirements which in turn increases the heat yield. Interestingly, if the best straight line through the average Y_H data in Fig. 3 is extended to zero O_c, which is equivalent to a hypothetical heat of combustion value, 14,4

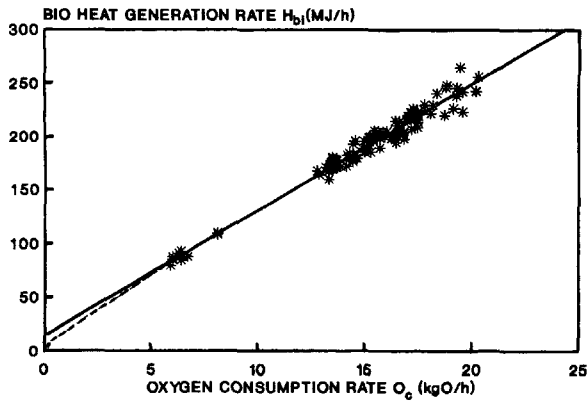## BIOLOGICAL HEAT GENERATION RATE VERSUS OXYGEN CONSUMPTION RATE

Figure 2

Plot of the biological heat generation rate (H_{bi}) versus O_c from the values measured during the 116 specific heat yield tests. The linear relationhsip between H_{bi} and O_c is shown with the slope of the line being the specific heat yield Y_H (MJ/kgO). The slight increase in Y_H which was observed with increased oxygen limitation is accounted for by the broken line passing through the origin

MJ/kgO is obtained, a value equal to McCarty's (1972) calculated heat of combustion value.

Oxygen transfer efficiency (OTE = O_c/O_s)

Examination of the data shows that OTE decreased as O_s increased. This is illustrated in Fig. 4 where the average values of O_c and OTE are plotted against O_s for the 7 different O_s settings, ranging from 6 to 24,3 kgO/h, at which the aerobic reactor was operated during the investigation. The inverse proportionality between OTE and O_s results from the Vitox oxygenation system transferring oxygen less efficiently as O_s increases, a feature in common with most oxygenation systems whether pure oxygen or air.

Respiration quotient (Y_{CO_2}), mol CO_2 produced/mol O_2 consumed

For the 116 specific heat yield tests, Y_{CO_2} varied from 0,53 to 0,85. Examining the data it was found that 6 were outliers, 2 at the top end and 4 at the bottom end, without which the range narrowed from 0,59 to 0,76. The 2 high values were rejected on the basis of the test for outliers by the procedure of Laubscher (ca.1970) and the 4 low values were rejected on the grounds that they occurred at step changes in O_s (see **Evaluation of oxygen limitation** below). The average Y_{CO_2} for the remaining 110 data is 0,66 ± 0,03. The low value of Y_{CO_2} could not be attributed to CO_2 dissolution into the sludge mixed liquor, taking due account of the increase in $H_2CO_3^*$ alkalinity and the high partial pressure of CO_2 in the reactor.

In many earlier research investigations into ATAD, O_c was estimated assuming 1,0 for Y_{CO_2} which is expected from stoichiometry of VS (e.g. $C_5H_7O_2N$) oxidation. This obviates having to measure the total vent gas volumetric flow rate because if Y_{CO_2} = 1,0 the dry influent and vent gas molar flow rates are equal and only the oxygen fraction in dry vent gas needs to be

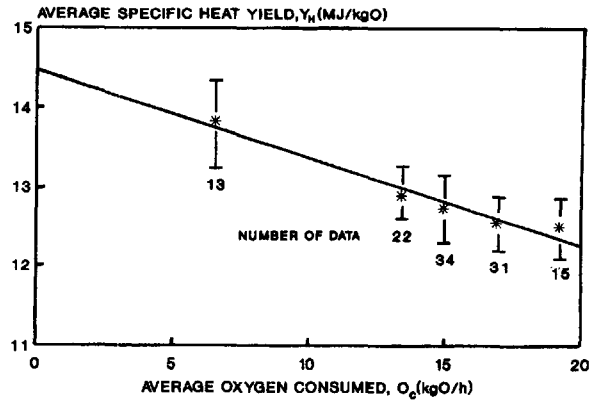## AVERAGE SPECIFIC HEAT YIELD VERSUS AVERAGE OXYGEN CONSUMPTION

Figure 3

Average and standard deviation specific heat yields, Y_H, calculated for 5 ranges of O_c, plotted against the average OCR for each range. The plot clearly illustrates an inverse proportionality between Y_H and O_c

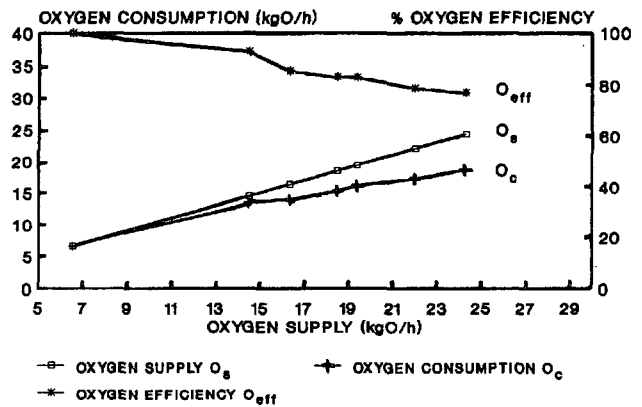### AVERAGE OXYGEN SUPPLY, CONSUMPTION AND UTILIZATION EFFICIENCY

Figure 4

The average oxygen consumption rate, O_c, and average OTE, calculated for the 7 ranges of oxygen supply, O_s, which were employed during the 116 specific heat yield tests

measured. In hindsight the accuracy of the specific heat yield values measured at Milnerton stemmed from the decision to not accept 1,0 for Y_{CO_2} but to measure the total vent gas volumetric flow rate; had 1,0 been accepted for Y_{CO_2} for the Milnerton pure oxygen reactor, the vent gas volumetric flow would have been overestimated, causing the O_c to be underestimated and the Y_H overestimated by more than 20%.

Degree of water vapour saturation

The vent gas temperature (T_{ge}) was found to increase linearly with the sludge temperature (T_{se}) during the heating phase but was 2 to 5°C below the sludge temperature depending on the vent gas volumetric flow rate. Taking the average vent gas temperature T_{ge} during a specific heat yield test and assuming that the vent gas was saturated with water vapour in a pure
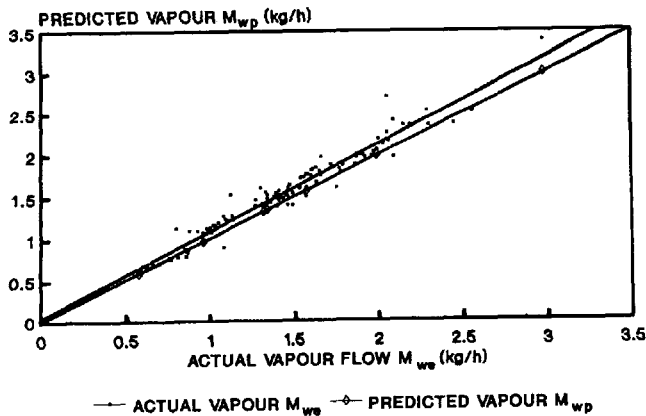
PREDICTED vs ACTUAL WATER VAPOUR FLOW RATES

Figure 5

Plot of predicted (M_{wp}) versus actual (M_{we}) mass flow rates of water vapour in the aerobic reactor vent gas measured during the 116 specific heat yield tests. On average the measured values are about 6% less than the predicted values due to the salinity of the sludge mixed liquor
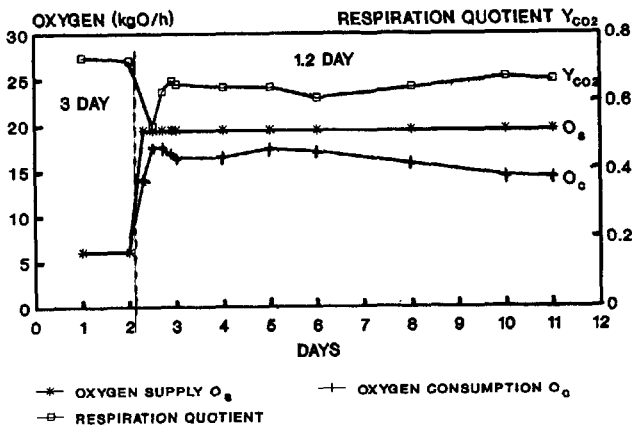
OXYGEN SUPPLY STEP CHANGE 2

Figure 6

The change, with time, in O_c, and the respiration quotient, Y_{CO_2}, in the aerobic reactor following a step increase in O_s, from 6,0 to 19,4 kgO/h with a simultaneous decrease in hydraulic retention time, R_H, from 3,0 to 1,2 d

water/gas equilibrium system at $T_{ge}°C$, the water vapour mass flow rate in the measured vent gas volumetric flow rate was predicted with the aid of the Antoine equation and ideal gas laws. The measured water vapour mass flow rate was obtained from the sum of the water vapour condensate accumulation rate in the water traps in cooling the vent gas to 20°C; and the water vapour remaining in the vent gas at saturation at 20°C. In Fig. 5, the predicted and measured water vapour mass flow rates are plotted against each other for the 116 specific heat yield tests and show very close correlation. The slightly lower measured values (6%) probably result from the presence of dissolved salts in the sludge mixed liquor which would suppress the water vapour pressure in the reactor relative to pure water in accordance with Raoult's

law. From this it was concluded that the vent gas was saturated with vapour at all vent gas volumetric flow rates.

Evaluation of oxygen limitation

In general, O_s was not selected on the basis of a planned experimental programme. It was selected simply to ensure that the reactor sludge temperature remained between 60 and 65°C to comply with pasteurisation specifications. However, 3 checks were performed in which O_s was deliberately increased in order to examine the oxygen limitation in the reactor sludge and the rapidity of response of O_c to an increase in O_s.

In each of the checks the reactor had been operating under steady state conditions for at least 8 d before the step increase in O_s and O_s, O_c and Y_{CO_2} was measured over a number of days before and after the step increase. The earliest a reliable O_c measurement could be made after the step increase was 2 h to allow purging of the reactor headspace gas which had been contaminated with air during the draw-and-fill operation. Nevertheless in each check it could be accepted that O_c was constant during these 2 h because the rate of sludge temperature increase (dT_{se}/dt) was linear. The 3 checks involved the following step increases in O_s:

(1) from 14,5 to 24,3 kgO/h (69%) at constant 1,25 d R_H;
(2) from 6,0 kgO/h at R_H = 3 d to 19,4 kgO/h (223%) at R_H = 1,2 d (see Fig. 6);
(3) from 16,5 to 22,0 kgO/h (33%) at constant R_H = 1,25 d.

For checks (1) and (3), the first specific heat yield test after the step increase in O_s, showed that O_c and dT_{se}/dt had both increased immediately (< 2 h). In check (2) (Fig. 6), where the step increase in O_s was the largest and was accompanied by a decrease in R_H from 3 to 1,2 d, the response of O_c was slightly slower than it had been in the other 2 checks. Following the step increase the reactor sludge foamed slightly for about 2 h, which prevented vent gas monitoring with the result that O_c could not be measured. However, an O_c of 14 kgO/h was deduced from the measured dT_{se}/dt. After 2 h the foaming ceased and in 2nd heating phase, after the step increase (4 h), an O_c of 17,4 kgO/h was measured, a value that remained stable over the next few days. The response of O_c in this check was slower than in checks 1 and 3 because of the need for growth of new active biomass in response to the sudden large increased availability of oxygen (223%) and the increase in sludge loading following the reduction in retention time. The sludge foaming was probably a consequence of the inability of the sludge to consume all of the available oxygen until sufficient biomass had developed. A further indication that an acclimatisation period seemed to be required, is that during this second check, unlike checks 1 and 3, the respiration quotient decreased to 0,53 4 h after the step increase (Fig. 6). Other than on this occasion, the reactor sludge only foamed during start-up with fresh sludge, ceasing once a fully developed biological culture had been established.

From the 3 tests it was concluded that:

• The OCR capability of the sludge was around 17 kgO/h, which yields an OCR_{bio} of 0,38 kgO/(m³.h) at 1,25 d R_H.
• Under oxygen limiting conditions (i.e. OTR < OCR_{bio}) O_s is a very convenient and virtually instantaneous control parameter for the reactor sludge temperature, T_{se}.

VS and COD reduction

During the investigation, 180 influent and effluent sludge sample pairs were tested for TS and VS, and 75 pairs for COD. For the TS and VS each sample was tested in duplicate and for the COD in triplicate, and the sample result was taken as the average. The results are summarised in Table 3. Also 31 sample pairs were tested for TS, VS and COD by the DWT laboratory, 12 of which were on the same samples.

VS removal: Comparing influent and effluent VS concentrations in Table 3, on average very little VS was removed in the reactor, only about 1,3%: Indeed on 80 sample pairs, the effluent VS was higher than the influent; a statistical t-test indicated that there was no significant difference between their means at the 95% confidence interval.

The low VS removal appears inconsistent with vent gas volume and composition measurements. At a retention time of 1,25 d (at which most of the VS and COD tests were done), the C removal through VS removal was 7,5 kgC/d [based on 14 kgVS ($C_5H_7O_2N$) removed/d], but the vent gas carbon mass flow was about 100 kgC/d. Because the carbon in the vent gas originated from the sludge VS, either there is something wrong with the VS tests or the biological action in the reactor is not simply VS oxidation. The reliability of the VS tests was confirmed by observing that:

- Individual results of duplicate tests performed on each sample differed by less than 1%
- The 31 DWT VS data compared favourably
- There was no statistical difference between the means of the 12 parallel Milnerton and DWT VS data sets
- A special sludge sample compositing procedure was used to minimise sample variation.

It was concluded that the biological reactions in the aerobic reactor cannot be described in the same manner as those in thermophilic aerobic digestion wherein endogenous respiration is presumed to be the principal heat generating reaction via VS degradation.

COD removal: The COD data appear more consistent than the VS data in that only 8 data out of the 75 showed higher effluent than influent concentrations. From Table 3 on average 6,3 g/ℓ COD was removed which is 12% of the influent concentration. A t-test indicated that the influent and effluent COD concentrations were significantly different at the 95% confidence interval. The coefficient of variation (standard deviation divided by mean) for the COD data was no better than that for the VS data. Results from the 31 DWT tests give an average COD removal of 14%, which compares very well with the 12% measured in the Milnerton laboratory. The difference between the means of the DWT and Milnerton influent and effluent CODs of the 12 parallel samples is less than 1,7% and yields no significant difference at the 95% confidence interval.

Influent and effluent COD/VS ratio: Because the reactor produced on average a larger COD reduction (12%) than VS reduction (1,3%), the COD/VS ratio of the influent and effluent sludges was different, viz. 1,721 and 1,548 kgCOD/kgVS respectively. A statistical t-test confirmed a significant difference at the 95% confidence interval. Therefore, apart from the observations that the VS or COD removal is very small and

TABLE 3 AVERAGE INFLUENT AND EFFLUENT TS, VS AND COD VALUES MEASURED ON THE AEROBIC REACTOR				
Average values	**TS** *g/ℓ*	**VS** *g/ℓ*	**COD** *g/ℓ*	**COD/VS**
Influent Std dev*	37,54 4,35	30,28 3,04	52,99 5,95	1,721 0,097
Effluent Std dev* Data PTS	37,31 3,84 180	29,89 2,59 180	46,69 5,56 75	1,548 0,098 75

*Standard deviation of the data

highly variable on daily composite sample pairs, to estimate the biological heat generation and oxygen consumption on the basis of VS removal kinetics (as is commonly done in thermophilic aerobic digestion models) by presuming a constant COD/VS ratio is inappropriate and unreliable.

Mass oxygen consumed and biological heat generation per kg COD removed: From 65 paired data the ratio kgO consumed/kgCOD removed was calculated. The ratio ranged from -24,9 to 29,6 kgO/kgCOD with an average of 2,34 kgO/kgCOD and a standard deviation of 5,88 kgO/kgCOD. From a COD (or electron) balance this ratio should be 1,0. The imbalance between the electron acceptors (oxygen) and donors (COD) could be due to electron donors in the sludge which are not oxidised in the COD test, interference in the COD test by chlorides or nitrification. However, after examination, none of these 3 reasons appeared probable. The poor COD balance was a perplexing problem and was the reason for fastidious compositing of samples, triplicate testing and interlaboratory cross-checks to check the apparently spurious COD data. No explanation for the poor COD balance can be advanced.

On daily paired values, the biological heat generation per kgCOD removed varied from -324 to 385 MJ/kgCOD removed with an average and standard deviation of 30,4 ± 76,3 MJ/kgCOD. Because the measurement of oxygen consumption and heat generation was precise and accurate, the wide variation in the MJ/kgCOD removed (and kgO/kgCOD removed) results from the wide variation in the daily value for the COD removal. The COD removal is a small difference between 2 large numbers both of which vary significantly. The practicality of precisely determining the COD removal makes it an inferior parameter. With the oxygen consumption rate showing itself such a useful and accurate parameter to quantify and control biological heat generation, it was concluded that COD and VS measurements, while useful to quantify the mass of sludge undergoing treatment, are not useful for quantifying biological heat generation in the aerobic reactor of dual digestion.

Conclusions from aerobic reactor investigation

In the investigation into the performance of the pure oxygen aerobic reactor of the Milnerton dual digestion system, heat balances and oxygen and sludge VS and COD mass balances

were carefully made over the reactor by monitoring the inflow and outflow sludge liquid and gas temperatures and mass flow rates over a period of 8 months. From the results it was found that (see Messenger et al., 1992 for details):

- Biological heat generation rate (H_{bi}, MJ/h) was directly proportional to the sludge OCR (O_c, kgO/h). The constant of proportionality between H_{bi} and O_c is the specific heat yield (Y_H) and was measured to be 13,1 MJ/kgO. This value conforms closely to thermodynamically and bioenergetically calculated values.
- Respiration quotient (Y_{CO_2}) i.e. mol CO_2 generated per mol O_2 consumed was measured to be 0,66 and not 1,0 as so often accepted from stoichiometry of VS degradation. In hindsight the accuracy of the Y_H data rested entirely on the decision to measure the vent gas volumetric flow rate and composition; had 1,0 been accepted for Y_{CO_2} a large error would have been made, not in the heat balance, but in the oxygen mass balance; O_c would have been underestimated by 20% and hence Y_H overestimated by 20%.
- Vent gas was saturated with water vapour at all vent gas flow rates.
- VS and COD removals were very low, i.e. 1,3 and 11,9% respectively, and the COD/VS ratio of the influent and effluent sludge changed from 1,721 to 1,548 kgCOD/kgVS. COD and/or VS removal rates were found to be very poor parameters for quantifying the biological heat generation rate and controlling the reactor temperature because the tests are prone to significant variability when dealing with sewage sludges and take too long to give a result. The variability was such that for 44% of VS and 11% of COD, the effluent values were greater than the influent.
- Reactor temperature increases (or decreases) could be completely, and virtually instantaneously, controlled by means of the increases (or decreases) in O_s for as long as the reactor was oxygen limited i.e. while the OTR of the oxygenation system was less than the OCR_{bio}. For the Milnerton sludge, which was a mixture of primary and humus (biofilter) sludge, OCR_{bio} was measured to be about 0,38 kgO/(m³·h) at an average concentration of 30 kgVS/m³ and retention time of 1,25 d. The temptation of converting the OCR_{bio} to a concentration specific rate should be resisted because it is not simply related to VS concentration; it is also related to thermophilic aerobic organism kinetics and reactor operating conditions.
- The close correlation, and rapidity of response between the biological heat generation rate (H_{bi}) and the OTR under oxygen limiting conditions, makes the OTR of the oxygenation system a pivotal parameter in design and simulation of autothermal thernophilic aerobic reactors in dual digestion.

The implications of the above results on design and simulation of oxygen and air oxygenated aerobic reactors is examined in depth in 2 sequel papers (see Messenger and Ekama 1993a; b).

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