Rheological characterisation of mineral slurries using balanced beam tube viscometry

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Synopsis

The efficient and accurate design of pipe and pumping plant for non-Newtonian mineral slurries remains a problem. The objective of this paper is to present the development of the Balanced Beam Tube Viscometer (BBTV), an instrument which could facilitate more accurate design for these slurries. The background of rotational and tube viscometry is reviewed and the fundamental principles and inherent advantages of the BBTV are given. The design, data acquisition and processing techniques are introduced and results showing the reliability of the new instrument are presented and discussed. It is concluded that the BBTV is a reliable and versatile instrument for both routine analyses and research work, and has the potential to provide data for the refinement of the design procedure for mineral slurry pipe and plant design.

Introduction

Transport of solid materials in pipes is extensively used in a wide range of industries, such as the mineral, oil and food industries. Although non-Newtonian slurry pumping is common in the mining industry, efficient design of pipe and pump plant for industrial and mining slurries remains a problem (Slatter, 1994). However, apart from large-scale pipe tests, there is no well established design method. Mun (1988) and Shook & Roco (1991) have shown that theoretical models yield different results when modelled to a particular slurry. Moreover, models become even more inconsistent when tested against a wide range of slurries. Hence, it is important to test the slurry to be used under design conditions in order to determine the pressure gradient and to establish the behaviour of the slurry before the design of the pipe-line can commence.

Rheological characterisation is important in designing pipeline systems and involves the measurement of shear stress in a fluid at various shear rates. The most common and reliable technique used to test slurries is that of large-scale pipe tests in which prototype pipe systems are used. The results obtained are reliable, but the test method is expensive due to the time factor involved and the size of the equipment. Furthermore, disadvantages such as particle degradation and temperature rise, normally associated with closed-loop pipe test rigs, create a further problem in establishing reproducible results which are correct.

It is the objective of this paper to develop a new test apparatus which is a reliable test viscometer, and which can solve many of the disadvantages encountered by pipe test rigs. It will also be shown that this apparatus, called the Balanced Beam Tube Viscometer (BBTV), can be used beyond viscometry, and is, in effect, a miniature pipeline and valid pipeline flow data can be obtained directly from it. This data can then be used for the design of non-Newtonian slurry pipeline systems with a greater degree of confidence than was previously available.

Background

Viscometry can be defined as the collection of physical data from tests on a sample of the fluid under investigation for the purpose of establishing the relationship between shear stress and shear rate. The instrument used to measure viscous properties is called a viscometer. There are two main types of viscometer—rotational and tube. The rotational viscometer usually consists of a concentric bob and cup, one of which is rotated to produce shear in the test fluid, which is located in the gap between the bob and cup. The shear stress is determined by measuring the torque on one of the elements, and the shear rate is determined from the relative angular velocity between the elements and the measuring gap. A tube viscometer is essentially a small diameter pipeline. The test

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fluid flows at a controlled, measured rate through the tube and the pressure drop over a known length of the tube is measured.

Although there are many advantages to using the rotational type, for non-Newtonian slurries the tube type of viscometer is preferred (Lazarus & Slatter, 1986; Shook & Roco 1991 and Wilson *et al.*, 1992). The main difficulties associated with the rotational viscometer is that relatively low shear rates are achieved and centrifuge action can occur in the measuring gap (Johnson, 1982; Slatter, 1986 and Shook & Roco, 1991). Centrifuge action causes the readings to decay with time, resulting in the erroneous identification of time-dependent (thixotropic) behaviour. Interpretation is further complicated by end effects. On the other hand, the tube viscometer is mechanically simpler, is geometrically similar to a pipe, and is in fact a miniature pipeline (Slatter & Lazarus, 1988). Ideally, test work for the prediction of turbulent energy gradients from rheology should be performed so that the wall shear stress in laminar flow for the tests is the same as the wall shear stress in the prototype in turbulent flow. This is usually not possible as the flow becomes turbulent at these higher shear stresses and flow rates, even for small diameter tube viscometers (Shook & Roco, 1991). Therefore, the rheology obtained is extrapolated, sometimes by several orders of magnitude, to arrive at the required shear stress. The accuracy of the rheological measurements and characterisation is therefore of utmost importance. For this reason it was decided to use as many different diameter tubes as possible. This is also desirable for experimental investigation into the effect of diameter on the laminar/turbulent transition and for scaling of turbulent flow data.

The balanced beam tube viscometer (BBTV)

The fundamental principles of the BBTV are as follows. The instrument consists of two pressure vessels which are located at either end of a steel beam, as shown in Figure 1. This beam is centrally supported on a knife edge and a load cell is located under the left-hand vessels. The load cell reading will indicate the mass distribution of the test fluid between the two pressure vessels. The vessels can be connected by transparent tubes of different diameter. The prime mover is compressed air which forces the slurry through a selected tube at a controlled rate. The load cell output is logged at regular time intervals and the average slurry velocity is obtained from the mass transfer rate. The pressure drop across a known length of the tube is measured using a differential pressure transducer. A 'run' is defined as the collection of a set of force, time and pressure readings. These are transformed into a single co-ordinate of$[V;\Delta p]$. A series of runs will comprise a 'test'. All the test section entry lengths can be changed to detect undeveloped low or time dependency.

The flow rate of the fluid in the selected tube is measured directly from first principles—literally by weighing the fluid transported through the tube over a given time interval. This has two incisive advantages. Firstly, the problems and errors inherent in the calibration and use of a secondary transducer such as a magnetic flux flow meter are eliminated (Heywood *et al.*, 1993) and secondly, there is in theory, no quantitative limitation on the flow rates that can be measured.

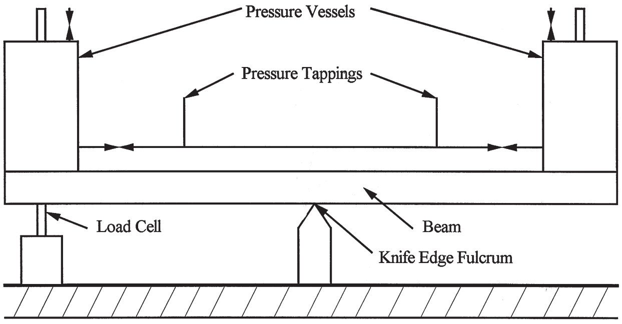

Figure 1—Schematic diagram of the balanced beam tube viscometer

Momentum transfer

As the test fluid is forced from the one vessel to the other through a selected test tube, there will be accelerations of the fluid which will give rise to unbalanced forces. However, due to the symmetry of the instrument, these forces will be equal and opposite, and will remain constant once steady state as been reached. Since it is only the rate of change in force which is used to determine the flow rate, this quantity remains constant over the course of a run. Accurate determination of flow rate is thus obtained.

Analysis techniques

The literature (Govier & Aziz, 1972) recommends that tube viscometer data be transformed using the Rabinowitsch-Mooney relation. However, this method has been found to have practical problems (Lazarus & Slatter, 1988), and the technique presently used is to fit the laminar pipe flow equation directly to the tube data (Lazarus & Slatter, 1986 and Neill, 1988) using 'least squares error' techniques.

Conceptual design

There are three basic parameters which affect the conceptual stage of the design. Firstly, the volume of the pressure vessels must be decided upon. This will be influenced by three factors—the diameter of the largest tube, the highest expected velocity in this tube and the minimum time required to perform a run. Secondly, the maximum air pressure required for the system must be arrived at. This will be determined by the pressure gradient and length of the smallest tube. Thirdly, the total length of the instrument will be fixed by the minimum entry and maximum test lengths required for the largest tube.

Once these three parameters were fixed, detailed design could continue. In order to make the final decisions, heavy emphasis was laid on previous operational experience. The largest tube diameter was influenced by the experience of Shook (1995) who found that the most useful diameter for test work was 50 mm. The minimum time required for a run of reasonable accuracy is known from previous test work to be approximately 10 seconds, and the previous speed record in the BBTV was 10m/s (Neill, 1988). This fixed the volume of the pressure vessels at approximately 200 litres.

Previous operational experience indicated that 6 mm would be the smallest practical tube diameter, which results in an overall tube length, including entry lengths and test length, of about 2,5 m, requiring approximately 10 bar air

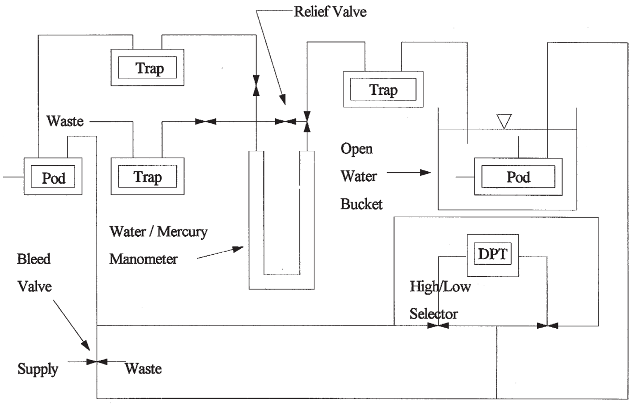

Figure 2—Fluid circuit diagram for calibration of the DPT on the BBTV

pressure for a velocity of 10m/s. The largest diameter of 50 mm results in an overall tube length of approximately 7 m, including entry lengths and test length. The detailed design of the pressure vessels was then specified for a working pressure of 10 bar. From practical considerations and given the above range of tube diameter, the maximum number of test tubes was decided as four, and the middle two tubes were chosen logarithmically between 50 mm and 6 mm. Tubes of four different diameters are used. The different diameters are 6, 13, 28 and 46 mm. The tubes are made of clear reinforced PVC. The tubes are transparent to allow the operator to actually see the change in flow patterns from laminar to turbulent flow.

Two pairs of pressure tappings are located on each pipe section. This arrangement allows for flexibility. The tappings are located at least 50 pipe diameters from each obstruction. This is done in order to allow the flow to be fully developed before the pressure drop readings are measured and to avoid the measurement of entrance and exit losses.

BBTV manometer

The fluid circuit diagram of the Differential Pressure Transducer (DPT) is shown in Figure 2. This fluid circuit facilitates flushing of air and slurry from the circuit using municipal supply water. Calibration is done using the water/mercury manometer.

Data acquisition and processing techniques

Data from the BBTV is collected electronically via a Data Acquisition System. The data are then processed to give the final major measured variables of average velocity and pressure difference.

The data acquisition system consists of a computer, data acquisition unit and transducers. The data acquisition unit measures the load cell and differential pressure transducer voltages. Thus, the primary output from the viscometer consists of successive voltage readings representing load cell output and DPT output. These outputs are logged at regular time intervals.

Processing techniques

The load cell determines the slurry mass distribution between the two vessels. A typical flow measurement consists of a number of readings of mass and time. The slope of a least squares linear regression on these data yield the mass flow rate. The differential pressure transducer output is also logged each time the load cell output is logged. The average of the pressure differences computed from these readings is taken as the pressure difference across the tube pressure tappings.

Raw data

Raw data and its processing is shown in Figures 3 and 4. The data are presented as a plot of mass versus time and pressure drop versus time. A linear regression is performed on the mass/time co-ordinates, and the slope of the regression line is used to determine the flow rate. The average value of pressure ordinates is used as the pressure drop.

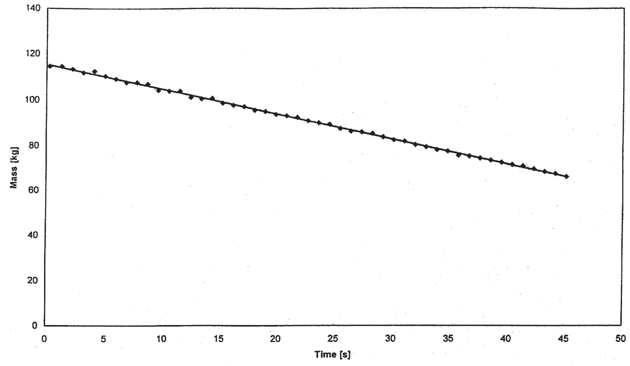

Figure 3—BBTV output of mass versus time

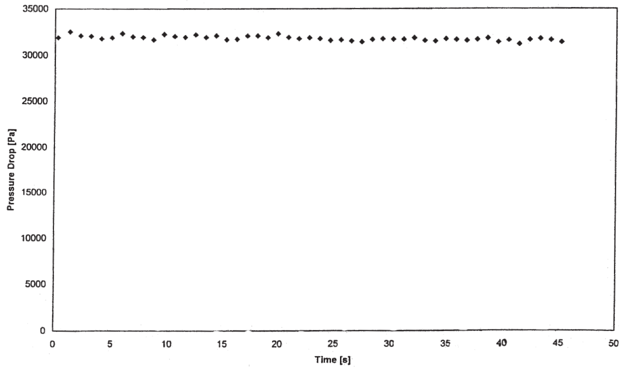

Figure 4—BBTV output of pressure drop versus time

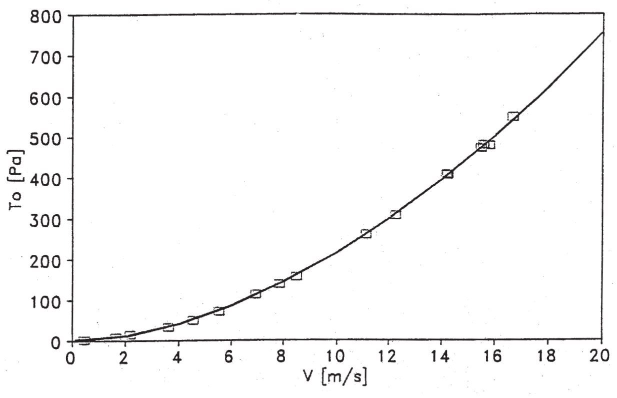

Figure 5—Clear water test results in the 13 mm tube

Results

Clear water tests

Whenever a series of tests is commenced, initial tests are conducted on the instrument using clear water. These tests are essential to ensure that the instrument hardware and software as a whole is functioning correctly and reliably. Clear water test results are shown in Figure 5.

Figure 5 shows the clear water data points plotted against the predictions of the Colebrook/White equation. It can be seen that the instrument is in fact performing reliably. Tests on the fittings also indicate that losses measured in the BBTV agree closely with those published in the literature for water.

Water tests

The main reason for water tests is actually the final acid test as to whether all the foregoing arguments in favour of the BBTV are in fact valid. The point of the argument is that if the BBTV can produce accurate and precise test results with clear water, for which the results can be theoretically predicted with considerable confidence, then the instrument is in fact working as planned. The BBTV does produce accurate and precise test results with clear water over wide ranges of flow conditions. It is therefore a valid test apparatus.

Slurry tests

Figure 6 shows typical slurry test results. This particular test was for a kaolin slurry with a relative density of 1,18 in the 6mm tube. The classical non-Newtonian laminar and turbulent slurry flow regimes can easily be identified in Figure 6.

The increased number of tubes enhances the reliability of rheological characterisations. One of the advantages of the BBTV over a pipe test loop is that a large number of data points in laminar flow can be captured without significantly changing the material properties. Rheological characterisations are therefore more accurate. Also, having more diameters, the BBTV produces more information for the scaling of the laminar/turbulent transition and turbulent flow data. The laminar/turbulent transition point is vitally important for designers to know (Slatter, 1995), otherwise settling and pipe blockage will occur (for unpredicted laminar flow)—or unexpectedly high wear rates will occur (for unpredicted turbulent flow). Meaningful turbulent flow data—which are impossible to obtain using a rotary viscometer—are also of vital importance for the slurry system designer. This data can be used to confirm theoretical predictions, as well as yield data for particle roughness turbulence analysis (Slatter *et al.*, 1996 and 1997a)

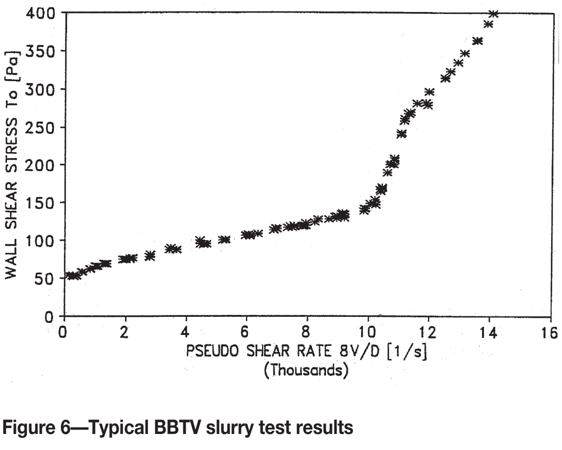

Figure 6—Typical BBTV slurry test results

The increase in tube diameter enables the capture of more realistic turbulent pipe flow data. Shook (1995) has shown that from many years of experience with the testing of mineral slurries, the 50 mm diameter tube is probably the most useful.

The disadvantages which the BBTV has is that it is limited to a maximum pipe diameter of 50 mm, and it requires a minimum sample of 200 litres for a test. Also, it is unlikely that the BBTV would be able to detect time dependent behaviour which has a relatively long time constant. However, it is a versatile instrument in that accurate headloss and visual flow data can be collected over wide ranges of diameter and velocity for laminar, laminar/turbulent transition and turbulent tube flow and for fittings. It is rare, if not unique, to be able to combine all these features in a single instrument. The BBTV, is therefore, useful not only for routine rheological analyses and characterisations—as its name implies—but it is also a valuable and versatile research tool.

Conclusions

It can be concluded that the BBTV is a reliable instrument and can be used to generate head loss data for homogeneous mineral slurries over wide ranges of laminar and turbulent flow. This will facilitate much needed research in this area in the quest for reliable theoretical models. The major developments in the second generation BBTV are an increase in the number of tubes of four, an increase in maximum tube diameter to 50 mm and a facility to measure head loss in pipe expansions, contractions and bends. The increased number of tubes enhances the reliability of rheological characterisations and produces more information for scaling of laminar/turbulent transition and turbulent flow data; the increase in tube diameter enables the capture of more realistic turbulent pipe flow data; and the fittings loss facility allows the collection of shock loss data for slurries of precisely known rheology.

Acknowledgements

The authors wish to acknowledge MINTEK, the Foundation for Research and Development and SOMCHEM for their support of this research.

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The Department of Chemical Engineering at the Cape Technikon

The Cape Technikon is a tertiary institution with a proud tradition and distinctive character. Situated on the Zonnebloem campus, the Cape Technikon has a breath-taking view of Table Mountain. The Technikon traces its origin to the Cape Technical College of which the foundation stone was laid in 1920. The establishment of this college followed more than 10 years of representations by the community for the consolidation of the technical courses which were offered at various venues in town. The Science Building, housing the Department of Chemical Engineering, was commenced in 1988.

The Department of Chemical Engineering started in 1978 with only one full-time lecturer. It has now grown to four full-time lecturers, one technician and three technical officers. The department offers qualifications in the form of National Diplomas (ND), Bachelor Degrees (B.Tech), Master’s Degrees (M.Tech) and Doctorates in Technology (D.Tech).

The Department of Chemical Engineering has been involved in research for many years, but the manpower was always a barrier. However, research flared up in 1992 when better facilities allowed students to carry out their in-service training at the Technikon, enabling more industry-related research. A wide variety of research topics are being covered in the Department of Chemical Engineering. Research projects are chosen such that the output is valuable to industry, hence the majority of the projects are sponsored by industry.

The main areas of research include:

- Environmental Engineering, which focuses amongst others, free cyanide removal from plant effluent using impregnated carbon, heavy metal removal via ion exchange, and an alternative process for free gold, i.e. the coal-gold agglomeration process.
- Adsorption processes with the emphasis on process adsorption and their interaction with adsorbates such as metal cyanides, organic compounds, inorganic substances, free cyanide, etc. The department continues to contribute to the knowledge of adsorbent-in-pulp systems for the South African minerals industry.
- Membrane Bioreactors and their applications in the field of minerals processing and chemical engineering.

Industrial involvement includes industries such as Karbochem, Eskom, Kynoch, Sasol, Billiton, Crusader Systems, Chamber of Mines, as well as government para-statal bodies such as Mintek, the Foundation for Research Development (FRD), and the Council for Scientific and Industrial Research (CSIR).

The department is heavily involved in activities of the South African Institute of Mining and Metallurgy (SAIMM), and is co-organiser of the Annual Mineral Processing Symposium.

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Department of Chemical Engineering
University of Stellenbosch

General

The University of Stellenbosch is situated in scenic surroundings in Stellenbosch and traces its origin to the Stellenbosch Gymnasium which was founded in 1866. The Stellenbosch Gymnasium became known as the Victoria College in the following year which marked the 50th anniversary of Queen Victoria's reign. The college achieved university status in 1918 and was renamed the University of Stellenbosch, the first Afrikaans university in the country. Today the university has 12 faculties and more than 16 000 students of which Faculty of Engineering has approximately 1400 students and the Department roughly 200 students.

The Faculty of Engineering was established in 1944. The original Departments of Civil, Mechanical and Electrotechnical Engineering, today known as Electrical and Electronic Engineering, and Applied Mathematics, were later augmented by the Departments of Chemical, Metallurgical and Industrial Engineering. The Faculty is housed in large modern buildings and has fine teaching and research laboratories.

Bachelor degrees have been awarded in the Department of Chemical Engineering since its inception in 1969. The Department offers two degree programmes, i.e. Chemical Engineering and Chemical Engineering with Mineral Processing as an option. The Department has a wide range of research and teaching interests and is supported by the well-developed infrastructure of the university, including the library system, computer centres and analytical and other laboratory equipment. In 1994 the Departments of Chemical and Metallurgical Engineering merged to form the Department of Chemical Engineering. The Department is involved in the activities of the Western Cape Branch of SAIMM since its inception as well as the organization of the Annual Mineral Processing Symposium.

Research Programmes

The Department is actively involved in diverse research programmes covering a wide spectrum of industrial activities, the majority of which are sponsored by industry. Figure 1 shows the main research areas and their interrelationship. Besides the industrial orientation of research, the Department maintains close ties with other academic institutions, both locally and internationally.

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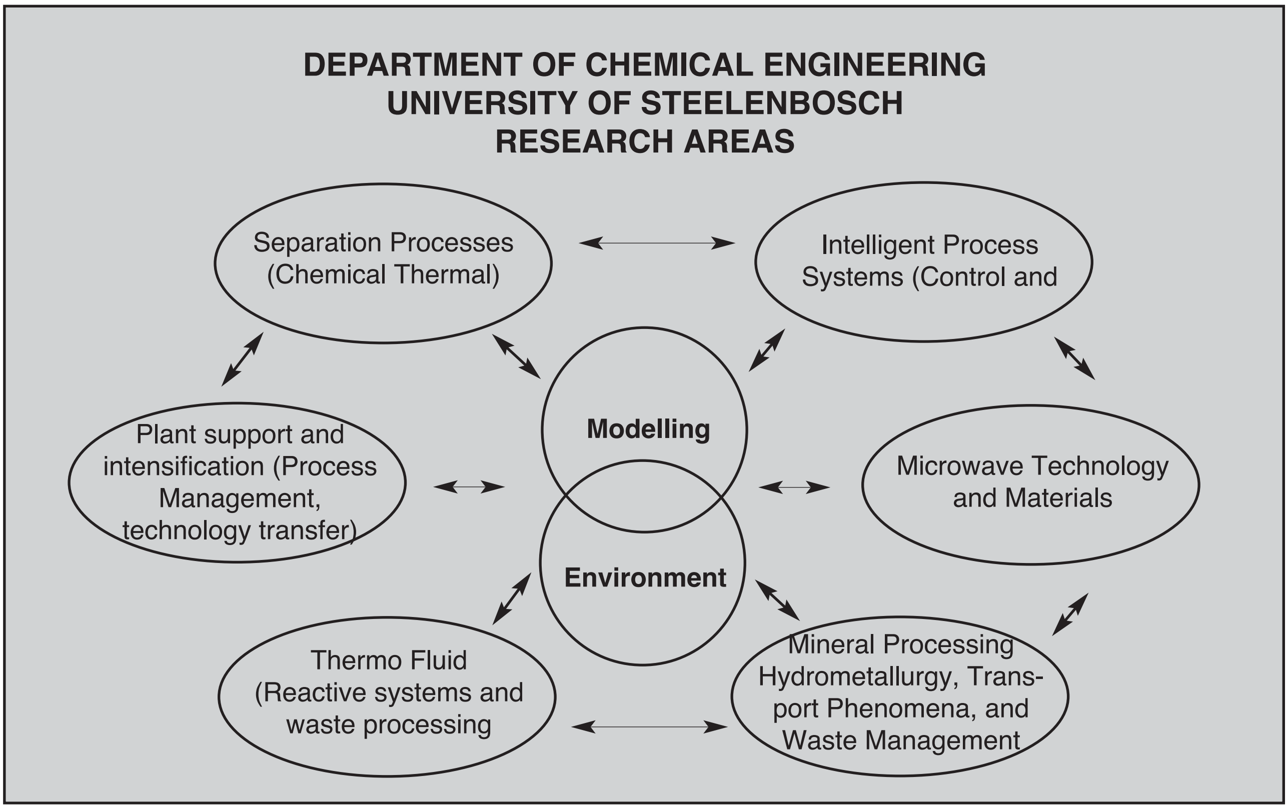

Figure 1—Diagrammatic representation of research activities in the Department