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Bead production with JetCutting and rotating disc/nozzle technologies

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Abstract

Different technologies for the production of solid beads from liquids via a single droplet state are compared. The mentioned technologies include simple dropping, electrostatic-enhanced dropping, vibration, rotating disc, rotating nozzle and especially the JetCutter, which is discussed more in detail. The JetCutter is a simple and efficient technology for the production of monodisperse spherical beads from solutions, melts and dispersions. Currently, it is the only technology which is also able to satisfactorily process fluids with a viscosity up to several thousands mPa·s. The cutting process and the reduction of the losses are presented in detail. New developments in JetCutter technology like a pre-gelation line, a heating device and a two-fluid nozzle for simultaneous coating are discussed. Finally, manifold applications in various industrial fields are presented.

Keywords: JetCutter, rotating disc, rotating nozzle, beads, spherical particles, encapsulation

1 Introduction

Solid particles (pellets, beads) in the size range between µm and mm play an important role in various industries like agriculture, biotechnology, chemical, pharmaceuticals and the food industry. Thus, plenty of particle production technologies exist and their further development is of major interest both from an economic and scientific point of view.

Generally, single and discrete solid particles may be produced with three different approaches:

1. from larger solid entities by grinding,
2. from smaller solid entities by agglomeration, granulation, pressing or tabletting - small fluid entities may also be used if in-situ drying is applied -, or
3. from fluid entities in the same size range with an immediate physical or chemical solidification step.

Although it is necessary to produce solid particles in industrial quantities, in recent years, solid particles are required more and more to have an ideal spherical shape. Such beads are much easier to dose, and pose less danger to humans and equipment during manufacturing (less respirable abrasion and lower explosion risk). Last but not least, they look much nicer from an aesthetic point of view, which is very important if the beads are part of a final product.

From the three different approaches named above, the third is, in principle, best suited for the production of ideal spherical beads. Only with this approach can the solid bead be a more or less equally sized liquid droplet – which is perfectly round due to the surface tension – directly prior to its solidification. Correspondingly, numerous different techniques exist which use the principle of generating a droplet which immediately afterwards is solidified to a spherical bead by physical means, e.g. cooling or heating, or chemical means, e.g. gelation, precipitation or polymerisation. This paper will give a short overview of these techniques with the focus on high-throughput techniques, like the rotating nozzle and rotating disc technique and particularly the JetCutter.

2 Technologies for bead production

2.1 Dropping technologies

Three different methodologies are considered dropping technologies: simple dropping, electrostatic enhanced dropping and vibrational jet-breakup. In this order the technologies become more and more complicated but also more sophisticated. A scheme of these technologies is shown in Figure 1, the literature about these technologies is summarised by Kuncová 2002, Nedović 2002 and Lacík 2002.

Bead production by simple dropping (Figure 1, left) is by far the easiest method. When a liquid flows out of a nozzle or a cannula, a droplet begins to form at the end of the nozzle. The "growing droplet" first adheres to the nozzle. When the gravity force of the growing droplet exceeds the adhesion force at the nozzle, the droplet will be pulled off the nozzle and will fall down. During falling the droplet will assume a spherical shape due to the surface tension of the liquid. Afterwards the generated single droplets may be collected, e.g., in a gelation bath.

The bead size depends mainly on the viscosity of the liquid and the diameter of the nozzle. Generally, only large beads (Ø > 2 mm) are accessible by simple

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dropping, smaller beads will only be generated if an additional annular air flow around the nozzle is applied. This air flow often leads to a significant broadening of the size distribution, which otherwise is usually very narrow. Other disadvantages are the low throughput of this technology, which limits its applications to the lab-scale, and the fact that only low-viscous fluids can be processed without problems (usually below 200 mPa·s).

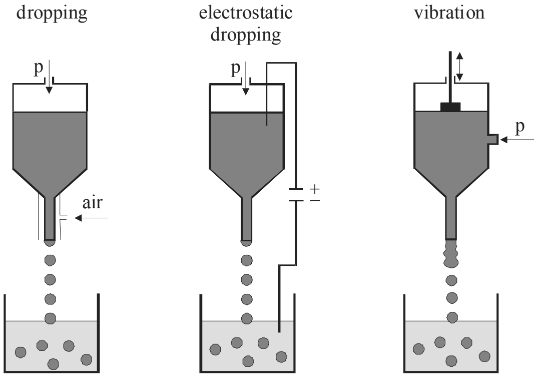


Figure 1:
Scheme of different dropping technologies for bead production

The electrostatic enhanced dropping (Figure 1, middle) is a quite similar technique. In this case, a growing bead will be pulled off the nozzle, if the sum of the gravity force and the electrostatic force exceeds the adhesion at the nozzle. This technique allows the production of very narrowly distributed beads in a broad accessible size range (approx. 0.3-5 mm). Nevertheless, the limitations concerning the low viscosity of processible fluids and the low throughput are still present, so that this technique is restricted to lab-scale. Further details about this technique can be found in this issue (Nedović et al. 2002).

The vibrational jet-breakup, or simply vibration technique (Figure 1, right), is the most sophisticated dropping technique. Bead production is achieved by superposing a oscillation on a fluid jet coming out of a nozzle. This vibration leads to a definite constriction of the jet which finally disintegrates into discrete beads which can be collected afterwards. The vibration technique also enables the production of very narrowly distributed beads in a broadly accessible size range (approx. 0.3-5 mm), but again, the low viscosity of the processible fluids limits its applications. A scale-up of this technology by multi-nozzle systems has already been done, so that this technology might also be used on a technical scale. Detailed information about this technology can also be found in this issue (Heinzen et al. 2002).

2.2 Rotating disc and rotating nozzle atomizer

Quite different from the dropping technologies are the rotating disc and nozzle technologies (Figure 2, for a literature overview see Prüße and Vorlop 2002a). In these cases, the bead generation is achieved by a spinning device which is either a disc (Figure 3) or a multi-nozzle device (Figure 4) not too different from a drum screen or the drum inside a washing machine. The fluid is either fed onto the spinning disc or into the spinning nozzle system and will flow over the perimeter of the disc or through the nozzles. If the disc/nozzle rotates, the flowing fluid disintegrates, driven by the centrifugal force and its own inertia. Depending on the rotation speed, three different disintegration regimes might be distinguished:

1. slow rotation: single beads are formed directly at the disc perimeter or the nozzle
2. medium rotation: ligaments are formed at the disc perimeter or the nozzle which disintegrate after a certain ligament length
3. fast rotation: a fluid film is formed which disintegrates in a irreproducible manner

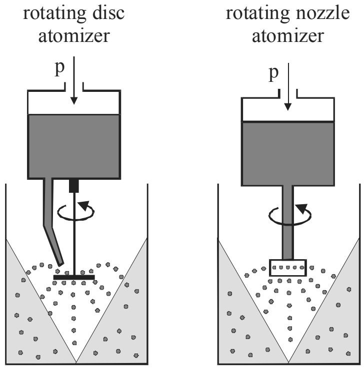


Figure 2:
Scheme of the rotating disc and nozzle technology for bead production

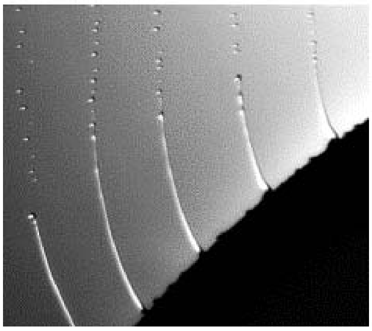


Figure 3:
Photo of bead formation (ligament regime) by a rotating disc device (Koch and Walzel 2001)

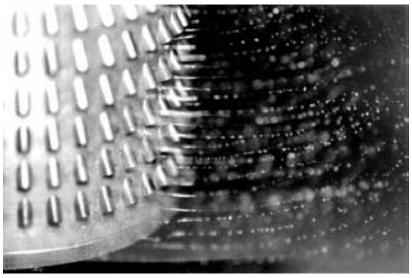


Figure 4:
Photo of bead formation by a rotating nozzle device (Walzel 2001)

The bead size accessible with these technologies ranges from between a few hundred microns up to several millimetres. The size is mainly influenced by the viscosity of the fluid and the rotation speed of the disc/nozzles. The throughput has to be adjusted to the spinning speed in order to be within the desired disintegration regime.

In any case, the bead formation with these technologies is not as well defined as for the dropping technologies, so that generally the particles are quite broadly distributed. Another, very severe problem is the occurrence of satellite beads (Champagne et al. 2000). Satellite beads are beads which are significantly smaller than the beads which were produced. They are generated by a non-ideal disintegration of the ligaments. Although satellite beads might also be generated by dropping technologies if the device is not run correctly, they can almost entirely be eliminated for the dropping technologies. In contrast, for the two rotating technologies, the avoidance of satellite beads is more the exception than the rule. Another disadvantage is again a severe limitation in the fluid's viscosity, which usually has to be below a value of approximately 200 mPa·s. Nevertheless, as these two classical technologies possess a very high throughput, they both are widely used for industrial processes.

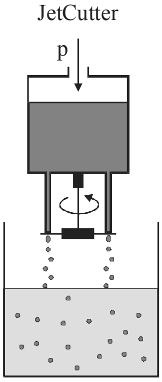


Figure 5:
Scheme of the JetCutter technology for bead production

2.3 JetCutter

The JetCutter technology is based on a completely different principle from bead generation and is achieved by a mechanical cut of a solid liquid jet (Figure 5). The JetCutter is described in detail in the next chapter. For a literature overview see Prüße and Vorlop 2002b.

3 The JetCutter

3.1 Principle and device

In bead production by the JetCutter, the fluid is pressed with a high velocity out of a nozzle as a solid jet. Directly underneath the nozzle the jet is cut into cylindrical segments by a rotating cutting tool made of small wires fixed in a holder. Driven by the surface tension, the cut cylindrical segments form spherical beads while falling further down to an area where they finally can be gathered.

Bead generation with JetCutting is based on the mechanical impact of the cutting wire on the liquid jet. This impact leads to the cut together with a cutting loss, which in a first approach can be regarded as a cylindrical segment with the height of the diameter of the cutting wire. This segment is pushed out of the jet and slung aside where it can be gathered and recycled (Figure 6). As only a mechanical cut and the subsequent bead shaping driven by the surface tension are responsible for bead generation, the viscosity of the fluid has no direct influence on the bead formation itself. Thus, the JetCutter technology is capable of processing fluids with viscosities up to several thousand mPa·s.

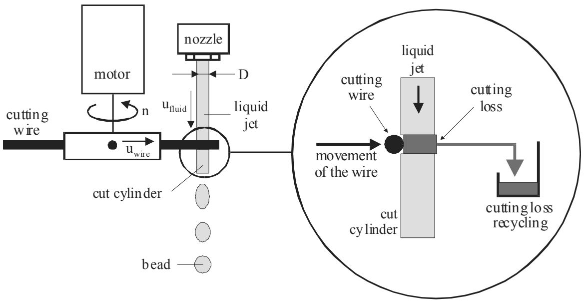


Figure 6:
Scheme of the cutting process, simplified model

The size of the beads can be adjusted within a range of between approx. 200 µm up to several millimetres. The main parameters are the nozzle diameter, the flow rate through the nozzle, the number of cutting wires and the rotation speed of the cutting tool. In order to get narrowly distributed beads one has to maintain a steady flow through the nozzle which may achieved with a pressure vessel or a pulsation-free pump and a uniform rotation speed of the cutting tool.

The cutting tool itself also has to fulfil one major requirement. In order to produce beads of the same size, the wires have to have equal distances. This is best achieved by a circular stabilisation of the wires on the outer perimeter as is shown in Figure 7.

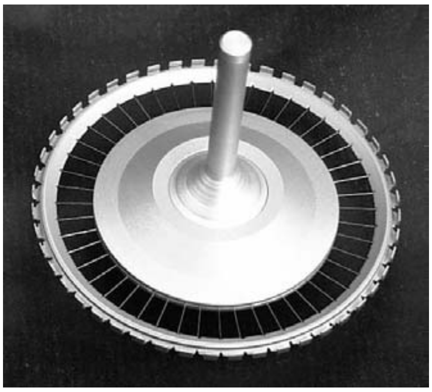


Figure 7:
Photo of a cutting tool with 48 stainless steel wires (Ø = 50 µm) and circular stabilisation

This circular stabilisation is essential even if the wire diameter is reduced in order to decrease the cutting losses (see also Figure 6). The diameter of the cutting wire may be decreased down to 30 µm. Usually, stainless steel wires are used, but the application of polymer fibres is also practicable.

Another requirement for the JetCutter is that a solid jet is formed. Therefore, special solid jet nozzles have to be applied. Even with these solid jet nozzles the liquid jet disintegrates after a certain length. This length depends on the viscosity and velocity of the fluid. In order to ensure a perfectly shaped jet at the point where it is cut by the wires, the cutting tool should not be too far away from the nozzle outlet, e.g. only a few millimetres (Figure 8).

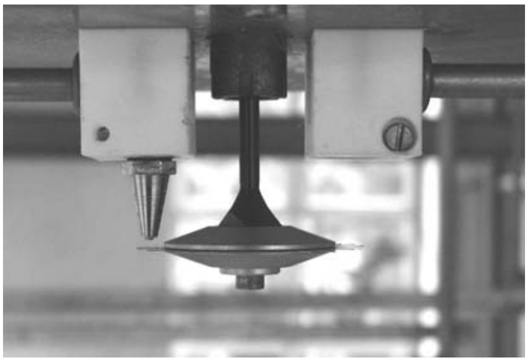


Figure 8:
Arrangement of nozzle (left, in the white holder) and cutting tool

3.2 Detailed description of the cutting process

At first glance, the principle of the JetCutter is very simple. Nevertheless, at second glance, it is much more complicated. The cutting process as shown in Figure 6 is idealised and only holds true if the velocity of the cutting wire is much higher than the velocity of the liquid jet. Actually, these two velocities are in the same range so that the progressive movement of the liquid jet has to be taken into account for a proper description of the cutting process (Figure 9, see also Prüße, Bruske et al. 1998 and Prüße, Fox et al. 1998a).

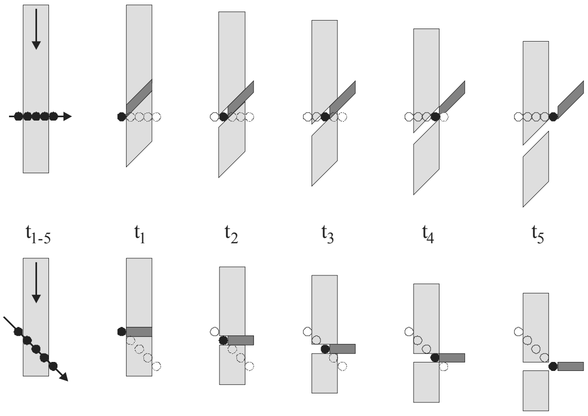


Figure 9:
Locally and temporally resolved schematic representation of the cutting process for a horizontal cutting plane (top) and an inclined cutting plane (bottom), actual position of the cutting wire: black circles, former and future positions of the cutting wires: blank circles, cutting loss: dark grey, liquid jet: bright grey, t = time

Figure 9 shows both a locally and temporally resolved scheme of the cutting process. On the very left hand side, the liquid jet and the positions of the cutting wires at the different times t_1 to t_5 (cutting plane) in relation to the liquid jet are shown. Further to the right, the progressive movement of the jet is shown at each time (t_1 - t_5) as well as the actual position of the cutting wire at that time (black circle). Prior and subsequent positions of the wire are indicated by blank circles. The cutting loss which is pushed out of the jet is also displayed.

In the case of a vertical nozzle and a horizontal cutting plane (Figure 9, top) it can be seen that the progressive movement of the liquid jet during the cutting process leads to a diagonal cut through the liquid jet. Accordingly, a proper inclination of the cutting tool should lead to a straight cut through the jet (Figure 9, bottom).

Figure 9 displayed that the progressive movement of the jet during cutting leads to a diagonal cut through the liquid jet. Thus, the cutting loss has a somewhat ellipsoidal shape – and is therefore larger than it is in the idealised model in Figure 6 – and the cut cylinders are distorted (Figure 10). Further, it is conceivable that the ends of the distorted cylinders might be torn off from the rest of the cylinder and form additional spraying losses. In that case the overall losses generated by the mechanical cut through the liquid jet would be quite high. Nevertheless, it is also shown that a proper inclination either of the cutting tool (Figure 10, middle) or the nozzle (Figure 10, bottom) lead to straight cut through the jet with the "normal" cutting loss and no additional spraying losses.

On the basis of this more sophisticated geometrical model a set of equations displayed in Table 1 has been derived which is capable of describing the cutting process both for a perpendicular arrangement of nozzle and cutting plane (horizontal cutting plane) as well as for an inclined arrangement (inclined cutting plane). Table 2 shows the check-up of the model. Here, the experimental values of the overall losses during the production of PVA beads in dependence on the diameter of the cutting wires used are displayed. Two sets of experiments are shown, one with a horizontal cutting plane (cutting losses and additional spraying losses) and one with a properly inclined cutting plane (only cutting losses). For comparison, the theoretical values are also given. Table 2 offers three important pieces of information:

1. The losses decrease if a proper inclination is applied.
2. Experimental and theoretical values are in good agreement, so that the model is suited to describe the cutting process.
3. By using small cutting wires and an inclined cutting plane, the losses can be decreased down to less than 2 %. Such low losses are tolerable, no loss recycling has to be applied.

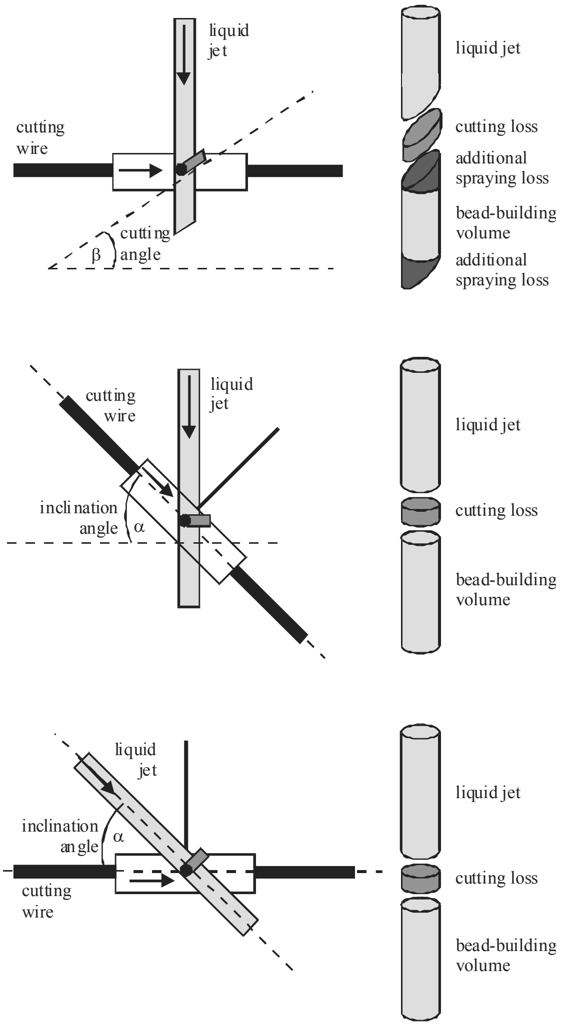


Figure 10:
Possible arrangements of nozzle and cutting tool and resulting losses, from top to bottom: perpendicular arrangement, inclined cutting tool, inclined nozzle

Table 1:
Mathematical model of the JetCutter

parameter	horizontal cutting plane	inclined cutting plane
angle	$\beta = \arctan\left(\frac{u_{fluid}}{u_{wire}}\right)$	$\alpha = \arcsin\left(\frac{u_{fluid}}{u_{wire}}\right)$
cutting loss	$V_{loss} = \frac{\pi \cdot D^2}{4} \cdot \frac{d_{wire}}{\cos\beta}$	$V_{loss} = \frac{\pi \cdot D^2}{4} \cdot d_{wire}$
overall loss	$V^*_{loss} = \frac{\pi \cdot D^2}{4} \cdot \left[\frac{u_{fluid}}{n \cdot z} - \frac{(d_{wire} + D \cdot \sin\beta)}{\cos\beta}\right]$	$V^*_{loss} = \frac{\pi \cdot D^2}{4} \cdot d_{wire}$
bead diameter	$d_{bead} = \sqrt[3]{\frac{3}{2} \cdot D^2 \cdot \left[\frac{u_{fluid}}{n \cdot z} - \frac{(d_{wire} + D \cdot \sin\beta)}{\cos\beta}\right]}$	$d_{bead} = \sqrt[3]{\frac{3}{2} \cdot D^2 \cdot \left[\frac{u_{fluid}}{n \cdot z} - d_{wire}\right]}$

Table 2:
Overall losses for horizontal (horiz.) and inclined (incl.) cutting plane in dependence on the diameter of the cutting wire, exp: experimental, calc: calculation

Wire diameter, mm	Overall losses, %			
	horiz. cutting plane		incl. cutting plane	
	exp	calc	exp	calc
0.1	8.8	7.9	2.4	2.0
0.2	10.4	10.1	4.0	3.9
0.3	10.2	12.5	6.6	5.8

But, although the model is able to describe the process in terms of losses and also the resulting bead diameter, it is still a model. Thus, it is not really surprising that the reality still looks different (Figure 11).

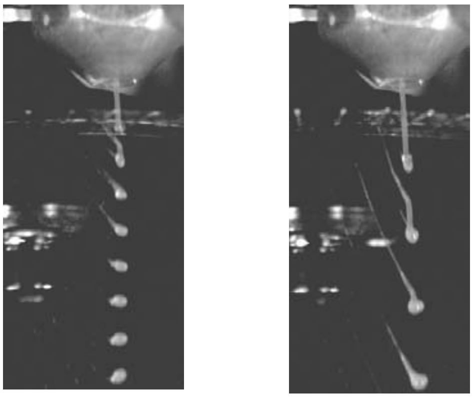


Figure 11:
High speed images of the cutting process during the production of alginate beads, left: high wire velocity and low fluid velocity = small beads, right: low wire velocity and high fluid velocity = large beads

In Figure 11, two photos of the cutting process taken with a high speed camera are shown. In both cases a horizontal cutting plane has been applied. It is obvious that the cut segments do not really have a cylindrical shape. Nevertheless, these segments are able to form spherical beads after a short period (Figure 11, left). With regard to losses, a bent end of the cut segment is on top, but it remains almost in contact with the cutting wire, which pulls it from the cut segment as if it were molten cheese (Figure 11, right). But in this case beads are still formed after a short period of time. The photos clearly indicate that there is still a lot of work to do in order to fully understand the process of bead formation by JetCutting.

3.3 Throughput and scale-up

A necessary requirement for bead production in JetCutting is that a really solid jet be pressed out of the nozzle and that this solid jet be maintained until it is cut by the wires. This can be achieved with a combination of special solid jet nozzles and a high fluid velocity (up to 30 m/s), the latter with corresponding high flow rates. Due to the solid jet requirement, the flow rate per nozzle is considerably higher for the JetCutter than for any other bead production technology. Nevertheless, since the two rotating techniques both contain multi nozzles or multi bead generation sites, the bead production rate from the rotating disc in each device is higher for these two technologies as compared with a single nozzle JetCutter. For the JetCutter technology two methods of scaling-up are possible.

First, a multi-nozzle JetCutting device can be applied, in which the nozzles are staggered near the perimeter of the cutting tool. In this case, special attention has to be paid to avoid additional spraying losses. If a horizontal cutting tool is used with vertically arranged nozzles, considerable additional spraying losses will be occur, which, of course, is undesirable. The application of an inclined cutting tool, although perfectly suited for a single-nozzle system, is not much better since the additional spraying losses can only be avoided at one single site on the circuit, whereas on the opposite side of the circuit these losses would be even higher than usual. The problem can be solved only if properly inclined nozzles are used together with a horizontal cutting tool. With this arrangement, the additional spraying losses can be avoided at any site on the cutting tool‘s circuit (Figure 12).

The second possibility for a JetCutter scale-up is the increase of the cutting frequency. The cutting frequency determines how often the jet is cut in a definite time period and, thus, how many beads are generated in that time. The cutting frequency is given by the number of cutting wires in the cutting tool and its rotation speed. Usually, the JetCutter is used with cutting frequencies between 5000 and 10000 Hertz (Hz) (maximum 14400 Hz), which means that from 5000 to 10000 beads per second are generated. A further enhancement of the cutting frequency will be achieved when a motor drive with a higher rotation speed and a cutting tool with more wires are applied. With this approach, for special applications cutting frequencies of up to 25000 Hz might be realised.

The production rates of a single nozzle JetCutter device for three common cutting frequencies are shown in Table 3. The rates are given in terms of L/(h·nozzle). Table 3 indicates that – depending on the desired particle size – even with the single nozzle JetCutter device and common cutting frequencies, the production rate per day can range between one kilogram and several tons of beads.

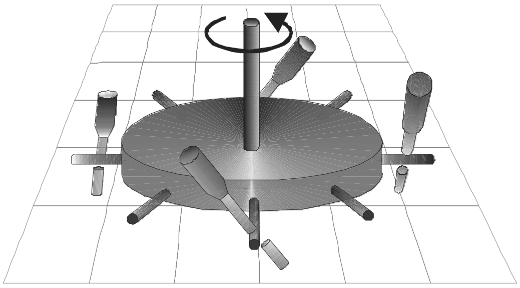


Figure 12:
Scheme of a multi nozzle JetCutter operating without additional spraying losses

Table 3:
Theoretical throughput of the JetCutter in L/(h·nozzle) for different bead diameters and a cutting frequency of 5000, 7500 and 10000 Hertz (Hz), respectively

Bead diameter,	Theoretical throughput, L/(h·nozzle)		
mm	5000 Hz	7500 Hz	10000 Hz
0.2	0.08	0.11	0.15
0.4	0.60	0.91	1.2
0.6	2.1	3.1	4.1
0.8	4.8	7.2	9.7
1.0	9.4	14.1	18.8
1.5	31.8	47.7	63.6
2.0	75.4	113	151
2.5	147	221	295
3.0	254	382	509
4.0	603	905	1206
5.0	1178	1767	2356

3.4 New developments

Currently, three major developments concerning the JetCutter are in process:

1. spraying tunnel for larger beads
2. heating device for melt processing
3. 2-fluid nozzle for simultaneous coating

The high fluid, and therefore bead, velocity is one of the advantages of the JetCutter, as high throughputs are easily realised. Nevertheless, this high droplet velocity is a problem for the collection of beads with a spherical shape, especially for larger beads. If the droplets were collected in a collection bath, e.g. a $CaCl_2$ bath for alginate beads, the droplets may be deformed at the liquid surface when entering the bath. For small droplets, the problems are minor even at speeds of up to 30 m/s. However, larger droplets which have such high speeds will be deformed at the collection bath surface due to their higher weight.

In order to overcome this problem, the droplets have to be pre-gelled prior to entering the collection bath. This pre-gelation is achieved by letting the droplets fall through a tunnel (5 m length) equipped with several spraying nozzles (Figure 13). The collection bath is permanently pumped through the spraying nozzles, which generate a fine mist (aerosol) from the collection bath inside the tunnel. While falling, the spherical droplets are covered with the mist and, thus, are pre-gelled, maintaining their spherical shape. The pre-gelation hardens the droplets – in fact they are not droplets anymore but capsules – so that they maintain their spherical shape when they enter the collection bath.

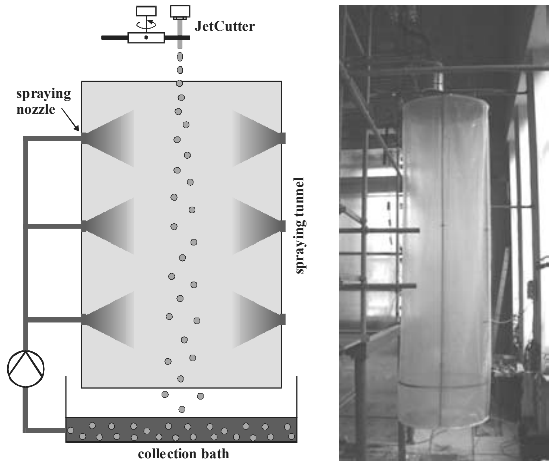


Figure 13:
Scheme (left) and photo (right) of the 5 m spraying tunnel for pre-gelation

The second new development covers the processing of all kinds of hot material, which might be melts, e.g. waxes, or hot solutions, e.g. gelatin solutions. In order to process such materials both the nozzle and the cutting tool have to be heated to avoid clogging. Therefore, the JetCutter has to be surrounded by a heating chamber (Figure 14).

Figure 14:
Heating chamber surrounding the JetCutter sitting on top of the 5 m tunnel

The heated JetCutter sits on top of the 5 m tunnel, which in this case acts as cooling line. This cooling line is sufficient to harden small beads, which have high velocities. In order to harden larger beads as well, the top of tunnel might be additionally equipped with a device to distribute cold gas in the tunnel.

The third new development is devoted to the simultaneous coating of beads by a 2-fluid nozzle (Figure 15). For details about this procedure see Prüße et al. 2000.

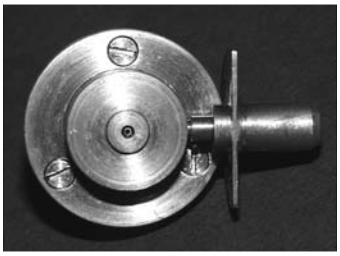


Figure 15:
2-fluid nozzle for the JetCutter

3.5 Applications

Since spherical beads are intermediates or products in different industrial sectors, e.g. agriculture, biotechnology, pharmaceutical, chemical or food industry, many applications exist for the JetCutter technology. Generally, each application field has its own requirements and restrictions concerning the materials to be encapsulated, the type and viscosity of the fluid, the desired particle size or the medium in which the beads should be gathered. In this connection it is advantageous that the JetCutter is capable of processing all kinds of liquid material covering

- solutions,
- melts and
- dispersions.

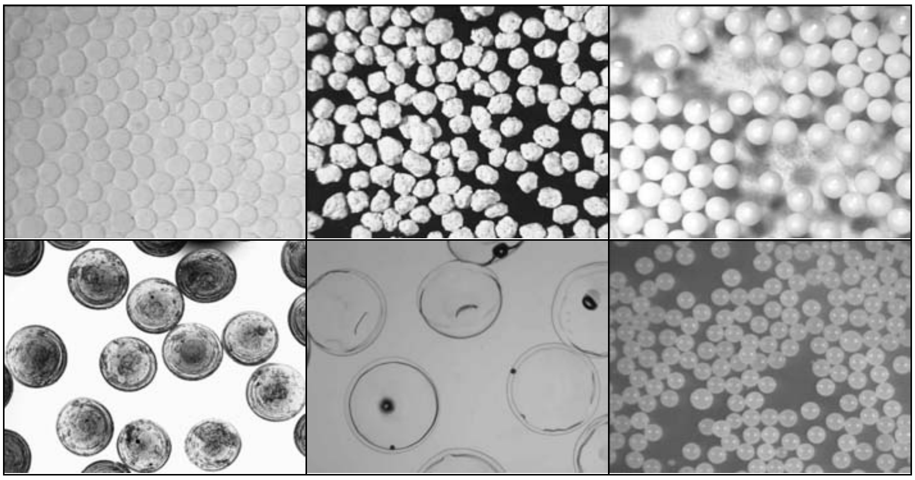
A tabular summary – not necessarily complete – of fluids tested so far or assumed to work with the JetCutter, as well as substances and materials to be encapsulated is given in Table 4.

Table 4:
Summary of fluids and materials applicable for bead production/encapsulation with the JetCutter

Fluids	Materials
• Alginate	• Pharmaceuticals, pesticides
• Pectinate	• Vitamins, amino acids
• Chitosan	• Fragrances
• Gelatin	• Bacteria, fungi, enzymes
• Cellulose derivatives	• Dyes
• Waxes	• Pigments
• Polymer melts	• Magnetite
• Inorganic sols	• Metal catalysts

Many of these substances can be connected to life sciences. Indeed, life sciences is the application field with the most diverse and challenging tasks for the JetCutter technology. For example, formulations of active agents or fragrances, controlled release systems or functional foods (e.g. vitamins, amino acids, probiotics) are generally made by encapsulation in spheri-

Figure 16:
Photos of different types of beads prepared by Jet Cutting (not in true scale). From top left to bottom right: Ca-alginate (Ø = 0.6 mm), Ca-alginate, freeze-dried (Ø = 0.3 mm), Ca-pectinate (Ø = 0.53 mm), chitosan (Ø = 0.5 mm), gelatin (Ø = 0.8 mm), wax (Ø = 0.7 mm)



cal beads. In these fields, special legal requirements may exist which affect the encapsulation materials or special substances, for example sensitive biological matter, may need to be treated in a special manner.

The common polymers applied as an encapsulation matrix in the life sciences (e.g. alginate, pectinate, gelatin, cellulose derivatives, waxes) have already been used for bead production by the JetCutter. Some examples of these beads are displayed in Fig. 16.

As already mentioned, one of the major advantages of the JetCutter is that the viscosity of the fluid does not limit bead generation. That means that not only the formulation recipes used at the moment can be applied to bead production by JetCutting, but also those whose transformation into products failed due to a too high viscosity. For the same reason biological matter can be treated at lower temperatures, i.e. more carefully, with the JetCutter since heating for viscosity reduction is not needed.

In biotechnology the JetCutter was used for the preparation of immobilised/encapsulated biocatalysts, i.e., enzymes, bacteria or fungi (Muscat et al. 1996, Prüße, Fox et al. 1998b, Leidig et al. 1999, Jahnz et al. 2001). In this field, the independence of the fluid viscosity also was proven to be advantageous since encapsulation matrices with high polymer contents and corresponding high viscosities can be used (e.g. polyvinyl alcohol) to form mechanically very stable, abrasion-free beads. Such beads were also used for the encapsulation of metal catalysts (Prüße, Morawsky et al. 1998).

As far as dispersions are concerned, sols, suspensions and emulsions may be processed with the JetCutter. Two examples of processed suspensions are shown in the Figures 17 and 18.

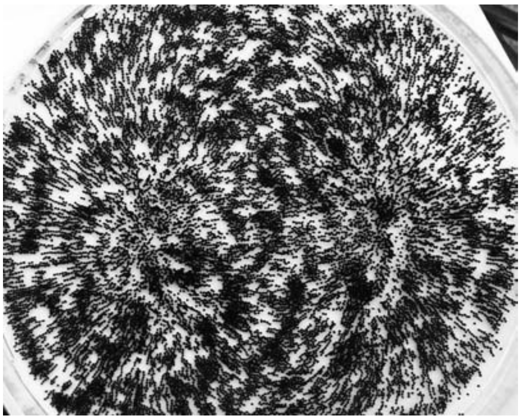


Figure 17:
20 % magnetite (in initial suspension) encapsulated in chitosan beads (Ø = 0.8 mm)

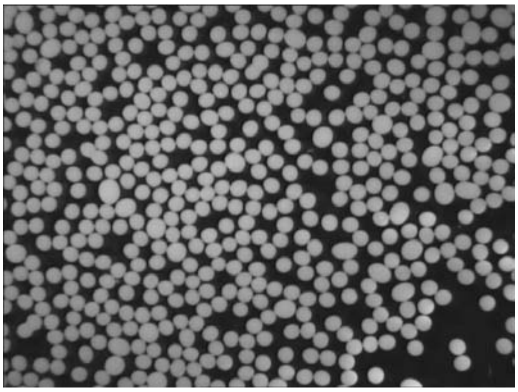


Figure 18:
40 % TiO_2 (in initial suspension) encapsulated in alginate beads (Ø = 1.3 mm)

4 Summary and prospect

Different bead production technologies based on the generation of droplets prior to their solidification were compared. Simple dropping and electrostatic-enhanced dropping are well suited for lab-scale applications. Vibrational bead production is further used in technical scale applications. The rotating disc and rotating nozzle technology suffer from the broad particle size distribution. But as real high throughput technologies they are widely used in industry. All these technologies are limited due to the viscosity of the fluids to be processed.

So far, the JetCutter is the only technology for which bead generation is not limited by the fluid viscosity. Thus, highly viscous fluids also can be transformed into beads. Furthermore, the JetCutter is a simple and efficient technology for the production of spherical beads. Monodisperse beads in the particle size ranging from approximately 200 µm up to several millimetres can be prepared with high production rates. In addition, scaling-up the JetCutter will be easily achievable. Losses can be regarded as negligible. None of the other technologies for beads production shows this combination of advantages. Further, the JetCutter may also be used to produce coated beads in a one-step process.

The JetCutter technology can be applied in different industrial sectors and for various applications such as solutions, melts and dispersions are processible. In the life sciences it might be used for the encapsulation of active agents or fragrances, as well as for the production of some functional foods (e.g. encapsulated vitamins or probiotics). In the chemical industry, applications such as the production of catalysts supports, packages for chromatographic columns or polymer pellets are possible. Many other applications are also imaginable.

The JetCutter is a very promising technology for the production of spherical beads with manifold application possibilities. According to the sum of its advantages, the JetCutter can be regarded as a superior technology for bead production. Accordingly, the first technical scale application of bead production with the JetCutter technology (capacity of about 1.2 tons/day for 1 mm beads with a density of 1 kg/L) started in summer 2002.

Symbols and abbreviations

calc	calculation
d_{wire}	diameter of the cutting wire
d_{bead}	bead diameter
D	nozzle diameter
exp	experimental
h	hour
horiz.	horizontal
Hz	Hertz
incl.	inclined
L	litre
m	meter, milli
mm	millimetre
n	number of rotations
p	pressure
Pa	Pascal
s	second
t	time
u_{fluid}	velocity of the liquid jet
u_{wire}	velocity of the cutting wire
V_{loss}	volume of the cutting loss
V^{*}_{loss}	volume of the overall loss
z	number of cutting wires
α	inclination angle
β	cutting angle
µm	micrometer
Ø	diameter

References

Champagne C, Blahuta N, Brion F, Gagnon C (2000) A vortex-bowl disk atomizer system for the production of alginate beads in a 1500-liter fermenter. Biotechnol Bioeng 68(6):681-688

Heinzen C, Marison I, Berger A, von Stockar U (2002) Use of vibration technology for jet break-up for encapsulation of cells, microbes and liquids in monodisperse microcapsules. Landbauforsch Völkenrode SH 241:19-25

Jahnz U, Wittlich P, Prüße U, Vorlop K-D (2001) New matrices and bioencapsulation processes. Focus on biotechnology 4:293-307

Koch M, Walzel P (2001) New findings on catalyst encapsulation in a pilot plant. 3rd European Congress on Chemical Engineering [CD-ROM] Dechema e.V. Frankfurt/Main

Kuncová G (2002) Web-based literature database "Encapsulation Technologies": Dropping. <http://www.genialab.de/WG3/>

Lacík I (2002) Web-based literature database "Encapsulation Technologies": Vibration. <http://www.genialab.de/WG3/>

Leidig E, Prüße U, Vorlop K-D, Winter J (1999) Biotransformation of Poly R-478 by continuous cultures of PVAL-encapsulated Trametes versicolor under non-sterile conditions. Bioprocess Eng 21(1):5-12

Muscat A, Prüße U, Vorlop K-D (1996) Stable support materials for the immobilization of viable cells. In: Wijffels RH, Buitelaar RM, Bucke C (eds) Immobilized cells: basics and applications, Elsevier, Amsterdam, pp 55-61

Nedović V (2002) Web-based literature database "Encapsulation Technologies": Electorstatic-enhanced dropping. <http://www.genialab.de/WG3/>

Nedović VA, Obradović B, Poncelet D, Goosen MFA, Leskošek-Čukalović I, Bugarski B (2002) Cell immobilisation by electrostatic droplet generation. Landbauforsch Völkenrode SH 241:11-17

Prüße U, Bruske F, Breford J, Vorlop K-D (1998) Improvement of the Jet Cutting Method for the Preparation of Spherical Particles from Viscous Polymer Solutions. Chem Eng Technol 21(2):153-157

Prüße U, Dalluhn J, Breford J, Vorlop K-D (2000) Production of spherical beads by JetCutting. Chem Eng Technol 23(12): 1105-1110

Prüße U, Fox B, Kirchhoff M, Bruske F, Breford J, Vorlop K-D (1998) New Process (Jet Cutting Method) for the Production of Spherical Beads from Highly Viscous Polymer Solutions. Chem Eng Technol 21 (1):29-33

Prüße U, Fox B, Kirchhoff M, Bruske F, Breford J, Vorlop K-D (1998) The Jet Cutting Method as a new Immobilization Technique. Biotechnology Techniques 12 (2):105-108

Prüße U, Morawsky V, Dietrich A, Dierich A, Vaccaro A, Vorlop K-D (1998) Encapsulation of Microscopic Catalysts in Polyvinyl Alcohol Hydrogel Beads. Stud Surf Sci Catal 118:137-146

Prüße U, Vorlop K-D (2002a) Web-based literature database "Encapsulation Technologies": Rotating disc, rotating nozzle. <http://www.genialab.de/WG3/>

Prüße U, Vorlop K-D (2002b) Web-based literature database "Encapsulation Technologies": JetCutter. <http://www.genialab.de/WG3/>

Walzel P (2001) <http://www.chemietechnik.uni-dortmund.de/mv/>