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(54) Title: FLOW REACTOR WITH EXTENDED FLOW PATH

(57) Abstract: A tubular reactor provided with means whereby the tube may be rotated through reciprocating arcs about the longitudinal axis of the tube to provide radial mixing combined with plug flow wherein process material continuously passes through the tubular reactor operating at predetermined reaction conditions and the path of the process material through the reactor is diverted from axial flow preferably by means of static and/or dynamic agitators provided within the tubular reactor in order to increase path length, increase process material flow velocity and improve plug flow.

FLOW REACTOR WITH EXTENDED FLOW PATH

The present invention relates to a method and apparatus for mixing fluids in tubes and is particularly useful for applications where good plug flow or good mixing are required and especially when both are required. The method and apparatus may be used for conveying non homogenous fluid mixtures which require constant mixing (such as slurries) but the preferred use is for applications where both good mixing and good plug flow are required. The process and apparatus of the invention is useful in a wide range of process involving physical, biological and/or chemical change. Blending, physical reactions such as crystallisation, gas phase, slurry phase, mixed phase reactions and reactions in the liquid phase. The range of applications include but is not limited to manufacturing processes for foods, pharmaceuticals, bio processes, fine chemicals, the entire range of chemical, petrochemical and refining processes, polymerisation and minerals processing.

A flow reactor is primarily a steady state system where process material undergoes physical, chemical or biological change as it passes through the reactor continuously. Only a proportion of the process material for a given process cycle is held in the reactor at any time (unlike a batch reactor where all the process material for a process cycle is present at some point). The advantages of flow reactors over batch reactors relate to reduced physical size which contributes to better mixing of the process fluid and improved heat transfer between the process fluid and the body of the reactor (by virtue of reduced size). The commercial benefits of flow reactors over batch reactors for industrial processes are dependent on application but variously include reduced capital cost, higher product yield, improved purity of the product, reduced solvent use, improved safety and lower energy requirements and thus reduced cost. These advantages are well documented in literature.

The difference between a conveyor for moving process materials and a flow reactor is that in a conveyor, material is transferred from one point to another whereas in a flow reactor the properties of the process material undergo a physical, biological or chemical change as it is conveyed through the reactor. The nature of the process material is therefore changing as the reaction takes place along the reactor. Plug flow implies that the process material travels through and leaves the reactor in the same time order as it enters. Plug flow is therefore important for controlling reaction time and optimising separation of unreacted and reacted material. Failure to achieve good plug flow can severely impair the reactor performance since,

without this the reaction time cannot be controlled and back mixing of the process material can result in unwanted reactions and reduced reaction rate (due to the dilution effects in the case of n^{th} order reactions). Good mixing and more preferably good radial mixing is also required to ensure efficient blending, homogeneity of the process material within the reactor and good heat transfer.

The present invention provides a tubular reactor provided with means whereby the tube may be rotated through reciprocating arcs about the longitudinal axis of the tube and means are provided within the tube whereby the flow path of the process material along the tube is diverted from axial flow.

In a further embodiment the invention provides a reaction wherein process material continuously passes through a tubular reactor operating at predetermined reaction conditions wherein the tubular reactor is rotated through reciprocating arcs about the longitudinal axis of the tube as the process material passes therethrough and the path of the process material through the tube is diverted from axial flow.

The following terms have the following meaning:

- Flow reactor – This is a channel or series of stages through which process material flows continuously and a physical, chemical or biological change takes place within the process material as the process material passes through it.
- Process material is the material which flows through the reactor. This may include both reacting and non reacting materials (such as diluents or catalysts) The composition of the process material will change along the reactor as the materials change or react to form the desired reaction product. The process material may be liquid, gas, vapour, a critical fluid or any other material capable of flowing. It may also be a mixture of these and the process material may also contain solid particles.
- Tubular flow reactor – A flow reactor where the overall length of the channel in the direction of flow is 3 times greater and more preferably 5 times greater and more preferably still 10 times greater than the diameter of the channel. A tubular flow reactor may be made up of a single tube or multiple tubes.
- Plug flow – is a well known term and is an orderly flow pattern through the reactor where minimum back mixing occurs and substantially all fluid elements have substantially the same residence time in the reactor. Ideal (100%) plug flow cannot be achieved in practice due to

the influences of diffusion and fluid mixing. Plug flow in this document means residence time control comparable to at least 10 tanks in series and more preferably 20 tanks in series per reactor tube (a reactor may use multiple tubes) or greater. In many cases, the required plug flow quality will vary in response to changes in the reaction rate as occurs in n^{th} order reactions. In these applications, different diameter tubes along the channel length can be used to take account of the different plug flow requirements. This means using small diameter tubes (which give higher velocity and therefore better plug flow) where the quality of plug flow needs to be higher.

- Mixing – All fluids mix to some extent by molecular diffusion. Mixing as used herein refers to differential movement of bulk fluid elements so as to achieve desired conditions of blend uniformity, shear, heat transfer and plug flow. The mixing conditions may be turbulent or laminar.
- Axial mixing – This is mixing in the axial plane in the direction of the net flow direction of the process material typically along the tube.
- Radial mixing – This is mixing in the radial plane which is at 90 degrees to the net flow direction of the process material typically across the tube. The preferred mixing action is to have a high degree of radial mixing with a low degree of axial mixing.
- Static mixer (or agitator) – This is a mixing element which remains stationary relative to the reactor body.
- Dynamic mixer (or agitator) – This is a mixing element which moves in relation to the reactor body.
- Baffle – This is a plate across the diameter of the flow channel with apertures to allow fluid to pass along the tube in the axial direction.

The process material may have a high solids concentration but the preferred concentration of solids in the process material is less than 50% by volume and more preferably less than 25% by volume. The changes due to reaction of the process material include but are not limited to precipitation, crystallisation, chemical reaction, biological reaction, oligomerisation, polymerisation and extraction.

Mixing can be characterised in many ways but in this document, mixing implies adequate mixing. For homogenous fluids mixing refers to blending times of less than 10 seconds and more preferably less than 5 seconds and more preferably still less than 1 second. In some applications such as very slow reactions, longer blending times may also be acceptable. For

non-homogenous materials, adequate mixing should be comparable to or better than a 1 litre stirred vessel with a pitched turbine blade rotating at 100 rpm and more preferably at 200 rpm and more preferably still at 400 rpm. In some applications mixing may not be comparable to these.

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The reactor according to need may also have a system for adding or removing heat such as a temperature control jacket. Where the reactor is provided with an agitator shaft the shaft may contain a cooling system. The static and dynamic mixers may also contain a cooling system. A preferred temperature control system comprises a temperature sensor, a controller and a control element (such as a valve) for altering the temperature or flow of the heat transfer fluid so as to control the temperature of process material. In the case of electrical heating or cooling, the control element will vary the applied electrical power. The temperature sensor may be located in the heat transfer fluid stream or more preferably in the stream of process material. Multiple temperature control systems may also be used with multiple heating or cooling stages along the tube or in separate but connected tubes within the same system so as to address different temperature control requirements at different stages of the reaction.

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The flow reactor may also have in-line analytical devices such as optical analysers, pH sensors or calorimetry so as to monitor and/or control the operation of the reactor. The analytical devices may be part of a control system comprising an analytical sensor, a controller and a control element which controls one or more variables. The preferred location for a single analyser is at the point where process material discharges from the reactor although other positions may be used. The controlled variables may be the rate of flow of one or more feed materials, the system pressure, the system temperature or any other parameter which affects reactor performance. More complex control systems can also be used with multiple analysers controlling 1 or more parts of the reactor and these may be located in different positions within the reactor.

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The flow reactor may be provided with one or more internal baffles. The function of the baffle is to reduce back mixing (and hence improve plug flow) but may also be used to support an agitator shaft thus preventing excessive bending in said shaft.

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The invention described here provides an effective and economic solution to four key requirements for flow reactors:

- Volumetric capacity – Sufficient volumetric capacity is required to ensure that a reaction goes to completion for a given throughput. By virtue of generating efficient mixing which is not dependent on fluid velocity through the reactor (as is the case with conventional static mixer flow reactors), this invention provides volumetric capacity at a lower cost per unit volume than long thin tubes and with a lower pressure drop (since short large diameter tubes can be used without sacrificing mixing performance).
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- Plug flow – Establishment of plug flow provides the means for controlling reaction time and optimising separation of reacted and unreacted process material. For any process, a flow reactor will be smaller if good plug flow is employed since reacted material will be discharged in a timely fashion and not retained. For many processes such as n^{th} order, competitive or consecutive reactions, good plug flow is required for maximising yield per unit volume, selectivity and purity. This invention provides a method for generating a high ratio of radial to axial mixing which is desirable for good plug flow. This invention provides the means for achieving plug flow at lower velocities and pressure drops than would be required in a simple tube or static mixer.
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- Mixing – The benefits of good mixing include; fast blending times, good heat transfer coefficients, good mass transfer between non-homogenous fluids, good slurry transfer and promotion of good plug flow (by the elimination of poorly mixed zones of fluid travelling at different axial velocities). These requirements will vary according to process application. This invention provides for efficient mixing over a wide range of applications and it does so irrespective of fluid velocity through the reactor.
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- Heat transfer – Effective heat transfer is required to add or remove heat so as to maintain the process material at the desired temperature. This invention provides a means of fitting an external heating/cooling jacket and internal cooling tubes so as to control the process temperature. This design is suitable for a wide range of tube diameters and by selecting different tube diameters, different ratios of heat transfer area to working volume can be achieved.
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- Temperature control – Temperature control means the application of heating or cooling so as to change or maintain the temperature of the process material at the desired value. The preferred meaning of temperature control as applicable to this invention is reaction temperature control. This means that the process temperature is maintained or changed to the desired value where the reaction is exothermic or endothermic.
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Two broad classes of flow reactor are in common use. Static flow reactors rely on fluid movement through the reactor to generate mixing (by turbulent flow or splitting/bending/folding using baffles or static mixing elements). Conventional dynamic flow reactors use mixer blades mounted on rotating shafts. Such systems are expensive to build as they require mechanical seals or magnetic couplings. They also suffer from practical problems of shaft flexing in long tubes. In practice such systems are often built as stirred tanks in series. This adds to cost and complexity since many stages are required to achieve performance comparable to good plug flow. Patents WO 2008/068019 and WO 2011/124365 describe a method of dynamic mixing in flow reactors where the body of the reactor is subject to shaking which generates movement of internal agitators of a different density to the process fluid. The internal agitators are loose elements or they may be tethered to the vessel. When a tube filled with liquid is moved transversely (as described in the prior art), the position of the fluid in relation to the tube remains stationary. Under these conditions, mixing will only be generated if materials of more than one density are present.

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According to this invention the tube is rotated through reversing arcs around the long axis of the tube. Under these conditions, the inertia of the fluid will resist rotation thereby creating differential movement between the fluid and the inner surface of the reactor body plus any fixed elements within it. Unlike the prior art described above, this technique generates differential movement of the fluid (and therefore mixing) even when the reactor contents are of the same density. An additional feature of this invention is that rotating agitators can also be used mounted on one or more shafts. These also rely on the rotating motion of the reactor body to generate independent movement thereby increasing the mixing.

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The flow path of the process material is diverted from axial flow to increase the residence time of the material within the tube for a given length of tube. Additionally the increase in the length of the flow path increases the velocity of the process material which in turn gives a lower dispersion number and improves plug flow. Any suitable means may be employed to divert the flow of the process material however, a preferred method comprises positioning a series of discs along the axis of the tube with off centre apertures for flow of process material past the discs so that the process material flow past adjacent discs at different distances from the axis of the tube. The discs may be mounted on a central shaft and every other disc can have a central orifice for flow of process material through the disc and the intermediary discs can be of smaller diameter than the tube to provide a gap between the circumference of the disc and the interior

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surface of the tube for the flow of process material past the disc. The surface of the discs can be shaped to enhance mixing as the process material passes over them.

The invention is illustrated but in no way limited by the accompanying drawings on which

- 5 Figure 1 shows a typical flow reactor
- Figure 2 shows a dynamic mixer and shaft
- Figure 3 shows a static mixer and shaft
- Figure 4 shows a reactor mounting and drive unit
- Figure 5 shows the flow path of a process material through the reactor
- 10 Figure 6 shows surface profiling on the plate
- Figure 7 shows the flow path of process material through the reactor

A typical flow reactor is shown in Figure 1 and consists of a channel (1) which will normally be a circular tube with a backing flange at each end (2). Sealing flanges (3) are bolted to the backing
15 flanges to form a sealed system. The tube will be fabricated in a material to provide adequate mechanical strength to resist distortion or damage when operating under ambient pressure, elevated pressure or vacuum. The tube may be fabricated in a variety of metals such as stainless steel, hastelloy, carbon steel etc. Alternatively it may be fabricated in glass, ceramic material or even plastic. Where a combination of high mechanical strength and good corrosion
20 resistance is required, the reactor body may be fabricated in one material and coated or lined with a different material. A feed pipe (4) is shown on one end flange and a discharge pipe (5) is shown on the opposite flange. Multiple feed and discharge pipes may be used and some of these may be located at intermediate points along the tube. A cooling jacket is shown (6) which is used to add or remove heat. The heat transfer feed pipe (7) is shown at one end of the jacket and the heat fluid discharge pipe is shown (8) at the other end of the jacket. The temperature
25 control system has been described previously. On some systems, other forms of heating or cooling may be applied such as electrical heating elements or Peltier elements. The description above is for illustrative purposes and many variations and alternatives to this arrangement are possible.

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A further embodiment of this invention is a tubular reactor containing a rotating shaft with rotating and fixed agitator elements mounted within the tube as illustrated in Figures 2 and 3 respectively where the shaft rotates and is driven by an external drive unit involving mechanical

seals or magnetic couplings. The rotation is in reversing arcs so that both agitators move relative to the reactor body at different speeds.

Figure 2 shows an exploded detail of a dynamic agitator, shaft and shaft mounting collar which
5 may be used in the present invention. The agitator (9) is a disc with a central boss (10) with a circular hole at the centre to allow passage of the process material. Figure 2 shows a further embodiment of this invention in which on one part of the disc is a weight (11) which makes the disc unbalanced. Alternatively the disc may be made such that one part of the disc is of a material of greater density so as to make it unbalanced. The agitator is mounted on a shaft (12)
10 with a loose fit. The agitator shaft and the internal hole of the agitator boss should have smooth low friction surfaces. O rings or a soft bush may be used to protect the moving surfaces where the process material contains abrasive solids. The agitator shaft (12) preferably has a flat face on the circumference to prevent the shaft from rotating on the shaft support collar (13). Other shapes of shaft including round shafts with profiled ends (to stop the shaft from rotating) or other
15 methods such as round shafts with locking nuts may be used to keep the shaft in a fixed position may be used. Shaft support collars are mounted at each end of the reactor body to hold the agitator shaft. The shaft support collars may form part of the end flanges of the reactor or be mounted on a separate frame or plate at the end of the tube. The preferred position of the agitator shaft within the reactor is along the central axis. For some applications however, the
20 agitator shaft may not be centrally mounted and in other cases two or more agitator shafts may be used. The agitator disc has gaps to allow the process material to travel past the disc. These may be apertures in the disc or annual rings between the plate and the wall of the channel.

Figure 3 shows an exploded detail of a static agitator, shaft and shaft mounting. The agitator
25 (14) is fixed to the shaft and allows process material to flow through the centre hole and not around the edge of the disc and in this example the agitator has a flat spot on the inner radius to prevent it from rotating on the shaft but other methods of locking it on the shaft can be used. The process material may flow around the perimeter but the preferred method is to use a seal (15) at the perimeter to prevent the process material from flowing around it so that it all flows
30 through the central hole. This may be a soft seal material or an O ring. Alternatively the plate may form a close fit with the wall of the tube to prevent material from flowing around the perimeter. It is preferred that the process material flows through apertures in the plate and more preferably at the minimum working radius as shown (16).

Figure 4 shows the reactor body. This is shown as a tube (17) mounted on a bearing (18) which allows the body of the reactor to rotate. The bearing which allows the reactor to be rotated through reciprocating arcs is shown around the reactor body but may alternatively be mounted in a rotating cradle or shafts projecting from the ends of the reactor. Alternatively (to bearings),
5 rubber bushes, springs, low friction sleeves or other flexible devices may be used to allow the reactor body to rotate. The preferred axis of rotation is the centre axis of the reactor tube. Alternatively however the axis of rotation may be off centre such as on a swing arm. Also shown is a drive mechanism (19) which causes the reactor to rotate in reciprocating arcs on the
10 mounting. The drive mechanism may be assisted by recoil springs, pneumatic pistons or other devices (one element mounted on a fixed object and the other on the rotating reactor) to conserve energy and help reverse the arc of rotation at the end of its travel. The drive mechanism (19) shown is a pneumatic or hydraulic piston. Alternative drive mechanisms may also be used such as gears, cogs, motors, electromagnetic devices etc. The drive mechanism rotates the reactor through reciprocating arcs (clockwise followed by anti-clockwise). The
15 maximum degree of rotation is 360°. The degree of rotation will vary according to application however the preferred degree of rotation is between 1° and 90° but the preferred arc of rotation is less than 45°. The speed of rotation will vary according to application and will vary from less than 1 rotation a minute to more than 10 cycles per second.

20 The reactor of this invention contains a series of plates within the tube which rotate through arcs as the tube is rotated. The plates may all be fixed to the shaft as shown in Figure 3 or they may rotate on the shaft as shown in Figure 2. More preferably the plates alternate between fixed and non-fixed plates as shown in Figure 5. The key feature is that the flow path is diverted away from the axis of the tube and the flow path across the plates preferably alternates between the
25 centre of the plate and the periphery of the plate as shown by the arrows (20) in Figure 5. It is also preferred that the process material flows around the periphery of the moving plates and through holes in the static plates at minimum radius of the plates. This arrangement has two advantages. Firstly it ensures that all the process material is exposed to the same heat transfer and mixing conditions and minimises the effect of temperature or compositional differences
30 arising across the tube. Secondly, the process material has to take a longer flow path through the system. By increasing the length of the flow path, the path length and velocity of the process material is increased. Increasing these parameters gives a lower dispersion number and therefore better plug flow.

The mixing plates may be flat surfaces or they may be profiled surfaces and many different shapes and sizes of profiling may be used. Figure 6 shows an example of surface profiling where the plate has a series of raised projections (21). These projections may be formed by pressing, moulding or machining. Alternatively they may be fixed to the plate by bonding, screws or similar. The profiling may be limited to one plate or one surface or may be used on both plates and both surfaces (or a variation of these combinations). The profiles on the adjacent faces may overlap so that the projections mesh with each other such that the discs can rotate without clashing. The profiling may also be used to create unbalanced rotating discs. This can be achieved by fixing profiles of higher density material or higher volume to one segment of the disc.

Stops can be used between the dynamic agitator disc and a fixed point on the agitator shaft or body of the vessel to limit the distance of rotation of the dynamic agitator. This increases the acceleration of the agitator.

The agitator discs can be fabricated in a variety of materials such as metals, plastics, composites, ceramics, coated materials or combination of these materials. It is preferable to use low density materials such as plastics for the dynamic agitators as this will reduce the load on the sliding sleeve. The static agitators can also be used to support the shaft. This helps to prevent excessive bending on the shaft.

Heating or cooling can be applied to the reactor through an external jacket. Heating and cooling can also be applied through the central agitator shaft. The agitator discs may also be used to assist heat transfer (extended fin principle). For this purpose, high thermal conductivity materials such as thermally conductive metals and silicon carbide are preferred. The static agitators will be more efficient for this since they are fixed relative to the body of the reactor.

The distance between the agitator discs along the length of the tube will vary according to application. Small distances of less than 5 mm are preferred for more viscous materials but plate gaps of up to 100 mm may also be used. The design principle however should be based on using the minimum thicknesses which provides adequate strength and rigidity. The boss thickness must also be sufficiently long to carry the disc without distortion or excessive wear. Where necessary, the surface profiling can be used to reduce the plate gaps by using overlapping teeth as described earlier.

The preferred design of this system will be static agitators made of thermally conductive material and dynamic agitators made of a light weight material such as plastic or a low density metal such as titanium or aluminium.

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For operation under laminar flow conditions (typically with viscosities of greater than 100 centipoise or higher and more preferably greater than 1000 centipoise or higher) the following operating conditions are preferred:

- A rotation arc of the reactor body of less than 10°. The angle of rotation of the dynamic mixer may be greater however and may also be continuously rotating.
- Surface profiling on the plate with spaces between the profiles of 10 mm or less and more preferably 5 mm or less.
- Flow channel between the plates of 10 mm or less and more preferably 5 mm or less.

15 For fluids with a viscosity of less than 100 centipoise, the preferred combination of arc of rotation, speed of rotation, plate spacing and surface profiling is such that the Reynolds number is greater than 2300 (turbulent flow).

20 The preferred conditions described above are general preferences only. Fluids of low viscosity may be operated under laminar flow conditions (for example for fragile process materials) and fluids of high viscosity may be operated under turbulent flow conditions (for example for mass transfer limited applications).

25 For more viscous fluids large diameters may be required in order to generate sufficient turning moment on the dynamic agitators. The diameter will also be subject to heat transfer constraints.

In some applications, the dynamic mixers will move through an arc and in other cases, the dynamic mixers will rotate continuously in one direction. This can be achieved by tuning the rotation conditions to generate continuous rotation. Continuous rotation can also be promoted
30 by designing the blade shape such that the drag resistance is greater in one direction of rotation than the other.

An alternative arrangement to the one described above is to have the dynamic mixers fixed to the shaft and have a rotating shaft. In this case the shaft support collar is circular on the inner

radius allowing free rotation of the shaft. Such a system could also be driven by an external shaft drive as an alternative to a rotating reactor body.

5 In other cases and particularly for viscous fluids a ratchet mechanism or similar can be employed which only allows the dynamic mixer to rotate in one direction. The ratchet mechanism (or stops) is formed between locking points (fixed relative to the reactor body) and the rotating mixer respectively. In some cases, the dynamic agitators can be arranged so that different agitators (normally adjacent ones) move in contra rotating directions. The continuously rotating agitator in this case can be balanced or unbalanced.

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The diameter of the disc mixers of this system should be the full diameter of the reactor body subject to the provision of enough space between the wall and the disc to allow process material to flow around the perimeter where required and for the discs to move where required.

15 The agitator shaft should be strong enough to carry the load of the agitators but the static agitators may also be used to support the shaft. The shaft and inner surface of the dynamic agitators should form smooth low friction surfaces. The dynamic agitator collars may also be in a softer material than the shaft (or vice versa) so that wear parts can be replaced.

20 The inlet and outlet connections for feeding and discharging the process material should be mounted on the tube at the maximum distance apart for orderly flow and so that full use of the reactor tube is achieved. The connections are fitted to the end plate. Where there is a need to access the end plates without disconnecting the feed and discharge pipes, the feed and discharge connections are fitted to the wall of the tube at a minimum distance from the
25 respective end plates. For processes where there is a need to make multiple additions (such as gas/liquid reactions or reactions which exceed the cooling capacity of the reactor at a given point) multiple addition points may be fitted along the length of the tube.

30 The reactor tubes may be mounted horizontally, vertically or at a slope. The preferred position of the reactor tube is horizontal to minimise wear between static and moving parts of the reactor. A slope is preferable where free draining is required or to assist the movement of light or heavy materials along the reactor tube where there are two phases (slope upwards to handle floating materials and downwards for sinking materials). Horizontal or near horizontal tubes are preferable where the process material has two or more phases of different densities. The

reactor tubes may be split in the axial plane but the preferred arrangement is a solid tube. A longitudinally split reactor tube may be used where high heat transfer is required and the static mixers may be inset into the wall of the reactor to improve heat transmission between the static mixers and the wall of the reactor.

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The length of the reactor tube will vary according needs from 50 millimetres or less to 10 metres or more but more preferably will vary from 0.5 metres to 3 metres. Tubes of less than 3 metres and more preferably less than 2 metres provide better access for inserting and removing the mixer assembly. Where tube lengths excess of the desired length are required (for access
10 reasons), it is preferred that multiple tubes are used coupled by flexible connections.

The diameter of the reactor tube will vary according to application and can vary from less than 1 millimetre to more than 2 metres. For fast reactions and exothermic reactions (typically reaction times of less than 1 minute), tubes in range of 5 millimetres to 50 millimetres diameter are
15 preferred. The reactor cost per unit volume is lower with large diameter tubes and therefore, where possible, the maximum diameter tube is desirable. Where reaction times are greater than 1 minute and not constrained by heat transfer needs, large diameter tubes from 50 millimetres to 200 metres or more are preferable. Given that reaction rates vary, the preferred solution for many applications will be to use a number of tubes connected in series and that the diameters
20 of the respective tubes may be the same or different according to the heat transfer at different stages of the reaction.

The reactor can be operated over a wide range of pressures and temperatures subject to selection of the right materials of construction and material thicknesses. Containment of process
25 material is aided by absence of moving joints such as mechanical seals.

The system may be used for unidirectional flow or counter current flow. In counter current flow, two fluids are fed at different ends of the reactor tube and each discharges at the opposite respective ends. This method can be used for some types of reaction and also for counter
30 current extraction. For such processes to work the counter current fluids must be substantially insoluble in each other and of different densities. Counter current systems preferably have unmixed separation zones at each of the reactor and may also have unmixed intermediate separation zones at stages along the reactor length. For counter current flow, the hole

arrangement across the agitator plates may not be as described previously and the holes may be closer to the centre of the plate and at different radiuses as required.

A flow reactor requires feed and discharge pipes to transfer fluids from fixed objects such as tanks and pumps to the rotating reactor. These pipes must have sufficient flexibility to take the rotational movement of the reactor body. If the movement is small, rigid connection pipes can be used with sufficient length and bends to absorb stress of the movement. Where the extent of movement is large rigid pipes with long radius bends can be used or flexible tubes such as plastic tubes or corrugated metal tubes.

Good plug flow is one necessary parameter for controlling residence time of process material in the reactor. The other parameter is delivering process material at a controlled feed rate. This can be achieved with metering pumps, non-metering pumps whose flow has been calibrated, gravimetric feeding at constant and calibrated heads. The feed rate can also be controlled using or flow control systems comprising of a flow measuring device, a controller and a control element such as a flow control valve to regulate the flow.

The features of this invention are as follows:

- The body of the reactor is rotated to generate mixing in the reactor. This eliminates the need for agitator shafts connected to an external drive unit by mechanical seals or magnetic couplings.
- The diversion of the flow path from axial flow along the tube increases the flow path and the velocity of the process material reducing the dispersion number and enhancing plug flow.
- By limiting the rotation to arcs of 360° or less, the reactor body can be connected to fixed objects by flexible fluid transfer pipes, electrical cables and instrument cables. By repeatedly reversing the direction of rotation, the process material and/or dynamic agitators move at different velocities and in different directions at some points thereby generating improved mixing. The use of reversing arcs also reduces the need for high rotation speeds thus reducing wear on the shaft or dynamic agitators.
- The reactor body can be fabricated as a simple tube with no internal features (such as baffles). The agitator assemblies are pushed or pulled in. This design reduces fabrication cost and makes cleaning and maintenance simpler.
- A thinner agitator shaft can be used as it is fixed in relation to the body of the reactor and can be supported at intermediate points.

- The use of a combination of static and dynamic mixers gives enhanced mixing.
- The use of an agitator shaft which has a flat face as described or similar, the baffles and agitators can be pushed into place and depending on their internal shape permitted to rotate or stay fixed on the shaft.

5

The present invention differs from prior art described in Patents WO 2008/068019 and WO 2011/124365 in that the agitators of this system are part of or rotate around a fixed axis. It embodies mixing principles of static mixing and dynamic mixing or a combination of the two. Unlike the prior art given above, this prevents impact between the agitators and the reactor
10 body and allows the agitator position to be fixed at the optimum position in the diameter of the reactor tube. These features can be used in systems with tube diameters of less than 50 mm but are more desirable in larger system with tube diameters of greater than 50 mm.

The commercial applications of this invention are varied. The value of this invention relates to
15 both performance and fabrication cost:

- For processes handling non-homogenous materials, this reactor provides high mass transfer rates by virtue of efficient mixing and can also provide horizontal flow of the process material (or near horizontal). The significance of horizontal flow is that the distance by which heavy phase materials have to be lifted (and vice versa for lighter phases) is smaller than in
20 vertically mounted tubes. This design also suits slurry handling where large diameter tubes and good mixing are desirable.

- The required volumetric capacity of a flow reactor is determined as follows:

Volumetric capacity (litres) = volumetric flow (litres/second) x reaction time (seconds)

Where high volumetric capacity is required, it is preferable to use short large diameter tubes
25 for reasons of cost and minimum pressure drop. This invention provides a dynamically mixed flow reactor where efficient mixing can be achieved independently of fluid velocity through the tube. This allows large diameter tubes to be used at low fluid velocities without compromising mixing efficiency. For this reason reactors of this type can be used for a wide range of applications where high volumetric capacity is required. Whilst reactors of this type
30 can operate effectively with volumetric capacities of less than 100 millilitres, they offer economic solutions for systems up to 100 litres per tube or more.

This invention is similar to the subject matter of another patent application filed on the same date but it adds the feature that the path of the process fluid is deliberately diverted away from

axial flow along the tube. This is illustrated in Figure 7 where the static mixers (22) have apertures near the centre of the reactor tube diameter and the dynamic mixers (23) have apertures at the periphery. The flow path of the process material in one half of the tube is shown as an arrow (24) (there will be a similar flow path in the other half of the tube) as opposed to a substantial axial flow path material redistribution is required in the radial plane, baffles or stirring action of the agitators are used for said purpose.

The nominal length of the flow path of this invention (P_d) is:

$$P_d = n(R_1 - R_2)$$

10 Where n = the number of flow spaces between the plates.

R_1 = the radius of the inner apertures across the plates

R_2 = the radius of the outer apertures across the plates

In the co published patent, the nominal length of the flow path (P_g) is:

$$P_g = L$$

15 Where L = the axial length of the reactor tube. In practice the path length in the co-published patent may be longer than L given that the baffles may create some travel between the centre and periphery but the distance will be shorter.

20 This invention has many applications but the preferred application is for polymerisation processes where a high heat transfer area to volume, good mixing and good plug flow are critical to an optimum outcome and where the process materials may have high viscosity.

CLAIMS

1. A tubular reactor provided with means whereby the tube may be rotated through reciprocating arcs about the longitudinal axis of the tube and means are provided within the tube whereby the flow path of the process material along the tube is diverted from axial flow.
2. A tubular reactor comprising of a vessel with connections for continuous feed and discharge of process material whereby the body of the vessel is capable of rotation through reciprocating arcs to mix the process material and means are provided within the tube whereby the flow path of the process material along the tube is diverted from axial flow.
3. A tubular reaction according to Claim 1 or Claim 2 that is a tubular flow reactor with plug flow performance equivalent to or better than 10 stirred tank stages per tube.
4. A tubular reaction according to any of the preceding claims that is a tubular flow reactor with plug flow performance equivalent to or better than 20 stirred tank stages per tube.
5. A tubular reactor according to any of the preceding claims containing agitators within the reactor.
6. A tubular reactor according to Claim 5 in which the agitators comprise the means to divert the flow path of the process material.
7. A tubular reactor according to Claim 5 or Claim 6 in which the agitators are flexible.
8. A tubular reactor according to any of Claims 5 to 7 wherein the agitator is mounted on a shaft that is fixed in relation to the reactor body.
9. A tubular reactor according to any of Claims 5 to 7 wherein the agitator shaft is free to rotate in relation to the reactor body.
10. A tubular reactor according to any of Claims 5 to 9 in which the agitators are static mixers.
11. A tubular reactor according to Claim 10 in which the agitators are dynamic mixers.
12. A tubular reactor according to any of the previous claims provided with internal baffles.
13. A tubular reactor according to any of the previous claims provided with a means to add or remove heat to or from the process material.
14. A tubular reactor according to Claim 13 in which the means to add or remove heat comprises a temperature sensor, a temperature controller and a temperature control element.
15. A tubular reactor according to any of the previous claims provided with a means to monitor the process conditions.
16. A tubular reactor according to Claim 15 in which the means to monitor the process conditions comprises one or more analytical devices.

17. The use of a tubular reactor according to any of the preceding claims for reactions comprising physical, chemical or biological change.
18. A reaction wherein process material continuously passes through a tubular reactor operating at predetermined reaction conditions wherein the tubular reactor is rotated through reciprocating arcs about the longitudinal axis of the tube as the process material passes therethrough and the path of the process material is diverted from axial flow as it passes through the reactor.
19. A reaction according to Claim 18 wherein the reciprocating arcs comprise 360° or less.
20. A reaction according to Claim 18 or Claim 19 wherein the passage of the process material through the reactor is plug flow.
21. A reaction according to Claim 20 in which the plug flow performance is equivalent to or better than 10 stirred tank stages per tube.
22. A reaction according to any of Claims 18 to 21 in which the path of the process material within the tube is diverted by means of agitators located within the tubular reactor.
23. A reaction according to any of Claims 18 to 22 in which the agitators cause radial mixing.
24. A reaction according to any of Claims 18 to 23 wherein heat is added or removed from the process material as it flows through the reactor.
25. A reaction according to any of Claims 18 to 24 comprising physical, chemical or biological change.

20

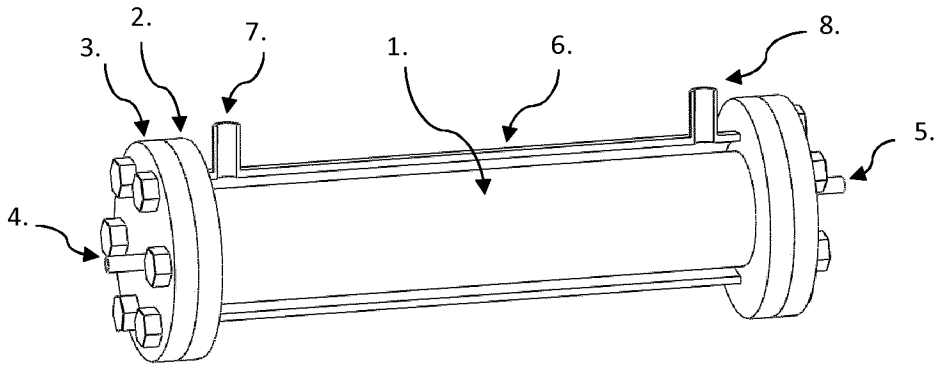


Figure 1 - Typical flow reactor

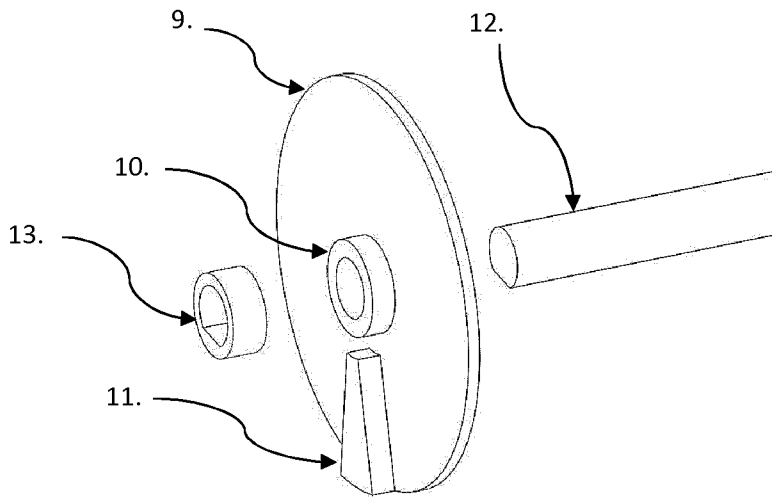


Figure 2 - Dynamic mixer and shaft detail

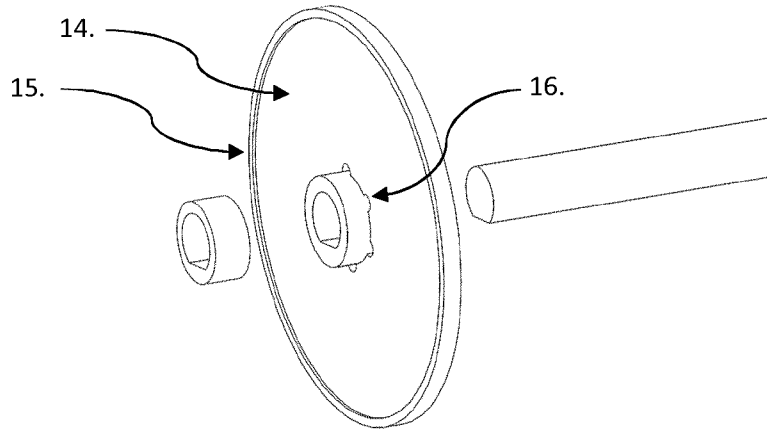


Figure 3 – Static mixer and shaft detail

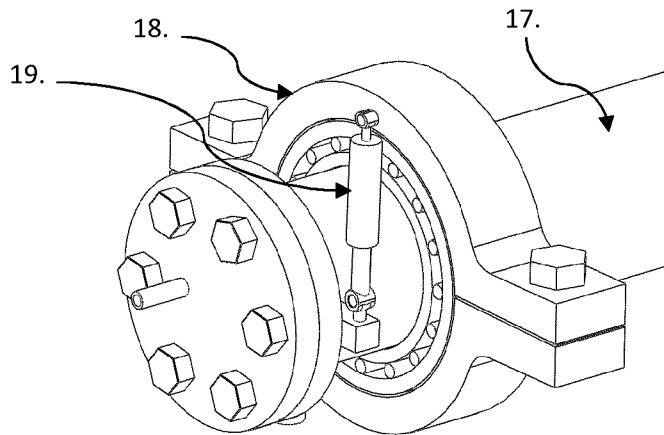


Figure 4 – Reactor mounting and drive unit

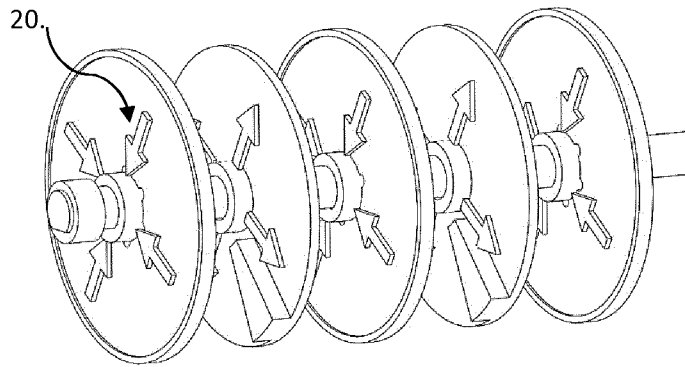


Figure 5 – Flow path of process material through the reactor

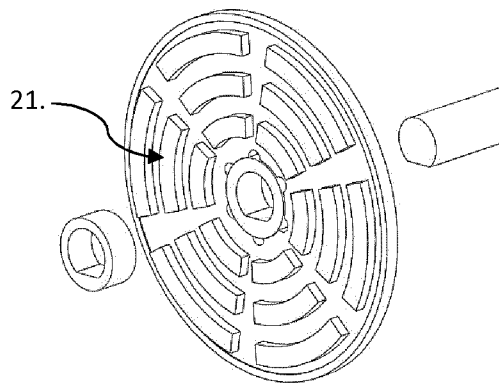


Figure 6 – Example of surface profiling on the plate

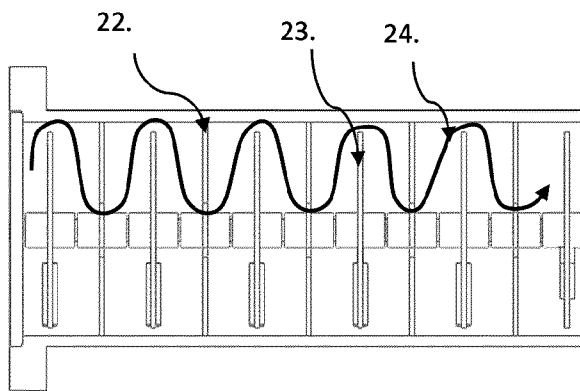


Figure 7 – Process flow path through the reactor