Application of ultrafiltration membranes for solids – liquid separation in anaerobic digestion systems: The ADUF process[†]

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Abstract

ADUF (anaerobic digestion (AD) ultrafiltration (UF)) is a new generation process for the treatment of industrial organic wastes which effectively eliminates the sludge concentration and retention problems associated with conventional systems. Laboratory and pilot-scale trials on a diverse range of industrial waste digesters have established the merits of the ADUF process. One of the principal merits of the system is its flexibility in integrating the biological and the physical functions of the digester and the UF unit.

Process design criteria are available for full-scale application of the process in South Africa. The process utilises locally manufactured UF membranes instead of imported technology. ADUF process costs compare favourably with costs of conventional treatments. Membrane operated processes may be expected not only to herald a new era in anaerobic digestion but also to influence concepts of waste-water treatment and biotechnology in general.

Introduction

The essential prerequisites for successful high-rate anaerobic processing of soluble/colloidal organic wastes are biomass concentration and biomass retention. Various anaerobic designs are advocated with a view to longer sludge retention times and shorter hydraulic retention times, viz. anaerobic filters, fluidised-bed reactors, upflow anaerobic sludge blanket reactors (UASB), and rotating contactors. At digester space load rates above 10 kg COD.m^{-3}.d^{-1} none of these designs is consistent in yielding high quality effluent free of suspended solids.

In recent years attention has been directed towards the use of membranes for biomass separation in biological treatment processes. Dorr-Oliver developed and patented a membrane sewage treatment system (MSTS), consisting of an activated sludge reactor followed by an ultrafiltration (UF) stage for solid liquid separation (Bemberis *et al.,* 1971). Application of MSTS to anaerobic operation led to the membrane anaerobic reactor system (MARS) (Epstein and Korchin, 1981 and Li *et al.,* 1985). Anderson *et al.* (1986a) report laboratory studies on a two-phase anaerobic digester using porous polyethylene membranes for treating synthetic wastes. Bindoff *et al.* (1987, 1988) describe the development of crossflow microfiltration technology for the concentration of sewage works sludge streams. Anderson *et al.* (1986b) describe results obtained with crossflow microfiltration in anaerobic digestion.

Independent pilot-scale research into the use of locally manufactured UF membranes for solid-liquid separation in the anaerobic treatment of wine distillery waste was commenced in 1987 at the Distillers' Corporation, Stellenbosch and continued at the Paarl Sewage Works during 1988. Significant differences, relative to overseas practice, in UF membrane design, support modules and integration with the digester system prompted the development of what has come to be known as the ADUF process (anaerobic digestion ultrafiltration) for the treatment of organic industrial effluents.

This paper discusses the results of pilot and bench-scale ADUF research with special reference to the treatment of industrial effluents in general.

The ADUF Process

Fig. 1 shows a simplified diagram of the ADUF process. The design incorporates two main unit processes; an anaerobic digester and an external ultrafiltration unit. The features of each unit process and the integration of the two processes are described below.

Anaerobic digester

The digester has neither internals i.e. no gas/liquid/sludge separators as encountered in UASB plants, nor plastic packing as used in attached-growth anaerobic filters. Feed substrate is introduced via an external ring main at the base of the digester, by means of which it is evenly distributed over the bottom area.

The digester output is withdrawn via another collector at the top op the digester and pumped to the UF unit. Sludge circulated

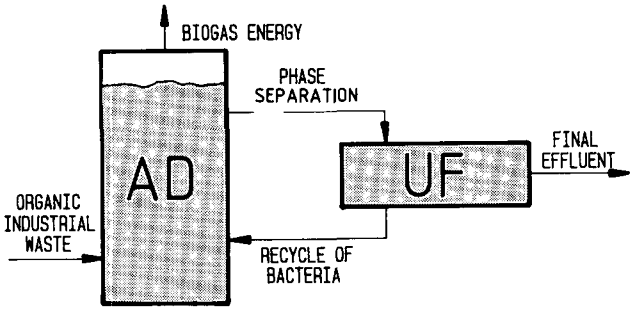

Figure 1

Schematic diagram of ADUF (anaerobic digestion ultrafiltration) process

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through the UF unit and recycled back to the digester provides sufficient mixing in the digester to enhance its performance. Heating and pH control of the digester contents are achieved by means of an external heat exchanger and pH controller, respectively.

Ultrafiltration unit

Ultrafiltration is a physical process whereby the liquid is separated from a solid/liquid mixture (Strohwald, 1986). Separation is effected by a membrane acting as a filter. Pores in the membrane allow liquid passage (called membrane flux) while the solid particles are rejected at the membrane surface. The membrane is in the form of a tube with the membrane forming the tube wall.

The digester sludge mixture is introduced into the tube at a relatively low operating pressure of 500 kPa. The membrane flux results from the pressure differential from the inside to the outside of the tube wall, with the mixture flowing down the tube i.e. across the membrane surface, becoming progressively more concentrated.

In contrast with conventional filtration, in which flow direction is perpendicular to the filter medium, flow direction in a tubular UF system is parallel to the membrane surface, greatly reducing the vulnerability to clogging. Because the transport of matter across a UF membrane involves viscous porous flow, the flow rate (flux) and rejection will be determined by the physical structure of the membrane. In the ADUF process the permeate is the final effluent, while the sludge concentrate containing the bacteria, nutrients and buffer components is rapidly recycled back to the digester with minimal activity loss and temperature drop.

The specification of the tubular UF modules used in the ADUF process and manufactured in Paarl by the firm Bintech (Pty) Ltd has been reported by Strohwald (1986). The most recent advance in UF membrane technology is the local manufacture of 9mm-diameter tubes not requiring the customary high pressure support system.

Typical UF membranes possess an asymmetrical structure (Fig. 2). The top surface or "skin" is generally very thin (0,1 to 1,0 micron) and is supported by a substructure which is much more porous, thereby offering relatively little resistance to product flow. The substructure provides mechanical and hydraulic strength and supports the skin layer. The substructure itself is usually bonded to a supporting polyester fabric. The supporting fabric gives added mechanical strength to the fragile membrane structure and facilitates easy handling of membranes.

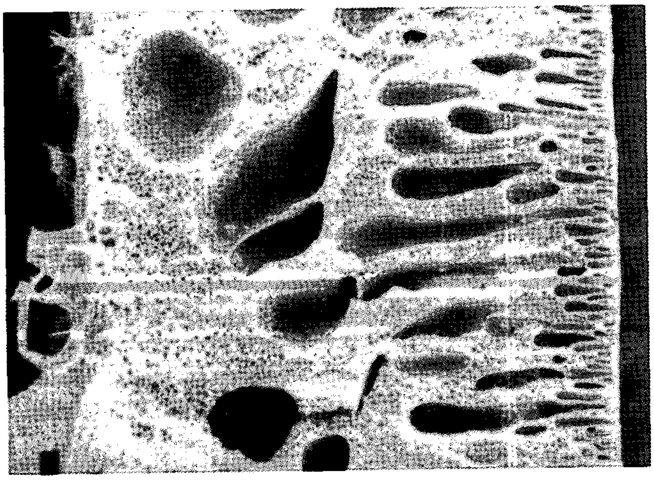


Figure 2

Cross-section of a polyethersulphone membrane: Magnification 700X

UF involves the rejection of macromolecules or particles at the membrane surface with the rejection being governed by membrane pore size (0,001 to 0,1 micron). The membranes have a molecular mass cut-off point of between 20 000 to 80 000.

Flux decreases with time in a manner which depends on the nature of fouling and on the nature of the fouling species. In theory flux drops in proportion to the inverse log of the retentate concentration. Flux regeneration can be effected by chemical cleaning. The UF membranes are made from polyethersulphone and can tolerate temperatures of up to 90°C, pHs from 0,5 to 13 and high chlorine levels. Polyethersulphone membranes are also compatible with a variety of digester feed substrates and cleaning agents.

UF membranes are affected by concentration polarisation, as are RO membranes to a lesser extent. Concentrated macromolecular solids and colloids form a gel layer on the membrane surface that becomes a secondary membrane, usually offering major resistance to flow. To maintain high flux values, when the solids content of the feed solution is high, the building-up of the gel layer must be limited. Gel layer thickness can be controlled by high fluid velocities across the membrane. At high linear velocities (2,0 to 3,5 $m.s^{-1}$) the polarisation layer is sheared off and an equilibrium film thickness is established. Higher linear flow velocities lead to higher flux values at the cost of higher energy input (pumping cost).

Integration of the anaerobic digester with the UF unit

Ultrafiltration and anaerobic digestion are complementary processes: anaerobic digestion decomposes organics which would otherwise foul the filter membranes, while for their part these membranes serve to retain biomass which would otherwise be lost in the digester effluent. Certain parameters differentially influence the digester and the UF unit, e.g. biomass concentration; operating temperature; digester space load rate; biodegradability and degree of purification of substrate; flow velocity and pressure across the membrane, etc. Some of these parameters are synergistic in the integrated system, others antagonistic. Great flexibility is achieved in the integration of the biological and physical functions of the digester and UF units. ADUF appears especially suitable for treating smaller volumes of concentrated waste as opposed to larger volumes of dilute waste. Selection of digester capacity and membrane area for processing a given waste should be based on pilot-scale studies, and a balance struck between digester cost and membrane cost.

Additional features of the ADUF process

- The process is completely enclosed - no undesirable odours are detectable in the vicinity of the plant. This is especially important in sensitive areas e.g. around food-processing and beverage plants.
- No strict SRT control is necessary, and permissible biomass concentration is governed by its influence on permeate flux. The digester need not be a completely mixed system, and sludge can be withdrawn from the digester, and returned to the UF unit, at different levels.

- The external UF unit is modular and makes provision for additional membranes to accommodate an increase in flow rate.

Pilot-scale ADUF studies on the anaerobic digestion of wine distillery waste

Wine distillery waste (37 kg.m^{-3} COD) has been treated in full-scale anaerobic plants at the Paarl and Stellenbosch sewage works for over 25 years (Heunis, 1986). Both upflow clarigester and contact-type plants are currently used for this purpose. These plants rely on clarifiers to concentrate and recycle the biomass back to the digestion compartment. Gravity separation restricts the digester mixed liquor suspended solids (MLSS) concentration from 15 to 20 kg.m^{-3} and clarifier upflow velocities to 0,1 m.h^{-1}. The sludge has poor settling properties owing to its diffuse (non-granular) and somewhat filamentous nature (Fig. 3). Research has shown that settling and retention of this sludge becomes problematical at load rates above 4 kg COD. m^{-3}.d^{-1}, as a result of residual gasification and consequent sludge rise in the clarifier compartment (Ross *et al.,* 1981; Ross *et al.,* 1988a).

A pilot plant comprising a digester and an external UF unit was commissioned at Distillers' Corporation, Stellenbosch during 1987 (Fig. 4). The 2,4 m^3 digester operated at a MLSS concentration of 30 kg.m^{-3} and prior to the installation of the UF module could only be fed with wine distillery waste at a space load rate of some 4 kg COD. m^{-3}.d^{-1} at 35°C. A commercial Bintech UF module with a total membrane area of 1,75 m^2, was used for the test at an inlet pressure of 400 kPa. The high rate of sludge recirculation through the UF unit to comply with a linear velocity of 2 m.s^{-1} resulted in a permeate volume (2,4 m^3.d^{-1}) well in excess of that of the substrate feed rate (0,3 m^3.d^{-1}) to the digester. The oversized UF unit was accommodated by wasting a volume of permeate equivalent to the daily feed volume, and by recycling the excess permeate back to the digester. All the sludge concentrate was returned to the digester.

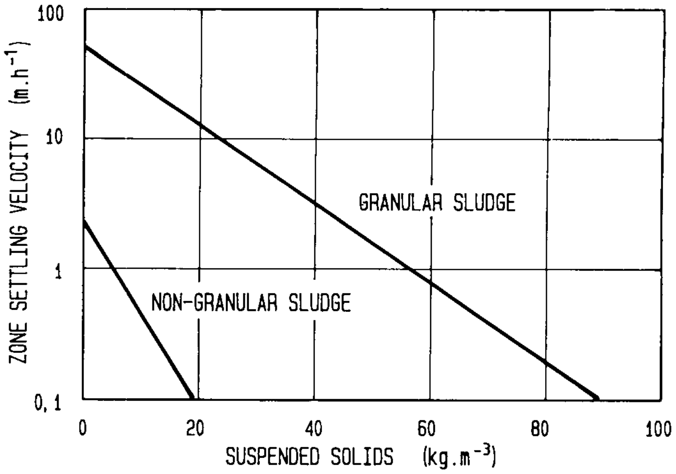


Figure 3
Zone settling velocity of anaerobic sludges

The experimental results obtained on the ADUF system may be summarised as follows (Ross *et al.,* 1988b):

- The extremely high initial permeation flux of 1,5 m^3.m^{-2}.d^{-1} at 400 kPa inlet pressure gradually decreased to 0,9 m^3.m^{-2}.d^{-1} after 7 months' continuous operation (Fig. 5). Temporary substitution of the original module by a new one also gave a flux of 0,9 m^3.$^{-2}$.d^{-1}, indicating that the flux decline was not caused by membrane fouling but by changes in the digester contents, e.g. the SS in the digester had increased over the seven-month period to 50 kg.m^{-3} from an initial concentration of 30 kg.m^{-3}.
- No suspended solids were lost in the effluent (permeate) which was completely clear. Anaerobic bacterial counts before and after ultrafiltration were carried out and illustrated one of the

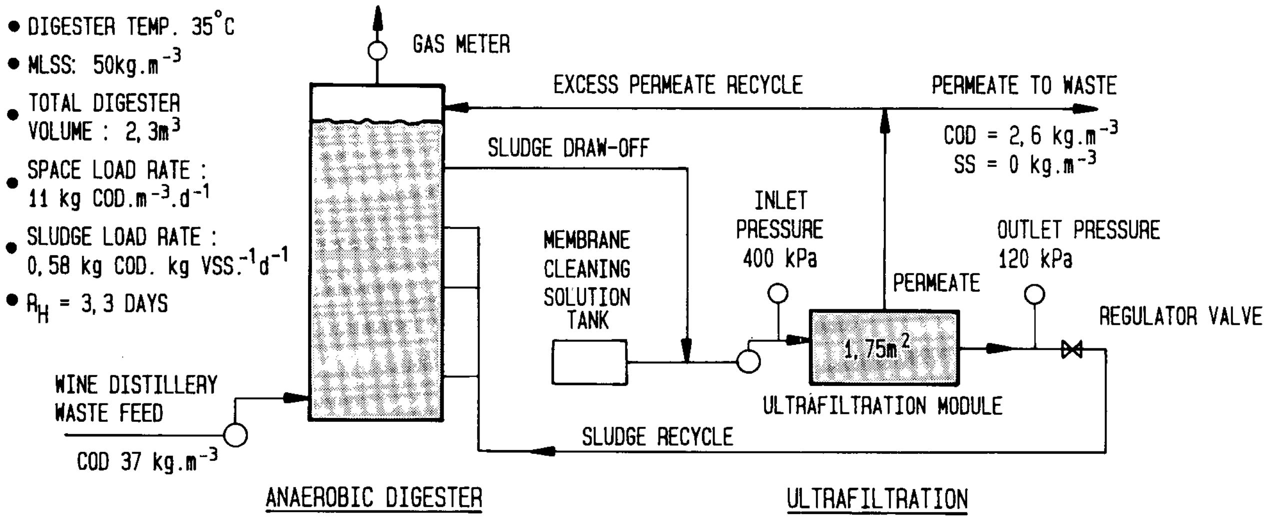


Figure 4
Diagram of pilot-scale ADUF process applied for the anaerobic treatment of wine distillery waste

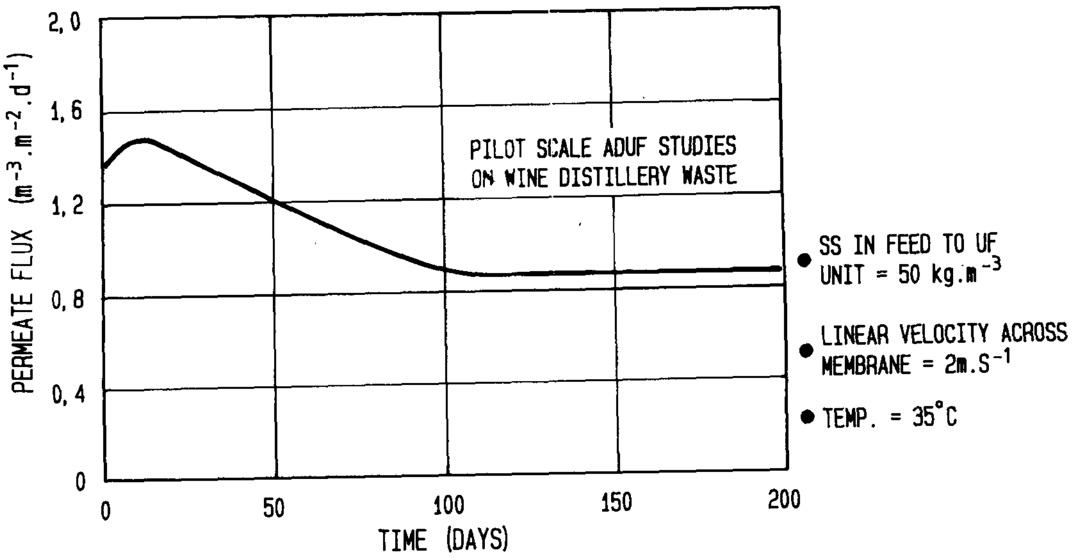


Figure 5
Variation of permeate flux with time

important advantages of ADUF, i.e. recycling of bacteria back to the digester.

- A build-up of biomass occurred in the digester, with a concomitant increase in permissible space load rate notwithstanding the poor settleability of the sludge. During the study period, the load rate increased from 4 to 12 kg COD.$m^{-3}.d^{-1}$ (Fig. 6).
- The operating flux was successfully maintained for a period of several weeks before cleaning of the membrane was necessary.
- The degree of COD removal was 93%, based on a feed and effluent concentration of 37,0 and 2,6 kg.m^{-3} respectively.

Bench tests on factors influencing permeate flux

Permeate flux through the membrane is mainly a function of operating pressure, temperature, suspended solids concentration and viscosity. Bench tests were carried out on anaerobic sludge treating wine distillery waste using a standard UF module to establish the basic interrelationships between these parameters.

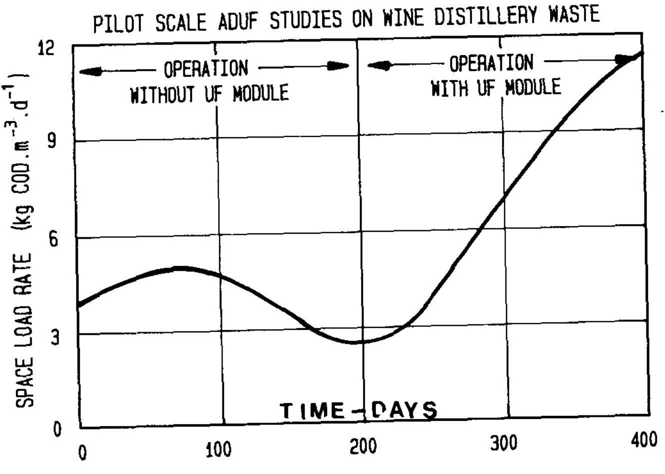


Figure 6
Increase in space load rate after installation of UF module

Operating pressure

The dependence of operating pressure on flux is related to the relative resistances of boundary layer and membrane. In most cases, the boundary layer resistance controls flux. In these cases any increase in flux associated with increased pressure is immediately counteracted by an increase in boundary layer resistance. The result is that flux is often virtually independent of the applied pressure above 200 kPa (Strohwald, 1986).

Operating temperature

Temperature is an important parameter in optimising permeate flux due to its effect on viscosity and hence on turbulence and boundary layer thickness. The relationship between membrane flux and operating temperature is illustrated in Fig. 7. Flux increases markedly with rising temperature (roughly 2% per degree) and fairly closely obeys the Andrade equation describing the relationship between viscosity and temperature (Findlay, 1953): Viscosity = $Ae^{b/rt}$ where A and b are constants for a given liquid. This is a significant factor and offers the designer a choice between a mesophilic (35°C) or thermophilic (55°C) ADUF system. Thermophilic digestion permits a 40% permeate flux increase over mesophillic digestion.

Suspended solids

Bench studies were carried out to determine the permeate flux at different suspended solids concentrations (Fig. 8). The results indicated a constant flux value of 1 000 $\ell.m^{-2}.d^{-1}$ up to a concentration of 40 $g.\ell^{-1}$, after which flux decreased rapidly to 400 $\ell.m^{-2}.d^{-1}$ at 60 $g.\ell^{-1}$. The results do not agree with those reported by Li *et al.* (1985) who found a proportional decrease in membrane flux with an increase in digester suspended solids.

Relationship between viscosity and suspended solids

In ultrafiltration, the degree of scouring in the vicinity of the tube wall will be affected by two factors:

- the velocity gradient at the tube wall; and
- the degree of turbulence, indexed by the Reynolds number.

These two factors are affected fundamentally by the rheology of the fluid. Both the velocity gradient at the tube wall and the degree of turbulence can be decreased by an increase in the viscous forces within the fluid at constant average velocity and tube diameter.

Rheological tests were carried out by Slatter and Lazarus (1988) on the same wine distillery waste anaerobic sludge at three different concentrations between 30 and 66 g.ℓ$^{-1}$ using a Haake rotational viscometer. The energy input per unit volume of sludge was of the same order of magnitude as would be expected to be dissipated during passage through a UF membrane. The rheograms are presented in Fig. 9 and the results are summarised in Table 1.

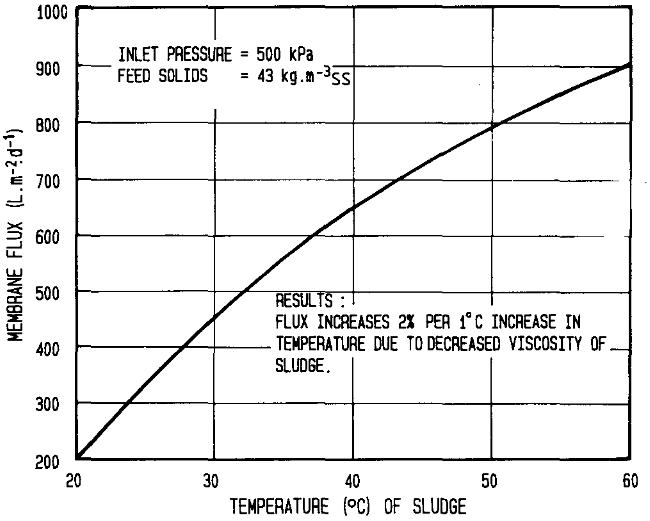


Figure 7
Relationship between temperature and UF membrane flux for wine distillery waste anaerobic sludge

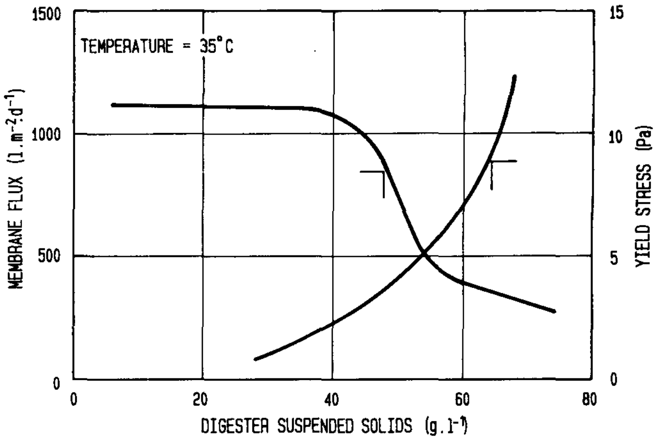


Figure 8
Relationships between UF membrane flux, digester suspended solids, and sludge viscosity for wine distillery waste sludges

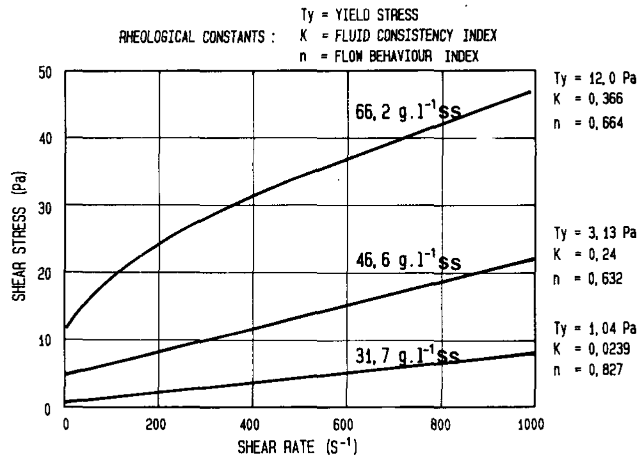


Figure 9
Rotary viscometer rheograms of wine distillery waste anaerobic sludge

TABLE 1
RHEOLOGICAL TESTS OF ANAEROBIC SLUDGE TREATING WINE DISTILLERY WASTE

Sludge sample	Sludge concentration (g.ℓ$^{-1}$SS)	Yield stress Ty (Pa)	Fluid consistency index K	Flow behaviour index n	Reynolds number Re	Velocity gradient $[du/dr]_o$ (ℓ.s^{-1})
1	31,7	1,04	0,0239	0,827	3 100	2 210
2	46,6	3,13	0,240	0,632	1 170	1 500
3	66,2	12,00	0,366	0,664	533	1 540

Tube velocity = 2 m.s^{-1} Tube diameter = 13 mm
Sludge density = 1 000 kg.m^{-3} Temperature = 35°C

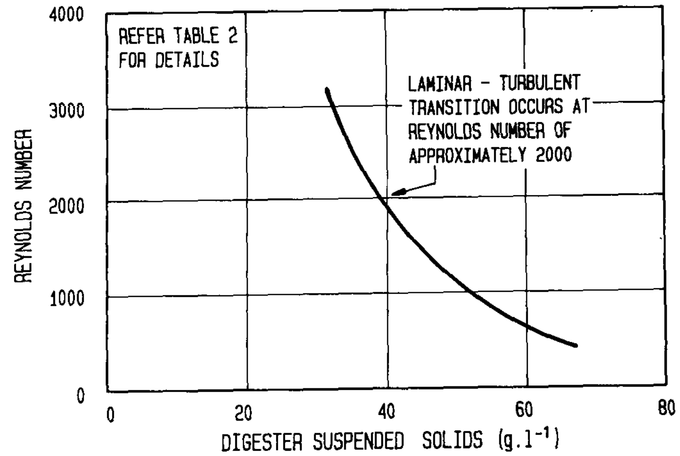


Figure 10

Relationship between Reynolds number and digester suspended solids

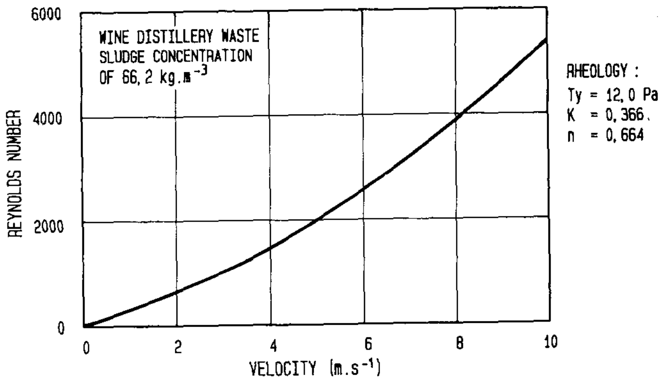


Figure 11

Relationships between Reynolds number and UF tube velocity

The sludges' behaviour described by these results is that of a pseudoplastic thixotropic (non-Newtonian) fluid. The rheological constants of yield stress (Ty), fluid consistency index (K) and flow behaviour index (n) were extracted for each rheogram using the "log of least squares" regression.

Fig. 8 illustrates the relationships between viscosity, membrane flux and suspended solids. The rapid decrease in UF membrane flux is accompanied by a rapid increase in the viscous forces of the sludge at a concentration of around 40 $g.\ell^{-1}$. These results are similar to those reported by Rose-Innes and Nossel (1982) for digested sewage sludges.

Fig. 10 shows Reynolds number plotted against sludge concentration. The laminar/turbulent transition supervenes at a Reynolds number of ca. 2 000. Thus Fig. 10 indicates that turbulence would cease at a concentration of aproximately 40 $g.\ell^{-1}$SS. Fig. 11 indicates that turbulence can be restored by increasing the average tube velocity. For sludge at 66,2 $g.\ell^{-1}$ an average velocity of at least 5 $m.s^{-1}$ would be required to achieve turbulence. Since flow becomes laminar at concentrations above 40 $g.\ell^{-1}$SS, these test results suggest that the decrease in membrane flux in Fig. 8 is attributable to the rheology of the sludge, by inhibition of the fluid cleaning action which is fundamental to the UF process.

Application of the ADUF process to the treatment of other industrial wastes

A survey was conducted on various pilot-scale and full-scale anaerobic digesters treating industrial wastes in South Africa with a view to assessing the applicability of UF membranes for phase separation of digester solids. A portable UF module was connected to the digester outflow under actual process conditions and operated for a period of approximately 40 h on each waste. The flux values have been normalised to reflect similar operating conditions of inlet pressure (500 kPa), temperature (35°C) and tube wall flow velocity (2 $m.s^{-1}$). This period of time, clearly too short to predict long-term trends in permeate flux behaviour, was nevertheless informative in establishing the general feasibility and merit of the ADUF process.

Fig. 12 presents the permeate flux values obtained on the various anaerobic plants. The stabilised flux values varied in the range 1 500 to 600 $\ell.m^{-2}.d^{-1}$, which was most encouraging considering the complex chemical composition of the wastes being treated. These flux values are well within the economically exploitable range. By way of comparison the portable UF module recorded a flux of approximately 2 500 $\ell.m^{-2}.d^{-1}$ on tap water.

Current research and development programmes concern the treatment of malting, egg processing and wine distillery wastes in mobile ADUF pilot plants. In all three instances, the operating flux is successfully maintained for periods of several weeks before cleaning of the membrane is necessary. The first full-scale industrial application of the ADUF process will be at the Egg Board, Kraaifontein, where a 80 m^3 capacity plant is being commissioned for the treatment of egg processing waste.

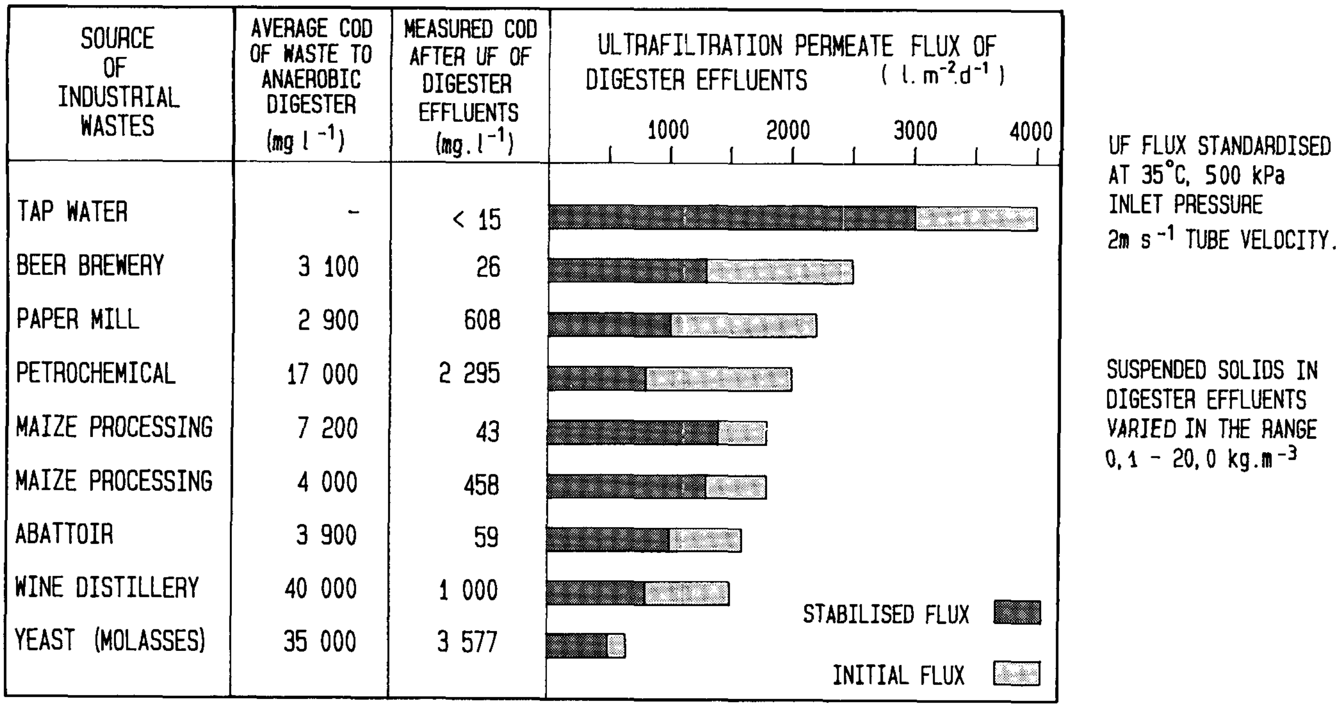
Cost aspects

The ADUF process, based entirely on South African technology and materials, holds important economic implications for the optimisation of anaerobic treatment:

- In contrast with most other types of purification processes, which consume energy, anaerobic digestion actually produces energy - a strategic consideration in a world of rising energy costs. Consumption of 1 t COD liberates 500 m^3 of biogas equivalent to 500 kg of coal.
- The current general municipal tariff for acceptance and treatment of industrial wastes in South Africa is 30c per kg, rising to an expected 120c per kg by the year 2 000 (national statistics). On-site anaerobic treatment offers significant savings in terms of effluent tariffs, effluent reuse capability and energy recovery.
- ADUF is a high-rate process with space load rates of 10 kg $COD.m^{-3}.d^{-1}$ and upwards (in the case of e.g. wine distillery waste roughly four times higher than the figure for conventional plants), with correspondingly reduced digester volume and capital cost, while the use of compact UF membranes for phase separation eliminates the necessity of large settling tanks (contact system) and packing material (fixed-bed systems).
- The current capital cost of a basic UF system is R300/m^2; membrane replacement R100/m^2. Membrane life is favourable because digestion occurs at neutral pH and hence without detriment to membranes or support structures. High membrane flux and long membrane life naturally have a very direct bearing on process costs.

Conclusions

Combining anaerobic digestion with ultrafiltration is a new-generation process with exciting potential. The main advantages



SOURCE OF INDUSTRIAL WASTES	AVERAGE COD OF WASTE TO ANAEROBIC DIGESTER (mg l $^{-1}$)	MEASURED COD AFTER UF OF DIGESTER EFFLUENTS (mg. l $^{-1}$)
TAP WATER	-	< 15
BEER BREWERY	3 100	26
PAPER MILL	2 900	608
PETROCHEMICAL	17 000	2 295
MAIZE PROCESSING	7 200	43
MAIZE PROCESSING	4 000	458
ABATTOIR	3 900	59
WINE DISTILLERY	40 000	1 000
YEAST (MOLASSES)	35 000	3 577

UF FLUX STANDARDISED AT 35°C, 500 kPa INLET PRESSURE
2m s $^{-1}$ TUBE VELOCITY.

SUSPENDED SOLIDS IN DIGESTER EFFLUENTS VARIED IN THE RANGE 0,1 - 20,0 kg.m^{-3}

Figure 12
Permeate flux values after ultrafiltration of various industrial waste anaerobic digester effluents

are the production of a clear effluent and maintenance of high digester biomass concentration. Fundamental concepts have been established which provide an integrated basis for process design and control. Continuing research may confidently be expected to lead to the development of rational quantitative criteria, more favourable economics and improved reliability.

Acknowledgements

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- Staff of Distillers' Corporation for operation and monitoring of the pilot plant at Stellenbosch.
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- All the industries referred to in Fig. 12 for permission to test the UF membranes on their anaerobic digesters.

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