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FLOW VISUALISATION AND VELOCITY MEASUREMENT IN A CLASSIFIER MODEL

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ABSTRACT

There are many industrial processes which rely on gravity to separate a particulate suspension from a fluid moving slowly through a container. When the requirement is to recover the particulate based on its size, the process is referred to as classification.

This investigation concerns a classifier in which particles suspended in a hot solution enter the classifier at the top, where the small particles and most of the liquid are directed to an overflow located on the rim of the tank. The remaining liquid and large particles are directed to an underflow at the bottom of the tank where they are drawn off.

In the current investigation, the effect on classification of the way the incoming flow is directed into the tank, and the effects of buoyancy and inertia forces on the flow patterns, are investigated. A scaled physical model has been constructed to enable visualisation of the flow patterns and the measurement of the flow velocities using streak photography. The model has been scaled geometrically and also dynamically using Reynolds number to characterise the momentum flow and Rayleigh number to characterise the buoyancy effects.

This paper describes the relative effects of momentum and buoyancy on the flow patterns and also reports on the effect of installing a modified diffuser within the tank. When the flow patterns are considered in conjunction with the velocity measurements, conditions that are likely to enhance classification efficiency can be identified.

INTRODUCTION

The purpose of this study is to observe the fluid flow patterns in a classifier model and make measurements of the flow velocities throughout the tank.

There are many industrial processes which rely on gravity to separate a particulate suspension from a fluid moving slowly through a container. When it is required to separate particles on the basis of their size, i.e. smaller than or larger than a specified size, this process is referred to as classification. Classifier efficiency is a measure of how sharply this separation is achieved and it is believed to be a function of the flow rate entering the tank, the geometry of the tank, the manner in which the incoming flow is introduced into the tank, and buoyancy effects (Salt and White, 1988).

Scientific investigation of the fluid flow in a full-size classifier is impractical, so a scaled model has been constructed to enable visualisation of the flow pattern using photographic techniques. Measurement of flow velocities were made in this study using streak photographs which were analysed to produce two-dimensional velocity profiles of the flow.

SCALING OF THE TANK MODEL

For bulk flows in a viscous incompressible fluid, the parameter normally used to model the fluid dynamics of forced flow is the Reynolds number (Re). This dimensionless group quantifies the ratio of the momentum forces to the viscous forces. When buoyancy forces due to density/temperature effects are present, a second dimensionless group (Rayleigh number (Ra)) is included. Ra quantifies the ratio of the buoyant forces to the viscous forces.

The relative contributions of buoyancy and forced flow on the overall flow structure is thought to be significant, hence the ratio of Re to Ra was made the same in the experimental model as for the full-size classifier. Table I lists the parameters of a typical full-size classifier tank and the scale model.

Table I. Operating characteristics of a classifier and experimental model under standard conditions

Item	Typical classifier	Experimental model
Overall height	25 m	2.3 m
Diameter	9.75 m	1.1 m
Liquid temp.	55°C	45°C
Tank wall temp. (typical)	54.9°C	42.75°C
Flow rate	227.0 L/s	1.0 L/s
Flow medium	Liquor	Water
Particles	Various	0.8–1.0 mm dia. polystyrene
Re (typical)	5.5×10^5	4.1×10^4
Ra (typical)	2.6×10^{11}	1.9×10^{10}

Geometric similarity between the classifier and the model was achieved, and the appropriate Ra to Reynolds number ratio was achieved by adjusting the temperature difference between the incoming fluid and the tank wall and the incoming flow rate. Ra and Re, as defined in eqns (1) and (2), allow us to characterise the large-scale or bulk flow patterns in the liquid.

$$Ra_d = g\,\beta\,(T_{inlet} - T_{wall})\,d^3\,\rho^2\,Cp\,\mu^{-1}\,k^{-1} \qquad Ra \qquad (1)$$

$$Re_D = D\,V\,\rho\,\mu^{-1} \qquad Re \qquad (2)$$

where
Cp = specific heat of the liquid ($kJ.kg^{-1}.K^{-1}$)
d = the diameter of the tank (m)
D = the diameter of the lance (m)
g = gravitational constant ($m.s^{-1}$)
k = liquid thermal conductivity ($W.m^{-1}.K^{-1}$)
T_{inlet} = inlet lance tip temperature (K)
T_{wall} = average tank wall temperature (K)
V = inlet velocity at the lance exit ($m.s^{-1}$)
β = liquid coefficient of expansion (K^{-1})
ρ = density of the liquid ($kg.m^{-1}$)
μ = dynamic viscosity (Pa.s)

DESCRIPTION OF THE EXPERIMENTAL EQUIPMENT

The tank model, control and data-logging equipment are shown schematically in Fig. 1. The tank model is a right cylinder with a conical bottom, the inflow occurs via a central lance with a circular baffle located beneath it. The overflow is a circular manifold located at the top of the tank. The underflow is taken off from the bottom of the cone. The inner cylindrical tank is surrounded by a square tank also filled with water. The

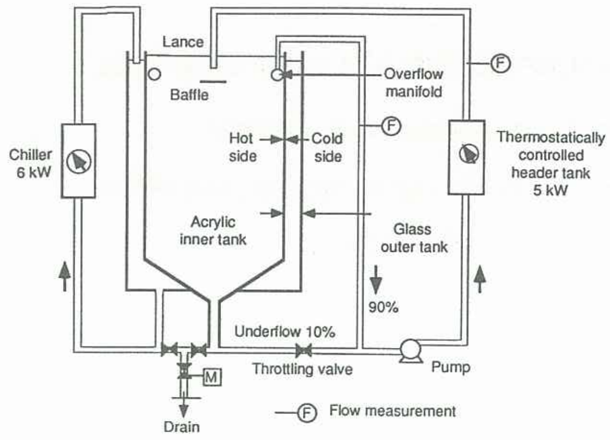

Figure 1. Experimental test facility.

outer tank serves several purposes: it balances the hydrostatic forces on the inner tank walls; it reduces optical distortion at the curved interface; it increases the temperature difference attainable between the bulk fluid and the wall (to increase the achievable Ra); and it enables a uniform temperature distribution to be achieved on the outer surface of the inner tank.

The cooling of the water in the outer tank is achieved by using a chiller set with a capacity of 6 kW, and the heating of the inlet water to the inner tank is achieved by pumping the water through a thermostatically controlled heating tank with a heating capacity of 5 kW. The pump used to circulate the fluid through the heating tank supplies the necessary velocity flows at the lance tip.

To observe the fluid flow patterns, the test tank (Fig. 1) was placed between air-cooled light boxes which produce a collimated light sheet approximately 7 mm thick, across the full height of the tank. The tank flow was then 'seeded' with 'neutrally buoyant' tracer particles chosen to follow the fluid flow in the classifier. The tracers comprised spheres of unexpanded polystyrene of 0.8–1.0 mm diameter and average specific gravity of 1.03. The motion of these particles was viewed from a position at right angles to the light sheet.

Temperatures and flow rates were recorded using a datalogger controlled by an XT IBM-compatible computer. The temperature transducers were copper constantan thermocouples and the total flow rate and overflow rate were measured using paddlewheel-type flow meters located as shown in Fig. 1; the underflow is thus obtained by difference.

Streak photographs were taken to enable velocity profiles to be calculated. In this process the length of a streak is measured using a digitising tablet and stored in a computer, the velocity is then calculated by dividing the length of the streak by the time of exposure. The streak length is calibrated against known dimensions of the lance and baffle.

EXPERIMENTAL PROCEDURE

Typical classifier operating conditions are shown in Table I. Also fixed but not listed is the ratio of the overflow to the underflow.

There are assumptions made when interpreting the flow patterns and calculating the velocity profiles within the tank: the flow is axisymmetric and steady, and the velocities measured are the two-dimensional component of the flow present. Given these conditions, the following experimental program was devised:

(1) For the typical condition, infer classification performance from the flow patterns.
(2) Investigate the effects of momentum and buoyancy on the model classifier flow patterns by varying the inlet velocity and the inlet to tank temperature difference.
(3) Investigate a modified lance in the form of a simple conical diffuser.

RESULTS AND OBSERVATIONS

In the results that follow, 'Temp. inner' refers to the mean water temperature down the centre of the inner tank, and 'Temp. outer' is the mean temperature of the water in the outer tank. The following description of the flow structure is subjective. It is based on photographs and direct observations made by the experimenter. Where possible and when it was considered appropriate, local velocities were calculated from streak photographs to complement the visual observations.

<u>Typical Lance-Baffle</u>

The typical lance and baffle arrangement used for photos Al–A3 is shown in Fig. 2. The overflow for all experiments is maintained at 90% of the inlet flow rate.

Photo A1 Inlet flow = 1.0 L/s Overflow = 0.9 L/s
Temp. inner = 45°C Temp. outer = 20°C

(a) The flow above the baffle is relatively clear indicating few particles in this region. Flow moves up each outer wall and then inwards, creating a recirculating annular cell.
(b) From the baffle down to the mid-height of the test tank the flow leaves the baffle and angles down slightly towards the wall (angle approx. 5°). When the flow strikes the wall it breaks into two streams, one proceeds down the wall to about half depth and then rotates inwards towards the central axis. The cellular motion observed is a two-dimensional section of a three- dimensional axisymmetric flow. The second stream gives rise to the flow described in (a). The central region of flow under the baffle does not display any preferred direction of flow, it is confused. This region is considered to be well mixed.
(c) In the bottom of the tank the particles fall more or less uniformly towards the bottom of the tank, and classification or thickening is quite pronounced.

Photo A2 Inlet flow = 2.0 L/s Overflow = 1.8 L/s
Temp. inner = 45°C Temp. outer = 20°C

(a) Above the baffle the flow is again relatively clear but with perhaps more particles in this region, and the cells appear to be rotating at higher speed.
(b) In the centre region, flow comes off the baffle as previously but penetrates slightly deeper down the walls of the test tank. Two recirculating cells are established one either side of the central axis of the tank, the cells rotate inwards towards the central axis. The cells are better defined and

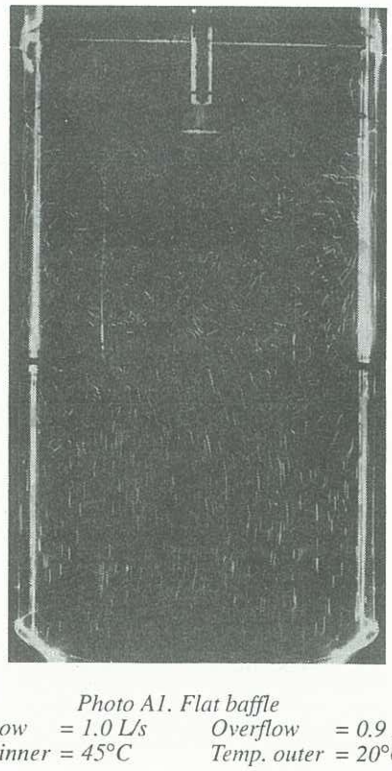

Photo A1. Flat baffle
Inlet flow = 1.0 L/s Overflow = 0.9 L/s
Temp. inner = 45°C Temp. outer = 20°C

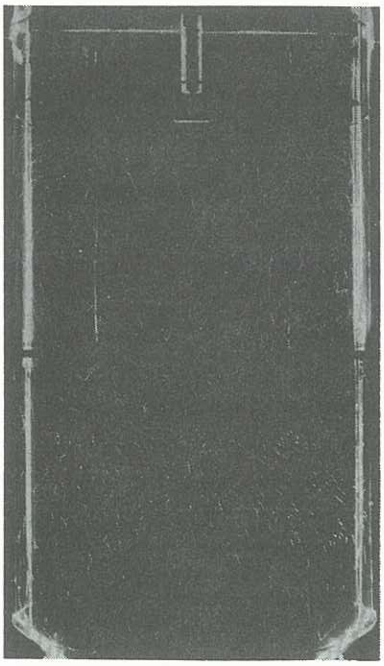

Photo A2. Flat baffle
Inlet flow = 2.0 L/s *Overflow = 1.8 L/s*
Temp. inner = 45°C *Temp. outer = 20°C*

rotating more vigorously than in Al. The centre region of the tank has strong up-welling beneath the baffle.

(c) The bottom region of the flow is quite different to Al, there is a weak downward flow along the tank walls to 75% of its total depth. The central section in the tank is confused and well mixed as in Al. The settling region only exists in the central bottom 20% of the tank.

These first two photographs show that the flow structure is sensitive to the inlet flow rate, or Re. When Re was increased, the central well-mixed region occupied more of the tank (the lower boundary moved further down), and the recirculation within this region became much stronger.

The next experiment was designed to assess the relative sensitivity of the flow to Ra. This was achieved by varying the temperature difference between the centre of the inner tank, to the inner tank wall, while keeping the flow rate fixed.

Photo A3 Inlet flow = 1.0 L/s Overflow = 0.9 L/s
Temp. inner = 21.5°C Temp. outer = 20.9°C

This experiment reduces Ra by reducing the temperature difference between the incoming fluid and the inner wall of the tank.

(a) The recirculating cells above the baffle are similar to those in Al.
(b) The inwardly rotating cells in the central region are more clearly defined than Al and extend further down into the tank. Up-welling below the baffle is very vigorous and extends from mid-tank to the baffle.
(c) Settling occurs in the bottom 25% of the tank.

From an inspection of Al and A3 it is clear that both buoyancy (Ra) and momentum (Re) influence the fluid flow structure. Re clearly has the largest effect on the flow, although buoyancy does modify the flow structures somewhat and cannot be ignored. This conclusion is lent further weight when the velocity profiles for Al and A3 are compared.

In the typical case Al, the velocities in the well-mixed central region are typically 5–10 mm/s and there is no preferred direction of flow. The settling velocity at the bottom of the tank is approximately 6–12 mm/s. At double the flow rate A2, the up-welling speeds are up to 30 mm/s but the settling speeds are unaffected.

For A3 the up-welling velocity under the baffle is typically 7–14 mm/s and the settling velocity at the bottom of the tank is approximately 4–7 mm/s. As A3 has a lower buoyancy component than A1, one would intuitively expect the settling velocity for A3 to be higher. However, this is contrary to observation and no plausible explanation is available.

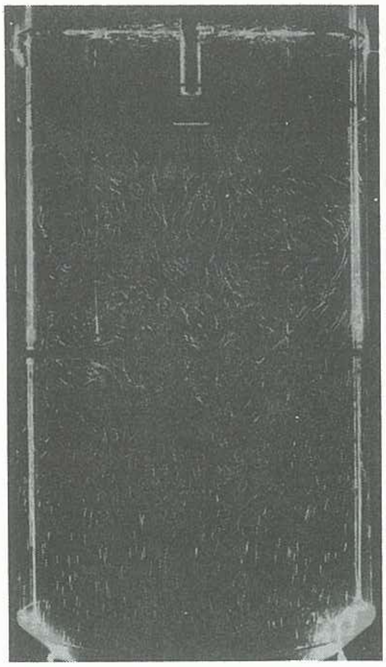

Photo A3. Flat baffle
Inlet flow = 1.0 L/s *Overflow = 0.9 L/s*
Temp. inner = 21.5°C *Temp. outer = 20.9°C*

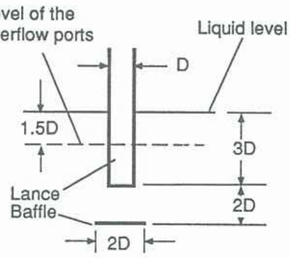

Figure 2. Flat baffle – typical configuration.

It is interesting to compare measured settling rates with theoretical settling rate for still fluid at standard conditions. For the tracer particle chosen, the settling rate is 12 mm/s (Beer, 1990). It should be noted that due to uncertainties in both the tracer particle diameter and tracer particle density, uncertainties in calculating terminal settling velocity of ±55% can occur. This means that the terminal velocity calculated for our tracer particle could be as low as 5.4 mm/s for some small and low density particles.

Conical Diffuser-Flat Baffle

To reduce the flow velocity at the lance exit, a simple cone diffuser was designed and attached to the end of the lance (Fig. 3).

Photo A4 Inlet flow = 1.0 L/s Overflow = 0.9 L/s
Temp. inner = 45–42°C Temp. outer = 20°C

In this configuration the lance has a conical diffuser on the end, and the standard baffle design is retained.

(a) There is no flow visible above the baffle.
(b) There is a well-mixed region with recirculation under the baffle extending across the full width of the tank and extending to approximately 20% of the tank depth. The depth of this region is substantially less than for the standard lance and baffle design.
(c) In the lower 80% of the tank the tracer particles fall uniformly to the bottom.

Photo A5 Inlet flow = 2.0 L/s Overflow = 1.8 L/s
Temp. inner = 45–43°C Temp. outer = 20°C

(a) The flow above the baffle is symmetric. It comprises one recirculating cell on either side of the lance. Particles are clearly entrained and move into the overflow.

(b) There is a well-defined central fully mixed region with recirculating cells.
(c) As before there is up-welling present under the baffle.
(d) The particles in the lower settling region of the tank fall uniformly from half the tank depth to the bottom of the tank. The flow is similar to the standard configuration at the typical flow rate.

In A4 the settling velocity was 8–12 mm/s, which is the same as the standard configuration. The settling velocity in A5 is 9–11 mm/s, which is again comparable to the standard configuration at twice the standard flow rate.

DISCUSSION

The aim of these experiments has been to observe and measure the flow structure for a typical lance and baffle configuration and investigate a simple geometry that is likely to achieve improved classification.

It is clear that for both inlet geometries considerable large-scale turbulence is present in the test tank, and this turbulence tends to keep the particulate in suspension and impede the settling of larger particles. The turbulence is due to momentum transfer from the incoming fluid to the bulk of fluid already in the tank, and free convective forces resulting from differences in temperature between the incoming fluid and the temperature at the inner wall of the tank.

The first three photographs (Al–A3) show that for the classifier operating at typical operating conditions, reasonable classification is achieved. When the flow rate is increased, greater turbulence is produced and particles are observed being drawn off by the overflow, indicating a drop in classification performance. The results show that the flow structure is primarily influenced by the momentum effects, but a comparison of photograph Al with photograph A3 indicates that buoyancy effects are also important and should not be ignored. The effects of buoyancy can be seen in two ways: firstly, by inspection the flow patterns in the two photographs are substantially different; and secondly, the terminal settling velocity for photograph Al is 6–12 mm/s and the terminal settling velocity for photograph A3 is 4–7 mm/s. For the conical diffuser settling regions in the bottom of the tank have been observed for all flow rates in this configuration and hence any interaction between the falling particles and the product lying on the bottom of the tank is minimised.

The flow structures observed are believed to be an improvement over the typical case, but at high inflow rates classification would be degraded due to the presence of large particles carried into the upper region.

CONCLUSIONS

(1) The model classifier in the typical configuration has three zones in the flow structure.
(2) Increasing the inflow rate increases turbulence in the central well-mixed region and degrades classification performance.
(3) Buoyancy forces modify the flow patterns but their effects are secondary compared to momentum effects.
(4) A conical diffuser tip on the lance improves classification.

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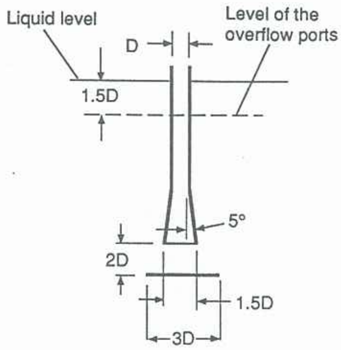

Figure 3. Conical diffuser.

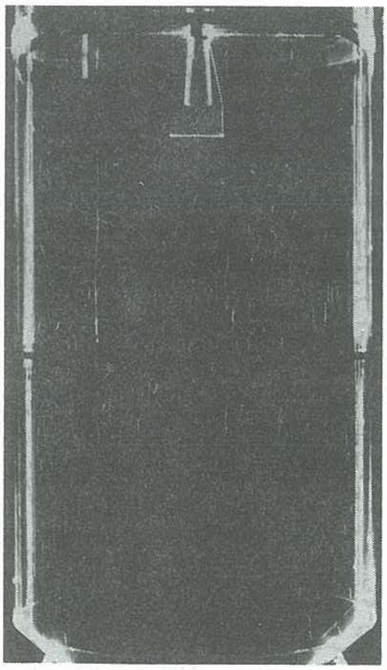

Photo A4. Conical diffuser
Inlet flow = 1.0 L/s Overflow = 0.9 L/s
Temp. inner = 45–42°C Temp. outer = 20°C

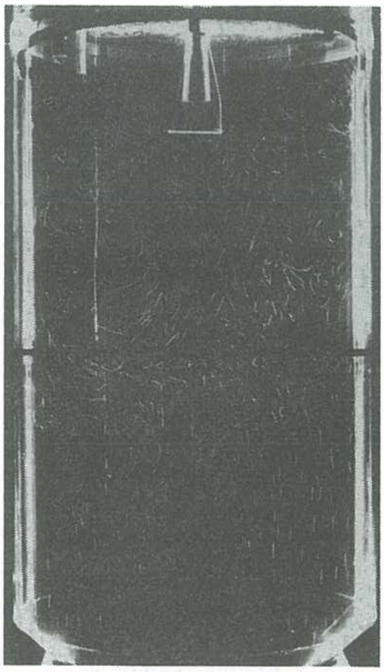

Photo A5. Conical diffuser
Inlet flow = 2.0 L/s Overflow = 1.8 L/s
Temp. inner = 45–43°C Temp. outer = 20°C