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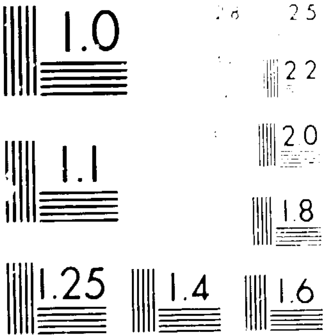
UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org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DESIGN AND OPERATION FOR LOW AMBIENT TEMPERATURE BIOGAS PRODUCTION *

by

A.C. Hollingdale **

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** UNIDO consultant.

1. INTRODUCTION

This paper represents a description of part of an application of a systems engineering approach to design and operation of an anaerobic digester for low **ambient temperature biogas production.**

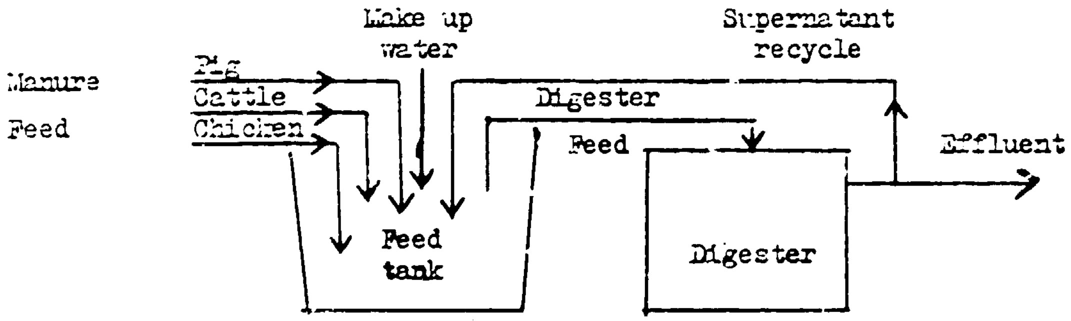
A systems engineering approach to a project requires the stages of analysis, design, implementation and operation (Ref. 1) system analysis relates to the process of problem formulation, project organization and to the setting of objectives and criteria for the work. The systems design which follows this stage is related to direct application of techniques such as forecasting, modelling, simulation and optimisation. A systems design procedure for a digester to produce biogas in **low ambient temperatures was** described in a paper by A.E. Chittenden of the Tropical Products Institute, United Kingdom (Ref. 2).

This paper extends this work on design for low **ambient temperature** biogas production and also examines the implementation and initial operation stages for such a system. The chemical engineering concepts required to optimise the design are outlined. Particular attention is given to the use of heat transfer models.

Much of this paper relates directly to a large experimental digester at the Office of Rural Development in Korea and run as part of the Korea-U.K. Methane Project. The knowledge acquired from winter operation of this digester is the practical basis for this work.

2. MASS & THERMAL BALANCES

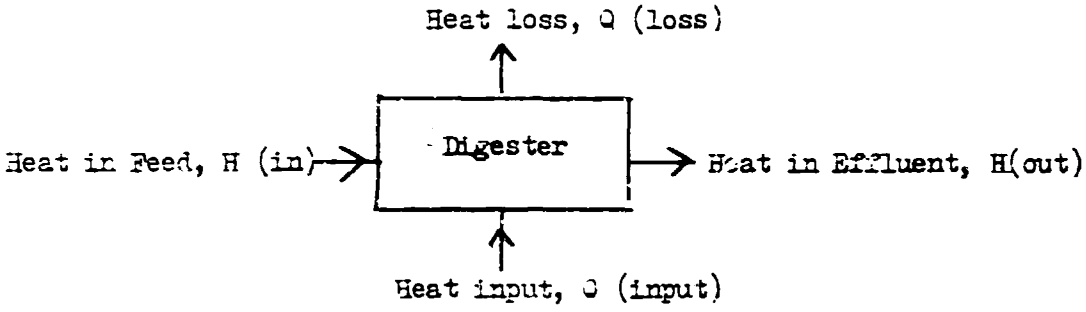
The design of digesters requires the application of certain flow sheeting procedures. For mass balances on an anaerobic digester a flow sheet would be as below:-



Continuation of 2.Mass & Thermal Balances

Normally results of digester operation are expressed in terms of the relationship between feed and effluent stream properties such as total solids %, volatile solids % etc. and these are derived from mass balances based upon this flow sheet.

For thermal balances such as will be discussed in this paper in relation to low temperature operation the flow sheet can be reduced to the following simple form.



In a steady state, the heat required to maintain the digester at its desired temperature, is given by the expression below

(Units Kcals/day)

$$Q(input)=(H(out)-H(in))+Q(Loss) \text{———————} (1)$$

To calculate Q(input) requires evaluation of the heat energy in the effluent and feed streams, H(out) and H(in). These quantities are calculated directly from the mass flow rates and temperatures. Also it is necessary to evaluate Q(loss), the heat losses from the digester. In low temperatures this may be a large quantity and much of this paper will describe the application of heat transfer concepts and the necessary analysis to evaluate this quantity.

3. PROCESSES OF HEAT TRANSFER

Heat transfer occurs by the three physical processes of conduction, convection and radiation. The process of conduction is commonly experienced when heat is conveyed through metals i.e. in the use of cooking vessels heat is transferred through the vessel by conduction. The actual heating of liquids in a vessel involves the process of convection. In the case of a liquid in an unstirred pan or a kettle this is a process of motion of the fluid particles arising from differences in densities of the parts of the fluid, known as free convection. If the liquid is stirred the process is described as forced convection. Heat transferred by the process of radiation is conveyed directly through space in the form of electromagnetic waves, i.e. heat from the sun or radiant heat from a cooking grill.

4. CONDUCTION & CONVECTION MODEL

For conduction and many cases of convection steady state heat transfer across a plane wall can be described simply by the equation:-

$$q = h \times A \times \Delta T \quad \ldots\ldots\ldots\ldots\ldots \; 2$$

q = heat flow across the wall, Kcals/hr

h = heat transfer coefficient Kcals/hr/metre^2/$^\circ$C

A = area of wall, metre **square**

ΔT = difference in temperature across the wall, $^\circ$C

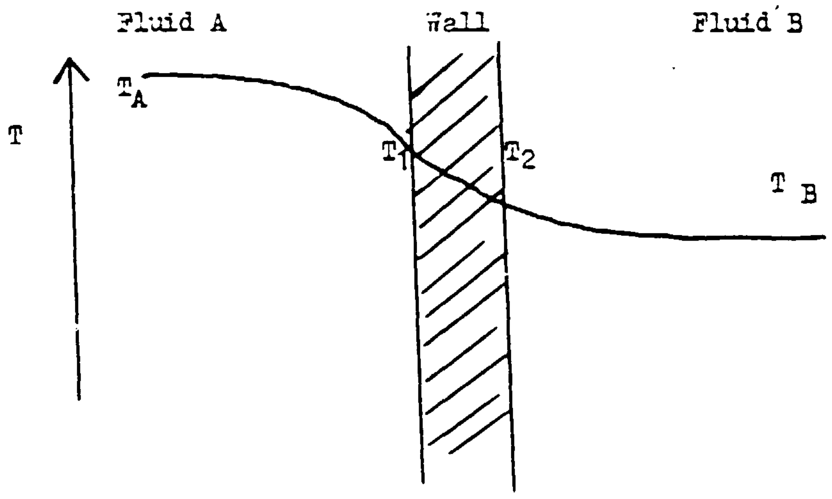
In the case of a wall of some solid homogeneous material all the heat transfer is by conduction and equation 2 takes the form.

$$q = \frac{k}{x} \cdot A. \, (T_1 - T_2) \quad \ldots\ldots\ldots\ldots \; 3$$

where k = thermal conductivity, Kcals/hr/metre/$^\circ$C
x = wall thickness, metres.

and T_1, T_2 are wall temperatures each side of the wall.

For most real situations the wall temperature is not actually measured but rather it is the bulk temperature of the liquid or gas in contact which is measured. It has been well established for low viscosity fluids that in such circumstances it is useful to consider the heat transfer across a thin film of the fluid close to and in contact to the solid. For this thin film, equation 2 can be used again where 'h' is now the film heat transfer coefficient and ΔT the temperature difference between the bulk of the fluid and the wall temperature. This can be shown as follows:-



Continuation of 4. Conduction & Convection Model.

For this system there are three equations for the heat flow from fluid A to fluid B. Equation 3 above describes the conduction across the wall. Equation 4 below describes the heat flow from the bulk of fluid A across the film to the wall as follows;-

$$q = h_A \times A \times (T_A - T_1) \quad .... \quad 4$$

where h_A = film heat transfer coefficient for fluid A to wall Kcals/hr/metre^2/^oC

and equation 5 below describes the heat flow across the film in fluid B from the wall to bulk of the fluid;-

$$q = h_B \times A \times (T_2 - T_B) \quad .... \quad 5$$

For steady state conditions these expressions for heat flow have the same value and they can be rearranged as follows;-

$$T_A - T_1 = \frac{q}{A} \cdot \frac{1}{h_A} \quad .... \quad 6$$

$$T_1 - T_2 = \frac{q}{A} \cdot \frac{x}{k} \quad .... \quad 7$$

$$T_2 - T_B = \frac{q}{A} \cdot \frac{1}{h_B} \quad .... \quad 8$$

By adding 5, 6 & 7 it is possible to eliminate the unknown (or unmeasurable) temperatures T_1 & T_2 in the new equation 9 below;-

$$T_A - T_B = \frac{q}{A} \cdot \left(\frac{1}{h_A} + \frac{x}{k} + \frac{1}{h_B}\right) \quad .... \quad 9$$

This equation can be rearranged as

$$q = U \times A \times (T_A - T_B) \quad .... \quad 10$$

where U = overall heat transfer coefficient from fluid A to fluid B, (Kcals/hr/metre^2/^oC) and described by the equation 11 below:-

$$\frac{1}{U} = \frac{1}{h_A} + \frac{x}{k} + \frac{1}{h_B} \quad .... \quad 11$$

These equations 10 & 11 are very useful since all the constants for U in equation 11 can be evaluated thereby enabling the heat flow to be calculated from a knowledge of the fluid bulk temperatures.

Continuation of 4. Conduction & Convection Model

If the wall is of a composite construction the same analysis can be applied to derive an equation as follows;-

$$\frac{1}{U} = \frac{1}{h_A} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \ldots\ldots \frac{x_n}{k_n} + \frac{1}{h_B} \ldots\ldots 12$$

where k_1, K_2, k_3 ..... k_n are thermal conductivities of the various layers of material in the wall, each of which have thickness x_1, x_2 ..... x_n. The above equations 10, 11 & 12 are the only equations which need to be considered in calculating conduction and convection heat losses from a digester. It is intended to demonstrate how with these equations and by making reasonable assumptions it is possible to do a complete thermal balance for a digester.

5. RADIATION MODEL

For heat transfer by radiation there are certain established physical laws which govern the heat transfer rates.

Theory of radiant heat transfer in it's application requires the use of the concept of a 'black body' which is an object which absorbs all the radiation incident to its surface. This concept is not realised in practice since all surfaces reflect to some extent. However, the variation from black body radiation can be allowed for to enable the theoretical laws to be used for modelling real systems. By the Stefan-Boltzmann law the radiation emitted by a black body, E_b, Kcals/metre^2/hr, is given by

$$E_b = \sigma\ T^4 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 13$$

The constant σ has a value of 4.88×10^{-8} Kcals/hr/metre^2/$^\circ K^4$. 'T' is the temperature of the surface of the body in °Kelvin(° C+273).

For so called "grey surfaces" the equation is modified as follows;

$$E_g = e \cdot \sigma \cdot T^4 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 14$$

'e' is a factor to allow for the reduction in radiant energy from a surface in relation to the black body radiation for a given temperature. It is known as the emissivity of the surface.

Values of 'e' for different surfaces can be applied in order to calculate radiant energy emitted from any surface. For example a surface with a value of 'e' = 0.5 at 15°C would radiate 170Kcals/hr/metre^2 according to equation 14.

Continuation of 5. Radiation Model.

An exposed object will gain radiant energy from the sun and other objects. Total daily solar radiation can be as high as 5,000Kcals/hr/metre^2. In some circumstances radiant energy transfer rates from surroundings can be quite significant but calculation of the interchange of energy between objects requires detailed consideration of the geometric configuration of the objects. In the examples considered in this paper the effect of radiation has been assumed small compared to convection and conduction. For this assumption to be valid special measures would be required which will be discussed later. It should be added, however, that there are **benefits** in closely examining the process of radiant heat transfer since it will be found that this offers potential for design improvements in digesters operating in low temperatures.

6. EXAMPLE OF HEAT LOSSES FROM DIGESTERS

Digesters may be of various designs, often underground. A general model can be posed, comprising of four components of heat loss identified Q_1, Q_2, Q_3 and Q_4 where

Q_1 = heat losses from sludge-wall-soil-air
Q_2 = " " " sludge-wall-air
Q_3 = " " " gas-wall-soil-air
& Q_4 = " " " gas-wall-air

For particular case where it is intended to calculate the heat loss then it is necessary to specify values A_1, A_2, A_3 & A_4 as related areas, and values of ΔT_1, ΔT_2, ΔT_3 & ΔT_4 for temperature differences. Finally it is necessary to evaluate values of U_1, U_2, U_3 & U_4 the overall heat transfer coefficients. This procedure will be illustrated below and equations 10 & 11 derived above will be used. The assumption in deriving these equation of heat transfer across a plane surface holds for square or rectangular digesters. For cylindrical digesters it is accurate for large radius, thin wall digesters.

6. (1) CALCULATION ASSUMPTIONS

The example to be considered relates to a large experimental digester operated by the **Office of Rural Development**, Suweon, Republic of Korea.

The digester is cylindrical, 6 metre is diameter and 6 metre deep with sludge contents to a depth of 5 metres. Walls are concrete and 0.25 metre thick. Operating temperature in 35°C.

Continuation of 6.-(1) Calculation Assumptions.

Temperature data for Suweon, is given in TABLE 1.

Season / Position	Winter Temperature	Summer Temperature
Air	-12	30
0.0-0.5 metre underground	-2	28.3
0.5-1.0 " "	1.1	23.8
1.0-1.5 " "	3.8	21.8
1.5-2.0 " "	5.7	20.2
2.0-3.0 " "	7.8	18.9
3.0-5.0 " "	11.2	18.2
5.0 " "	11.6	14.9

TABLE 1. - Temperature data for Suweon, Korea.

Film heat transfer coefficients are taken as;-

Slurry-concrete = 500 Kcals/metre^2/°C/hr
Soil-air = 5 " " " "
Concrete-air = 20 " " " "
Gas-concrete = 10 " " " "

Thermal conductivities are taken as;-

Concrete - 1.1 Kcals/metre/°C/hr
Soil - 1.2 " " " "
Insulation - 0.03 " " " "

Three cases will be considered for this digester

Case 1 - Digester above ground exposed to air inside a building.
Case 2 - Digester as in case 1 but insulated.
Case 3 - Digester 95% underground (as O.R.D. digester).

In each case total winter and summer heat losses will be calculated. Minimum winter and maximum summer temperatures are used. Radiation heat losses and solar heating are not included and are assumed small for the three cases described above.

6. (2) Case 1 - DIGESTER ABOVE GROUND IN BUILDING

(i) For heat transfer from sludge - wall-air by equation 11 and for A_2 = 122.5 metre^2,

$$\frac{1}{U_2} = \frac{1}{h_A} + \frac{x_2}{k_e} + \frac{1}{h_B}$$

where h_A = heat transfer coefficient for slurry-concrete=500
h_B = heat transfer coefficient for concrete-air = 20

and $\frac{1}{U_2} = \frac{1}{500} + \frac{.25}{1.1} + \frac{1}{20}$ and $\therefore$ $U_2 = 3.6$

Hence Q_2 (winter) = $U_2 \times A_2 \times \Delta T_2$
= 3.6 x 122.5 x (35-(-12))=20,700 Kcals/hr

and Q_2 (summer) = 3.6 x 122.5 x (35-30) = 2,200 Kcals/hr

(ii) For heat transfer from gas-wall-air by equation 11 and for A_4 = 47.1 metre^2,

$$\frac{1}{U_4} = \frac{1}{h_A} + \frac{x_1}{k_e} + \frac{1}{h_B}$$

where h_A = heat transfer coefficient gas-concrete = 10
h_B = " " " concrete-air = 20

Thus $U_4 = 2.6$

Hence, Q_4 (winter) = 2.6 x 47.1 x 47 = 5,760 Kcals/hr

and Q_4 (summer) = 610 Kcals/hr

For case 1, summing the elements (i) & (ii) gives the total heat loss a daily basis as;

Winter heat loss = 635,000 Kcals/day
Summer heat loss = 67,400 Kcals/day

6. (3) Case 2 - DIGESTER AS IN CASE 1 BUT INSULATED

(i) For heat transfer from sludge-wall-air, data is as in **Case** (i) above but if 75mm of insulation then using equation 13

$$\frac{1}{U_2} = \frac{1}{500} + \frac{.25}{1.1} + \frac{.075}{.03} + \frac{1}{20} \text{ and } \therefore U_2 = 0.36$$

Hence Q_2 (winter) = 2,200 Kcals/hr
and Q_2 (summer) = 221 Kcals/hr

Continuation of 6.-(3) Case 2 - Digester as in Case 1 but insulated.

(ii) For heat transfer from gas-wall-air data is as in Case 1 (ii) above but if 75mm of insulation then using equation 13.

$$\frac{1}{U_4} = \frac{1}{10} + \frac{.25}{1.1} + \frac{.075}{.03} + \frac{1}{20} \text{ and } \therefore U_4 = 0.34$$

Hence, Q_4 (winter) = 751

and Q_4 (summer) = 80

For Case 2 summing the elements (i) & (ii) gives the total heat loss on a daily basis as;

<u>Winter heat loss = 70,800 Kcals/day</u>
<u>Summer heat loss = 7,200 Kcals /day</u>

6. (4) Case 3 - BURIED DIGESTER

For heat loss calculation in the case of the underground digester the same equations as before are used. The calculation is more extensive since it is necessary to consider the distribution of soil depth covering the digester in order to calculate the elements of heat loss Q_1 & Q_3 which relate to heat loss through the soil. An assumption must be made that the soil coverage can be considered as an extension of the digester wall since as was stated previously the equations are for plane surfaces. More elaborate analysis is possible but using these simple equations gives useful information with reasonable accuracy (Data on soil coverage again relates to the C.R.D. digester and was the result of a contour survey).

(i) For heat transfer from sludge-concrete-soil-air, U_1 is given from equation 13.

$$\frac{1}{U1} = \frac{1}{h_A} + \frac{x_c}{k_c} + \frac{x_s}{k_s} + \frac{1}{h_B}$$

'U_1' is calculated from h_A, h_B, x_c, k_c, defined as before and k_s, the thermal conductivity of soil. However the value of x_s, the thickness of soil is variable and it is necessary to calculate different values of U_1 for different values of x_s. Average values for ranges of soil coverage are used and these can then be matched to the digester wall areas at these depths. (This information again relates to the C.R.D. digester but the method could be applied in other circumstances). Calculated results are given in Table 2.

Continuation of 6.-(4) Case 3 - Buried Digester.

TABLE 2 - BURIED DIGESTER HEAT LOSSES FROM SLUDGE-CONCRETE-SOIL-AIR

X_s metres	Digester Wall Area metre^2	U_1	Heat Loss (Kcals/hr)	
			Winter	Summer
0.75	1.59	.95	71	7.6
1.25	6.28	.68	201	21.4
1.75	12.50	.53	312	33.2
2.5	26.22	.40	493	52.5
4.0	33.36	.27	423	45.0
5.0	26.84	.22	277	29.5

and hence Q_1 (winter) = 1,780 Kcals/hr
and Q_1 (summer) = 189 Kcals/hr.

(ii) For heat loss from sludge-concrete-air U_2 is calculated as in Case 1 (i) above, taking $A_2=0.79$ metre^2.

Hence, Q_2 (winter) = 134 Kcals/hr
and Q_2 (summer) = 14 Kcals/hr

(iii) For heat loss from gas-concrete-soil-air, U_3 is given by

$$\frac{1}{U_3} = \frac{1}{h_A} + \frac{x_c}{k_c} + \frac{x_s}{k_s} + \frac{1}{h_B}$$

This is a similar relationship to that in (i) above and the same approach is required to calculate U_3 for different values of x_s, the soil cover. Values of heat loss calculated in this way are given in Table 3.

TABLE 3 - BURIED DIGESTER HEAT LOSSES FROM GAS-CONCRETE-SOIL-AIR

X_s metres	Digester Wall Area^2	U_3	Heat Loss (Kcals/hr)	
			Winter	Summer
0.4	3.14	1.16	171	18
0.75	18,31	0.87	749	80
1.25	1.2	0.64	36	4

Hence, Q_3 (winter) = 956 Kcals/hr
and Q_3 (summer) = 102 Kcals/hr

Continuation of 6.-(4) Case 3 - Buried Digester.

(iv) For heat loss from gas-concrete-air U_4 in given by the equation.

$$\frac{1}{U_4} = \frac{1}{h_A} + \frac{x_c}{k_c} + \frac{1}{h_B}$$

U_4 calculated in case 1 (ii) above as 2.4 and taking A_4 = 5.5 metre^2

Hence, Q_4 (winter) = 620 Kcals/hr
and Q_4 (summer) = 66 Kcals/hr

For Case 3 summing the elements (i) to (iv) gives the total loss on a daily basis as;

Winter heat loss = 83,800 Kcals/day
Summer heat loss = 8,900 Kcals/day

6. (5) OBSERVATIONS ON CALCULATED DATA

The data for cases 1-3 is summarised in the Table 4 below. Also the average of the winter and summer heat loss.has been calculated, together with the ratio of these quantities.

TABLE 4 - HEAT LOSS SUMMARY (Thousand Kcals/day)

Case Period	1 Exposed Digester in Building	2 Insulated Digester	3 Buried Digester
Winter	635	71	84
Summer	67	7	9
Average	350	40	46
Ratio $\frac{\text{Winter}}{\text{Summer}}$	9.4	9.8	9.4

Some points arise from these figures in relation to the Korean digester design for low temperature operation.

1) The results for the insulated digester (Case 2) and the buried digester (Case 3) are very similar. In both cases heat loss is reduced by about 90% compared with a concrete digester in air. This applies to both summer and winter conditions.

Continuation of 6.-(5) Observations on Calculated Data.

2) Heat losses in summer from insulated or buried digesters through conduction and convection are very small. (10,000 Kcals/day heat loss from a digester of this size is equivalent to a drop in temperature of the contents of $< 0.1^oC$/day.)

3) Ratios of winter to summer heat loss in about 10.

At this point it is valuable to estimate the order of magnitude of radiant heat transfer which occurs for structures of the size of the exposed digester in case 1 when in the open. Using equation 13 and taking the digester "radiation area" as equivalent to the area of a hemisphere of 6 metre diameter (56 metre^2) then for an average temperature of 15^{o}C and assuming the digester wall has an emmissivity of 0.5, the daily heat loss would be 226,000 Kcals.

This rediant heat loss would be compensated by a solar heat gain. To estimate this the area of the digester exposed to the sun is assumed to be an elliptical section through the digester at 15^{o}C to the vertical (40 metre^2) and an average solar heat rate is taken as 4,000 Kcals/day. Assuming further that 50% of the incident radiation in absorbed (absorbtion coefficient = 0.5) then solar heat gain would be 80,000 Kcals/day.

These rough calculations for radiation indicate therefore that on balance there would be radiant heat losses from an exposed digester. The order of magnitude of this quantity in 150,000 Kcals/day.

This figure for radiant heat loss would be much less with a building. For the assumption that it is reduced to a small level compared with convection and conduction losses to be valid then in the case of the insulated digester, cladding material of low emissivity would also be required.

An underground digester well covered with soil would lose a minimum of heat by radiation. From this analysis of heat losses it is clear that this common and simple form of insulation is very effective both in reducing heat loss by radiation and by convection and conduction.

7. TOTAL HEAT REQUIREMENTS

Once the digester heat losses are evaluated the calculation of the total heat requirements to maintain the digester at its operating temperature is straight forward. Using the equation 1 given in section 2 and taking the heat losses for a buried digester as described earlier the total heat requirements is calculated as;

Continuation of 7. Total Heat Requirements.

80,000 Kcals/day in summer
260,000 Kcals/day in winter.

(This assumes a 20 day retention, 10% solids loading and feed temperatures of 10°C and 25°C in winter and summer respectively.)

Gas consumption to provide this heat input (at 5,000 Kcals/M^3 and overall heating efficiency of 60%) would be 27 M^3/day in summer **and 87 M^3/day in winter. These are close to the actual gas consumption for the Korean digester.**

8. IMPROVEMENTS IN OPERATION

Certain improvements are possible to reduce the heat requirements for digesters. Examples of operational procedures which accomplish this are:-

1) Recycle of supernatant or effluent to use as dilution to the feed. Since the **total** solids in the feed is reduced substantially by the digestion process the effluent can be recycled to quite a large degree while adjusting the make-up water volume to maintain the required solids loading in the feed. If a 30% recycle in applied there is **approximately 20%** reduction in the heating requirements.

2) High solids level in feed. The higher the solids level in the feed the less make-up water is required for a given digester. This depends on the physical properties of the feed and the equipment used but a 10% total solids feed should be possible.

3) Using a source of heated feed water. Solar heating could have significant **benefits** in this area.

4) Optimising the operating temperature. For example running a digester at 25°C instead of 35°C would reduce winter heat requirements by about half. Gas production would however be reduced and for optimising in these circumstances a wider study of gas demand patterns would be required.

In relation to operating temperatures there may be **benefits** from a long term research view of the microbiology of anaerobic digester. Is there potential for promoting the action of microorganisms which are more active at low temperatures? The work of Hobson suggests that identification of anaerobic bacteria active in digestion is as yet only partially accomplished so there would seem to be many obstacles to be overcome before a specific low temperature active bacteria could be isolated for promoting gas production in the manner, in which, for example, yeast cultures are applied in yeast fermentation.(Ref. 3)

9. SOCIO-ECONOMIC FACTORS IN SYSTEM DESIGN AND OPERATION

Design and operation of a digester must incorporate an analysis of the social factors relating to the human activity system of which the digester will be a component. Such an analysis must also include an assessment of the process economics. This assessment must in turn investigate the wider aspects of waste recycling, energy utilisation and finance in the rural economy. From a broad systems point of view such things as potential investment, availability of operating skills, level of community involvement etc., all have a bearing on design criteria.

For example, the use of digesters in Korea may be considered. Here, until now, the main requirement has been to provide cooking fuel in place of wood, straw or coal (Ref. 4). The traditional cooker used in Korea has however also been the burner for the domestic heating which supplies underfloor heating for rooms in winter. In this situation winter production of biogas for cooking receives less priority since, while the traditional heating method is used, there are cooking facilities available and the fuel saving is, therefore, limited. If through technical improvements a larger gas production is available, sufficient to perhaps provide cooking and room heating, then it becomes possible to replace the traditional burner. Fuel savings are then potentially much higher but a different total system must be considered and it will be one which puts a greater priority upon low temperature production of biogas to meet winter fuel needs.

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