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Simulation of Non-Newtonian Fluids in Anaerobic Digesters

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Abstract

The non-Newtonian flow characteristics of sludge complicate the mixing processes within an anaerobic digester. This study uses numerical methods to investigate the effects of digester shape on the circulation of the non-Newtonian sludge. The equations governing the flow of fluids in the digester are the Navier-Stokes and continuity equations. The respective constitutive equations for shear thinning, shear thickening and Bingham plastic fluids are used in the simulation of the non-Newtonian flow of sludge in the digester. A penalty function Galerkin finite element method is used to solve these equations. A centrally located draft tube provides the impetus for fluid circulation in the digester. The circulation patterns and the size of the dead zones apparent in the upper half of the digestion vessel are found to depend on the type of non-Newtonian fluid used in the simulation. It is suggested that improved digested design will result if more attention is paid these phenomena.

1. Introduction

One of the products of aerobic biological wastewater treatment is a fairly concentrated suspension that usually requires additional treatment in an anaerobic digester. This digester-sludge exhibits non-Newtonian behaviour being pseudoplastic and in some instances having a yield stress. Although many studies of mixing in digesters have been made, most have ignored these essential flow characteristics by assuming that the sludge simply behaves like water. Different mixing behaviour resulting from non-Newtonian flow will affect the operation of the digester and could also have some bearing on the scale up of pilot plant operations. Some workers have assumed rheological behaviour for sludge[1,2,3], and it appears that the rheological behaviour varies widely depending on the precise composition of the sludge. Typically, sludge containing fine particles can behave as a shear-thickening fluid, but sludge is found to behave like a Bingham plastic or shear thinning fluid if it has a high grit or sand content[4]. As digester sludges contain solids it is necessary to keep them well mixed so that these solids do not accumulate in the vessel. Evidently, the energy required for mixing will vary depending on the fluid type. If digested sludge is a shear thickening fluid, low shear rate continuous mixing will require low power. In contrast Bingham plastic or shear thinning fluids require higher shear rates leading to the adoption of intermittent agitation to reduce energy consumption.

As experimental studies are difficult to perform and require long execution times, mathematical models and simulation procedures have been used to investigate the anaerobic digestion process. Most of the used mathematical models focus on the kinetics of the digestion process. In particular, these models assume that perfect mixing occurs in the digester, this means that the model predictions will not be effective at high feed density[5]. Casey[6] presents a simple model of mixing and dispersion of mixing energy for laminar flow of a pseudoplastic fluid. The non-Newtonian model chosen is a power-law with finite yield stress. It is concluded that a low intensity of mixing is adequate to satisfy process requirements, but for a large volume of viscous material, uniform dispersion is difficult to achieve. Hertle and Lever[7], while recognising the sludge has non-Newtonian properties, consider the mixing of sludge in anaerobic digester by modelling using the CSTR (Continuous Stirred Tank Reactor) approach.

The vessel configuration is one of other factors known to affect digester performance. In the present study, a preliminary evaluation of mixing in anaerobic digesters is made by simulating fluid circulation in a pilot-scale digester. The effect of an angle of the conical base of the vessel is investigated for various Newtonian and non-Newtonian fluids. Circulation and mixing in anaerobic digesters is a complex process requiring the numerical solution of the governing equations of flow. A Galerkin finite element method using penalty functions (FIDAP 7.52)[8,9,10] is employed to find the distribution of velocity and pressure in the digester. The calculations were carried out on a Fujitsu VPX240/10 supercomputer.

2. Mathematical model

Digester sludges are complex materials having time-dependent non-Newtonian properties that are, to date, incompletely understood. While wishing to retain some non-ideal properties of the system, some simplification of the problem is necessary to facilitate our preliminary investigation. To this end, it is assumed that the sludge is continuously circulated in the digester, is of constant density and shows time independent non-Newtonian behaviour. Solutions are sought for power law and Bingham plastic sludges in a cylindrical co-ordinate system appropriate to the digester shape. Under these conditions the governing equations for the conservation of mass and momentum are:

The continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho u) \tag{1}$$

where ρ is the fluid density and u is the three components of velocity. For an incompressible fluid, the density is constant and hence Equation (1) reduces to the simple form.

$$\nabla \bullet u = 0 \tag{2}$$

The Navier-Stokes equation

$$\frac{Du}{dt} + u \bullet \nabla = F - \frac{1}{\rho}\nabla P + \nu \nabla^2 u \tag{3}$$

where F represents components of the body force, ν is the kinematics viscosity ($\nu = \mu/\rho$).

If a centrally placed draft tube is used to induce circulation, then the problem is axi-symmetric. It is appropriate to make some simplifications of these equations in a cylindrical polar co-ordinate system. In particular, attention is restricted to incompressible flows which have reached a steady state with symmetry about the axis, $r = 0$, all the $\partial/\partial\theta$ derivatives vanishing. Under these assumptions the Navier-Stokes equation are [11,12]:

$$u_r \frac{\partial u_r}{\partial r} + u_z \frac{\partial u_r}{\partial z} - \frac{u_\theta^2}{r} = -\frac{\partial P}{\partial r} + \frac{1}{Re}\left(\frac{\partial^2 u_r}{\partial r^2} + \frac{1}{r}\frac{\partial u_r}{\partial r} - \frac{u_r}{r^2} + \frac{\partial^2 u_r}{\partial z^2}\right) \tag{4.1}$$

$$u_r \frac{\partial u_\theta}{\partial r} + u_z \frac{\partial u_\theta}{\partial z} + \frac{u_r u_\theta}{r} = \frac{1}{Re}\left(\frac{\partial^2 u_\theta}{\partial r^2} + \frac{1}{r}\frac{\partial u_\theta}{\partial r} - \frac{u_\theta}{r^2} + \frac{\partial^2 u_\theta}{\partial z^2}\right) \tag{4.2}$$

$$u_r \frac{\partial u_z}{\partial r} + u_z \frac{\partial u_z}{\partial z} = -\frac{\partial P}{\partial z} + \frac{1}{Re}\left(\frac{\partial^2 u_z}{\partial r^2} + \frac{1}{r}\frac{\partial u_z}{\partial r} + \frac{\partial^2 u_z}{\partial z^2}\right) \tag{4.3}$$

where all the parameters u_r, u_θ, u_z, P, r, z are now dimensionless.

In the finite element program various rheological models of non-Newtonian fluids are employed to simulate the behaviour of digester liquors. The power-law model is used to simulate the behaviour of pseudoplastic and dilatant of digested sludge while the Herschel-Bulkley model is used to simulate the behaviour of fluids with a yield stress.

The constitutive equation for a power law fluid is presented by the following equation

$$\tau = \mu_0 k |\dot{\gamma}|^{n-1} \dot{\gamma} \tag{5}$$

where τ is the shear stress, μ_0 is a constant viscosity, $\dot{\gamma}$ is the corresponding shear rate, k is the consistency and n is the power index. When n=1, the power law is reduced to Newtonian form. For n<1, the power law describes pseudoplastic, or shear thinning behaviour, and for $n > 1$, dilatant or shear thickening behaviour is described.

The Bingham plastic model is generalised as follows

$$\tau - \tau_y = \mu_0 k |\dot{\gamma}|^{n-1} \dot{\gamma} \tag{6}$$

where τ_y represents the finite yield stress required initiating flow.

3. Geometry and boundary conditions

The geometry of a digester considered in the present study is based on a pilot-scale cylindrical tank with a 1.0m. diameter and 1.0m. height that has been used for studies of residence time distributions. A draft tube is located at the centre of the vessel and fully immersed in the fluid. A diameter of the draft tube is 0.16m. Geometrical functions are varied the angle of the cone-like vessel floor, i.e. 0, 30, 45 and 60 degrees respectively. For the simulations it is convenient to use the axi-symmetric properties of the system, which allow the use of two-dimensional elements. The various domains in the digester are divided into topological rectangular regions by using the geometry and boundary keypoints. The density of the mesh is increased in the areas where there are relatively large gradients, typically the region where sludge flows from draft tube requires finer mesh than other regions (see Fig. 1). In the computer program, for the axi-symmetric case, the radial velocity component is constrained to zero and the axial velocity component is set to some desired values using the following boundary conditions;

at the axis	$u_r = 0,\ u_z = \text{free}$
at the inlet	$u_r = 0,\ u_z = u_z$
at the wall	$u_r = 0,\ u_z = 0$

4. Physical properties of fluids

The fluid properties used herein are summarised below and are taken to be similar to those of water and various sewage sludges[13].

Newtonian fluid	density (ρ)	= 996	kg m^{-3}
	viscosity (μ)	= 0.8x10^{-3}	Pa.s
Pseudoplastic fluid	density (ρ)	= 1005	kg m^{-3}
	μ_0	= 1	Pa.s
	k	= 0.009	
	n	= 0.8	
Dilatant fluid	density (ρ)	= 1100	kg m^{-3}
	μ_0	= 1	Pa.s
	k	= 0.008	
	n	= 1.2	
Bingham plastic	density (ρ)	= 1300	kg m^{-3}
	τ_y	= 0.14	Pa
	μ_0	= 0.003	Pa.s

Note that Equations (5) and (6) are formulated so that k has no units.

5. Results and discussion

Various configurations of an anaerobic digester are simulated by changing the shoulder angle at the base of the digester (see Fig. 1). Fig, 2 and 3 show the circulation patterns obtained for a shear thinning fluid in vessels with different cone angles at the base. In every simulation of flow in a flat bottom tank, the liquid at the bottom corner was isolated from the main flow of the tank. This is of interest because a flat base (cone angle 0°) is the commonest form of construction for an anaerobic digester vessel. This configuration of digester will have a significant dead zones linked to the streamlines as shown in Fig. 3. It is evident that the larger cone angles restrict the re-circulation zones and stagnation zones and in terms of mixing performance will consequently reduce the volume of dead zones.

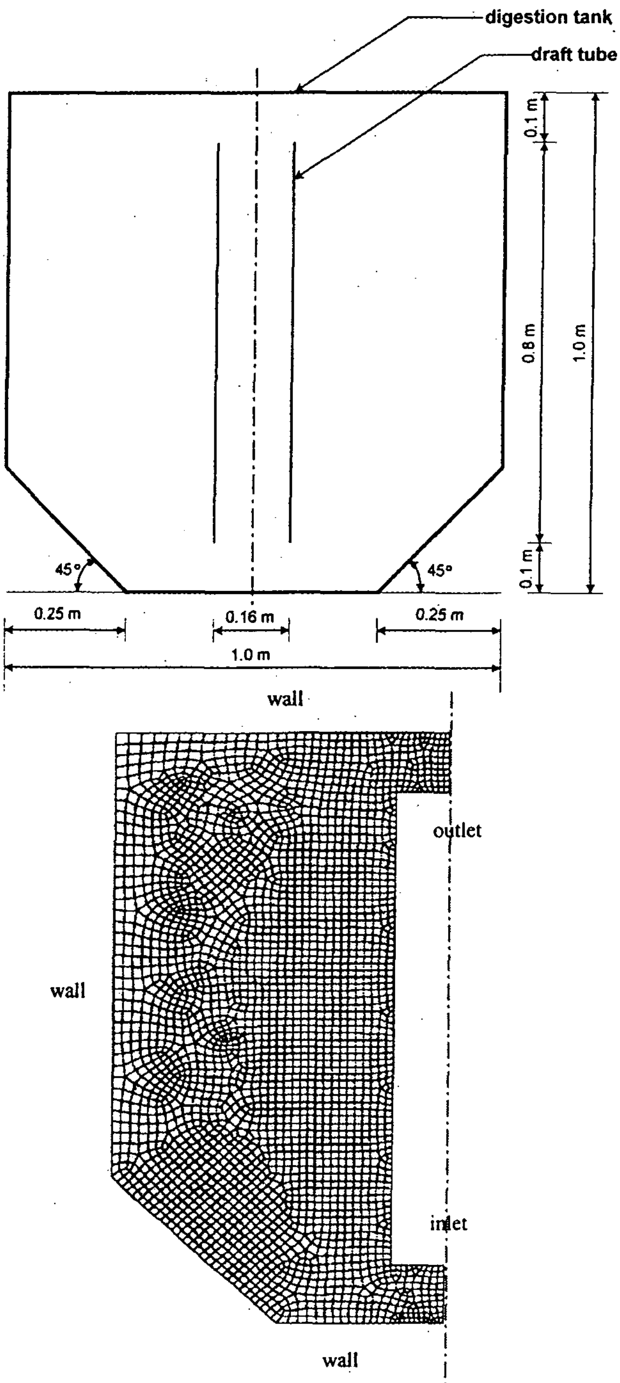

Fig. 1 Anaerobic digester: circular tank with 45° shoulder and a generated mesh.

Fig. 4 and 5 compare the growth of the recirculation eddy in Newtonian, shear thinning, shear thickening and Bingham plastic fluids respectively. Fig. 4 shows the distribution of the velocity vector and Fig. 5 shows the streamline contour plots. Apart form the Bingham plastic fluid, the re-circulation eddy is seen to vary in size with the different types of viscosity model. The size of the eddy seems to follow the power law index. The smallest eddy is seen in the shear thinning fluid and the largest in the shear thickening fluid. The Newton fluid, $n = 1$, fits between these extremes. In the case of the shear thickening fluid there is significant degree of counter rotation in a weak eddy in the upper part of the vessel (see Fig. 5). The Bingham plastic circulation does not have any re-circulation eddies and the circulation pattern is simple. If the local shear stress is less than the yield value of the Bingham plastic fluid, then the material does not shear and consequently moves as a plug. Generally the shearing rates in the digester vessel are low and the local shear only just exceeds the yield value. The viscosity of a sheared Bingham plastic material is very large and this leads to the observed flow pattern where the arrangement of the streamlines looks similar to that for low Reynolds number flow. In contrast the velocities in a shear thickening fluid seem to be very intense close to the inlet (see Fig. 4). There is also a region of flow intensification close to the wall of the draft tube. The shear thickening fluid shows a wide distribution of shearing rates resulting in very good mixing within the lower half of the digestion vessel. In contrast, because of the large viscosity, the Bingham fluid will require a much greater power input to create strong circulatory flows.

It is suggested that the non-Newtonian nature of digester sludge can play a significant role in mixing. As the main energy cost in the operation of such digesters is the maintenance of a uniform composition then the extra energy cost of mixing the non-Newtonian fluids should be considered in the initial design. This will lead to better performance and increased operating efficiency.

6. Conclusions

The results of simulations of flow in an anaerobic digester, using the Newtonian and non-Newtonian fluids, suggest that, for all types of fluid, the size of the re-circulation eddy at the base of the vessel can be controlled by the cone angle of the base. In general a conical shaped vessel is effective in promoting mixing and keeping sludge in suspension. Flat-bottomed vessels have significant stagnant zones where solids may accumulate and reduce the performance of the digester.

The value of the power law index, n, has a strong influence on the size of the lower re-circulation eddy. In the present work, the size of the eddy increases with increasing n. This implies that for a sludge with a viscosity that can be described by a power law relationship, the energy requirement for good mixing will depend strongly on the power law index. In addition, a Bingham plastic sludge requires a much greater power input to create strong circulatory flows because of its high viscosity. Evidently the non-Newtonian nature of the fluid plays an important role in the mixing operations that are required to prevent sedimentation.

To date little attention has been paid to the mixing requirements for anaerobic digesters. This preliminary study indicates that both the shape of the vessel and the characteristics of the sludge contained in the vessel can significantly affect the mixing within the vessel, and in particular attention is brought to the possible differences in operating conditions that will lead to reduced performance. It is suggested that improved digested design will result if more attention is paid these fluid phenomena.

References

[1] Babbitt, H.E. and Caldwell, D.H. (1939), Laminar Flow of Sludge in pipes, University of Illinois Bulletin, 319.

[2] Hess, I.H. and Weber, L.D. (1992), United State Patent, Liquid Circulation Device, (Patent No. 5,133,907), Date of Patent:28/7/92.

[3] Rundle, H. and Whyley, J. (1981), A Comparison of Gas Recirculation System for Mixing of Contents of Anaerobic Digesters, Water Pollution Control, No. 80, 463-480.

[4] Perry, R.H. and Green, D. (1984), Perry's Chemical Engineering's Handbook, 6th Edition, McGraw-Hill.

[5] Torre, A.D. and Stephanopoulos, G. (1985), Simulation Study of Anaerobic Digestion Control, Biotechnology and Bioengineering, Volume 28, 1138-1153.

[6] Casey, T. J. (1986), Requirements and Methods for Mixing in Anaerobic Digesters, Comm Eur Communities Report EUR9751, Anaerobic Digestion of Sewage Sludge, Organic and Agricultural Wastes, 90-103.

[7] Hertle, C.K. and Lever, M.L. (1987), Mixing in Anaerobic Sludge Digesters, Water, March 1987, 16-20.

[8] Taylor, C. and Hood, P. (1974), Navier-Stokes equations using mixed interpolation, Proc. Int. Conf. On FEM in Flow Problems, 121-132.

[9] Baker, A.J. (1983), Finite Element Computational Fluid Mechanics, McGraw-Hill, London.

[10] FIDAP (Fluid Dynamic Analysis Package) manuals (1992), Manchester Computing Centre (MCC).

[11] Bird, R.B., Stewart, W.E. and Lightfoot, E.N. (1960), Transport Phenomena, John Wiley and Sons, New York.

[12] Schlichting, H. (1979), Boundary Layer Theory, McGraw-Hill.

[13] James, A. E. (1996), Personal Communications.

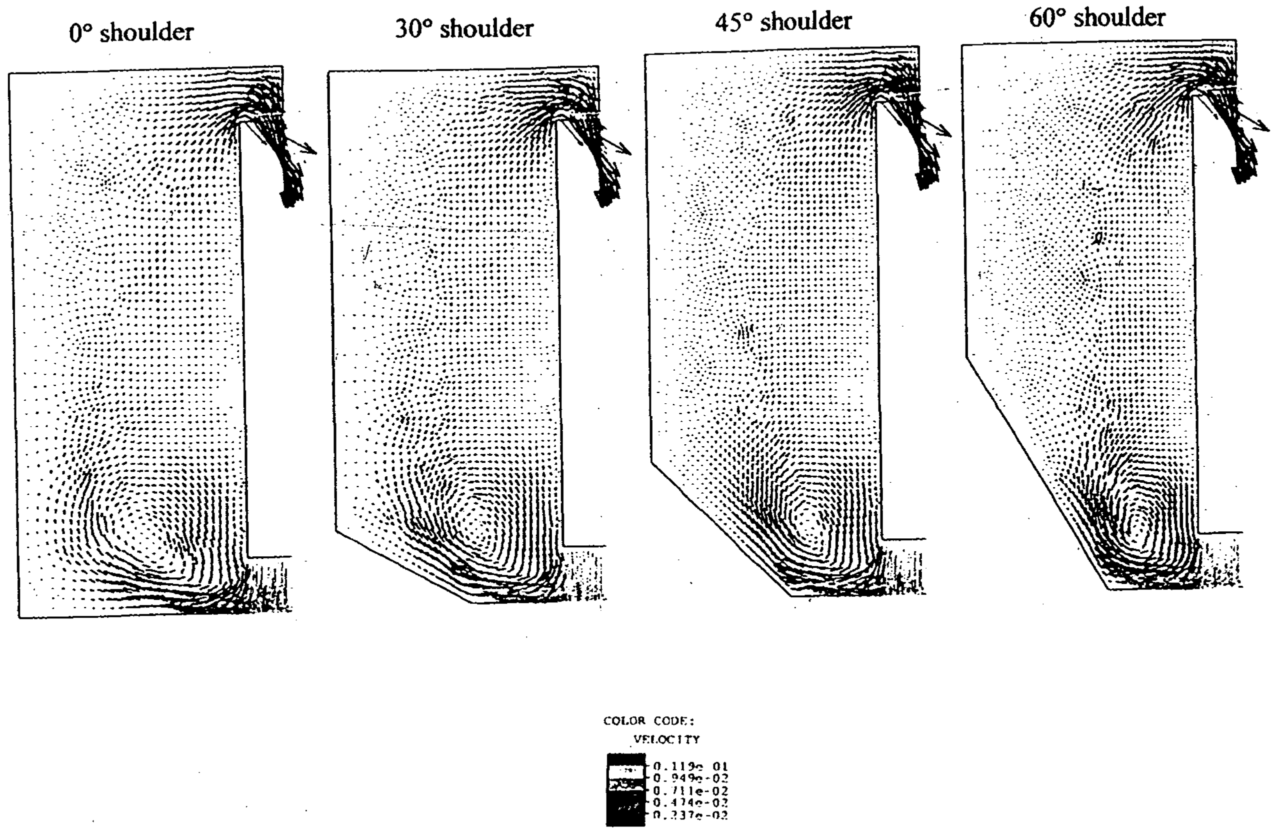

Fig. 2 Velocity vector plots in different tank shapes.

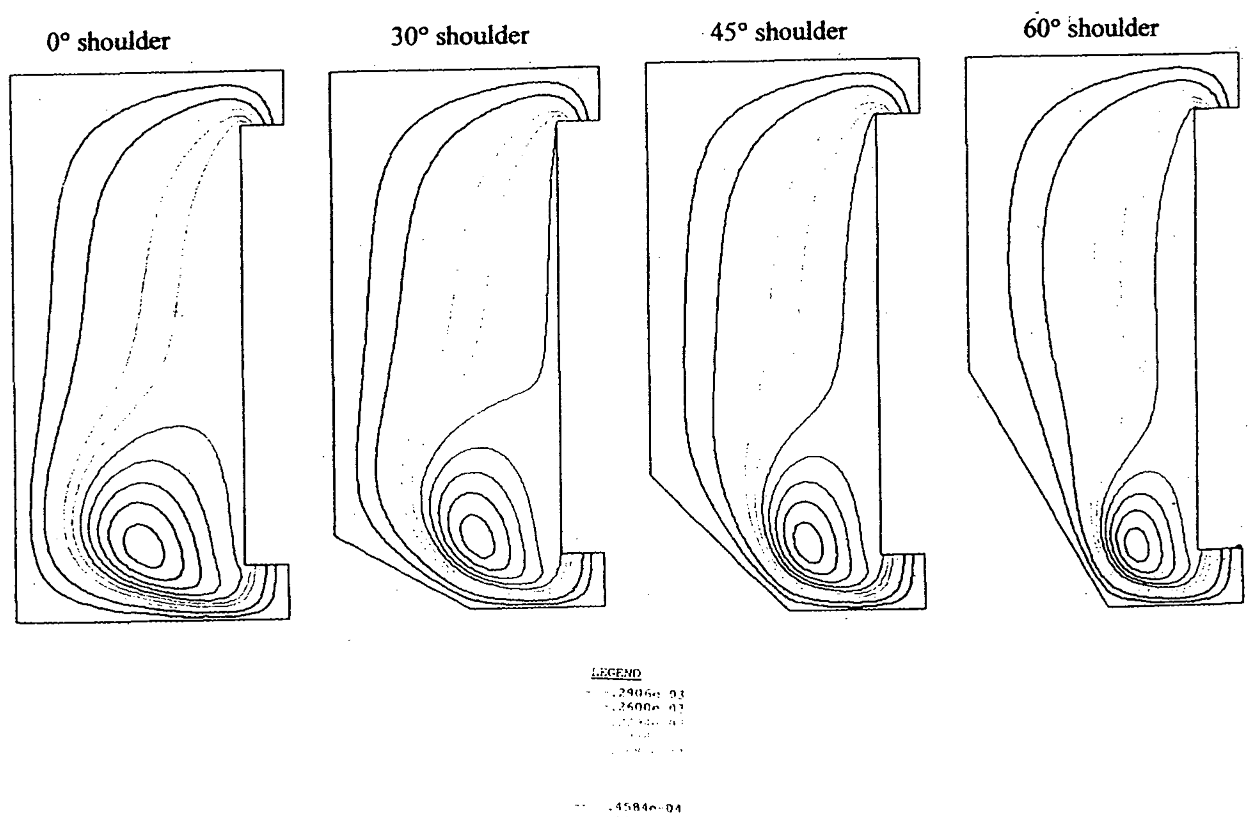

Fig. 3 Streamline contour plots in different tank shapes.

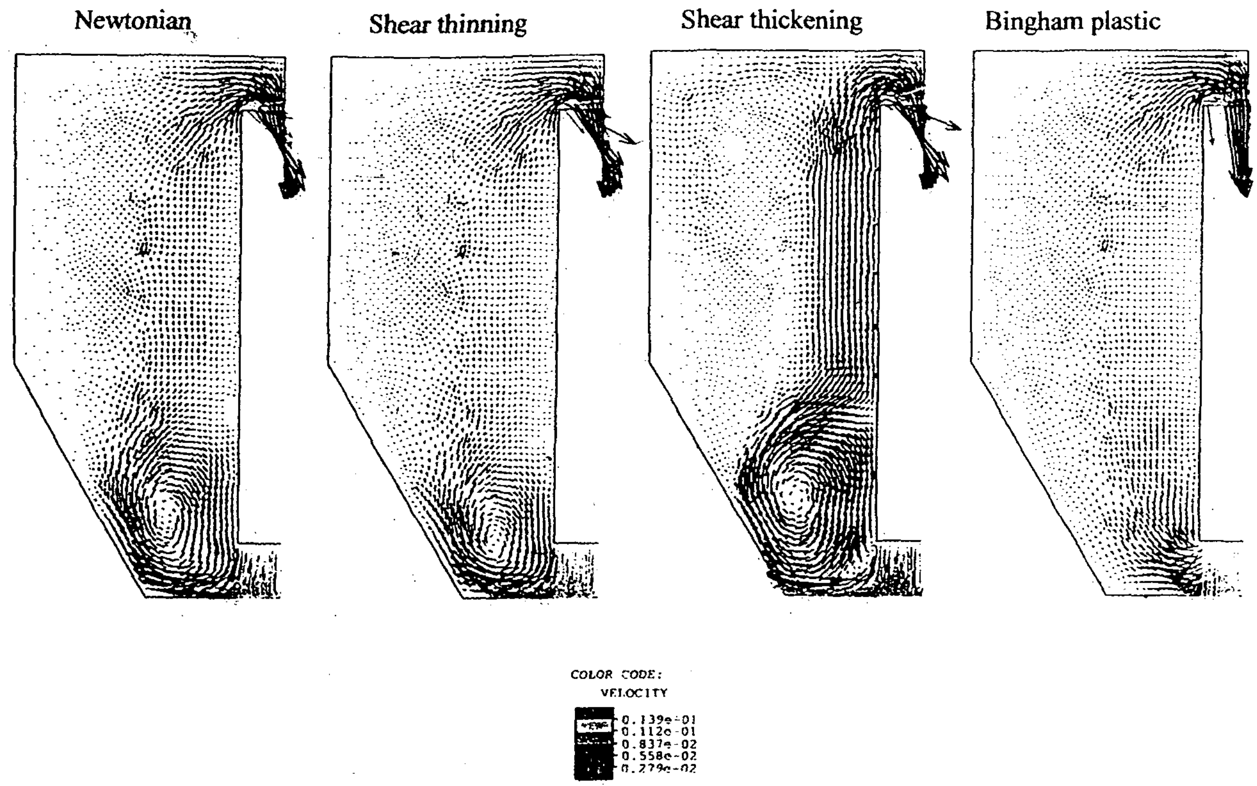

Fig. 4 Velocity vector plots of Newtonian and non-Newtonian fluids in anaerobic digesters.

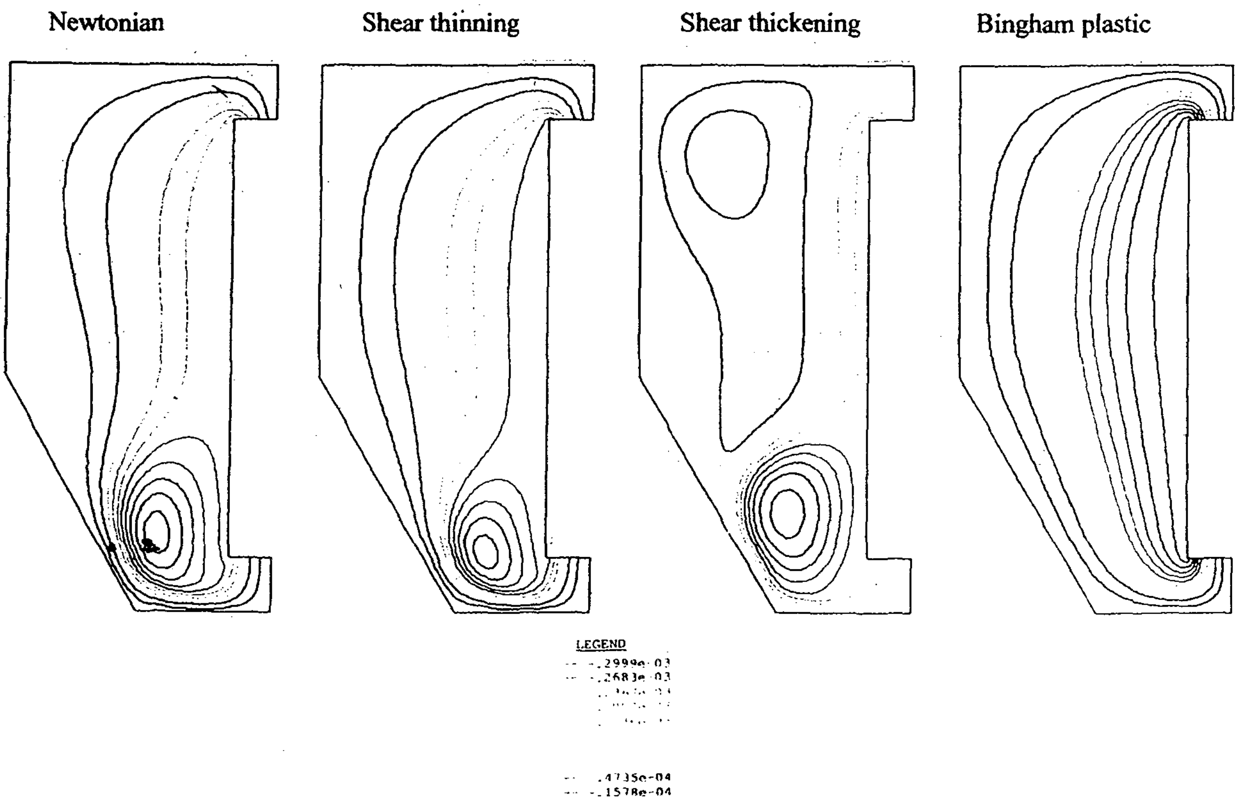

Fig. 5 Streamline contour plots of Newtonian and non-Newtonian fluids in anaerobic digesters.