DESIGN OF A BEARINGLESS BUBBLE BED REACTOR

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SUMMARY

In the past, several studies have found bubble aeration in animal cell cultures, especially the bursting of bubbles in the foam region, to be responsible for significant cell death. In order to reduce these detrimental cell-bubble interactions, the so called "bubble bed reactor was developed at the Swiss Federal Institute of Technology (ETH) Zurich. This modified loop reactor accumulates oxygen bubbles in the downcomer and has thereby a more than 10 times higher oxygen uptake than standard air-lift reactors. With the example of a 250L bubble bed reactor it has been shown that an oxygen yield in excess of 90% is reachable and that the bubble bed reactor is a gentle aeration method for animal cell cultures.

One of the main remaining sources for cell death in the bubble bed reactor is the shaft seal of the impeller. In this paper we present a concept for a bubble bed reactor with a totally magnetically suspended impeller. It is based on the technology of the "bearingless motor" and is therefore called the "bearingless bubble bed reactor". A single bearingless motor with a ring shaped rotor is at the same time a motor and a bearing system. The ring shaped rotor with the axial flow impeller is arranged around the downcomer inside the tubular reactor housing. The motor/bearing stator is arranged around the housing. The six spatial degrees of freedom of the rotor are stabilized magnetically through the housing wall which is in the air gap. Three degrees of freedom are stabilized actively (the rotation and the radial displacement of the rotor). The axial and the angular displacement are stabilized passively.

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MOTIVATION AND INTRODUCTION

One of the main functions of a bioreactor is to feed the growing cells with oxygen. For example for a typical cell density of 10^7 cells/mL an aeration rate of 150mg O_2/Lh is needed. Several studies with animal cell cultures in standard bioreactors have found bubble aeration, especially the bursting of bubbles in the foam region, to be responsible for significant cell death. In order to reduce these detrimental cell-bubble interactions, the so called "bubble bed reactor was developed at the Institute of Process Engineering of the Swiss Federal Institute of Technology (FIT) Zurich (Sucker et al., 1994). Figure 1 shows the functional principle of a bubble bed reactor.By generating a loop flow which is directed opposite to the emerging air bubbles in the downcomer, oxygen bubbles are accumulated there if the flow speed and the bubble speeds are equivalent (see figure 2). In this case, the accumulated bubbles form the so called bubble bed which gave the name to this type of bioreactor. Compared to conventional systems, the accumulated bubbles are for a much longer time in contact with the liquid. Therefore much more oxygen is dissolved. The bubble bed reactor has shown a more than 10 times higher oxygen uptake than standard air-lift reactors. In a 250l prototype, an oxygen yield of nearly 95% was reached (Trocha , 1997). With this prototype it has been shown that the bubble bed reactor is a gentle and very efficient aeration method for animal cell cultures.

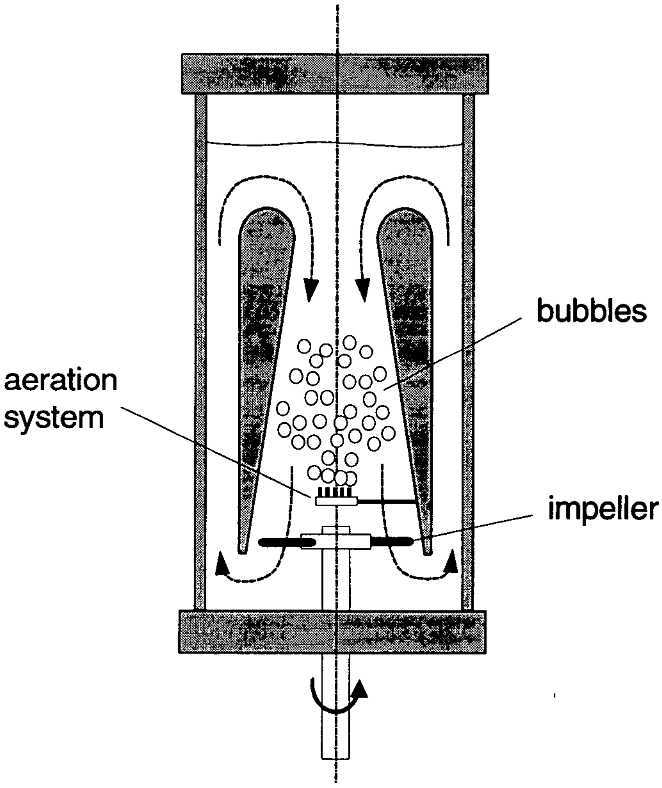


Fig. 1: Functional principle of the bubble bed reactor

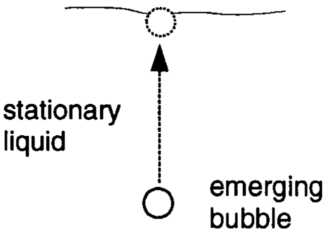


Fig. 2a: Air bubble in a standard air-lift reactor

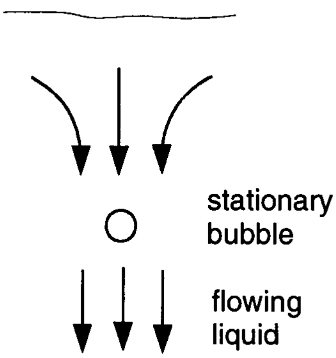


Fig. 2b: Air bubble in a bubble bed reactor

A drawback of the arrangement shown in figure 1 is the relatively inhomogenous flow field in the downcomer which can cause the release of bubbles. The slight turbulences are due to the central position of the impeller. An axial flow impeller at the circumference of the downcomer would lead to a more homogenous flow field in the downcomer. However, to mount and drive such a ring shaped impeller from a central shaft, a complicated support is necessary which also effects the flow field negatively. Furthermore, the shaft seal can also cause cell death and is one of the main reasons for bacteria infection.

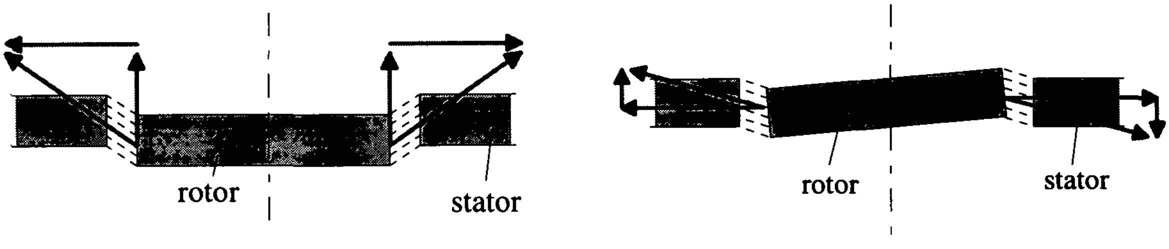
A possibility to overcome these problems could be to drive the ring shaped impeller through the reactor housing by an AC motor and to mount the impeller in magnetic bearings. The straightforward solution with an axial bearing, two radial bearings and a motor in between would require a lot of space and would be very expensive. Also the large air gap of at least 3 mm (because of the housing strength) might be a problem. A successful application of magnetic bearings in the bubble bed reactor requires a completely different approach.

THE NEW APPROACH

Recent developments in the field of electrical drives and magnetic bearings have led to so called "bearingless motors"(see Bichsel, 1990; Chiba et al., 1991; Ohishi et al., 1994; Schöb and Bichsel; 1994, Ooshima et al., 1996). In the context "bearingless" does not mean the lack of bearing forces, which are necessary in any case to stabilize the rotor, but the absence of significant bearings. In principle the bearingless motor is based on the contactless magnetic bearing of the rotor. In contrast to conventional magnetic levitated drives, the bearing forces are not built up in separate magnetic bearings placed on the left and right side of the motor, but in the motor itself. The active motor part generates the torque as well as radial magnetic bearing forces.

Normally, two motor parts are needed for the full stabilization of five spatial degrees of freedom. If the length of the rotor is small compared to its diameter, it is possible to stabilize three spatial degrees of freedom passively. Only one active radial bearing is needed. Figure 3 shows the functional principle of the passive levitation with this arrangement. It is provided that the rotation and the radial position of the rotor are controlled actively by the principle of the bearingless motor. The left part of figure 3 shows an axial displacement of the rotor. The displacement results in attractive magnetic forces which act in the opposite direction to the displacement and therefore stabilize the axial position of the rotor. The right part of the figure shows tilting of the rotor. It leads to stabilizing magnetic forces, as can be seen in the picture too.

The functional principal of this "bearingless slice motor" has been demonstrated before with the example of a relatively small rotor with 45 mm diameter (Schöb and Barletta, 1996). A first application for this type of motor has been developed in the field of pumps for highly clean liquids (Barletta and Schöb, 1995; Schöb and Meuter, 1997). With this success on small systems it seems obvious to use the same technology for the bubble bed reactor. This leads to a very simple, compact, and cost effective solution as is schematically shown in figure 4.



axial displacement of the rotor

tilting of the rotor

Fig. 3: Passive stabilization of the axial displacement (left) and tilting of the slice rotor (right)

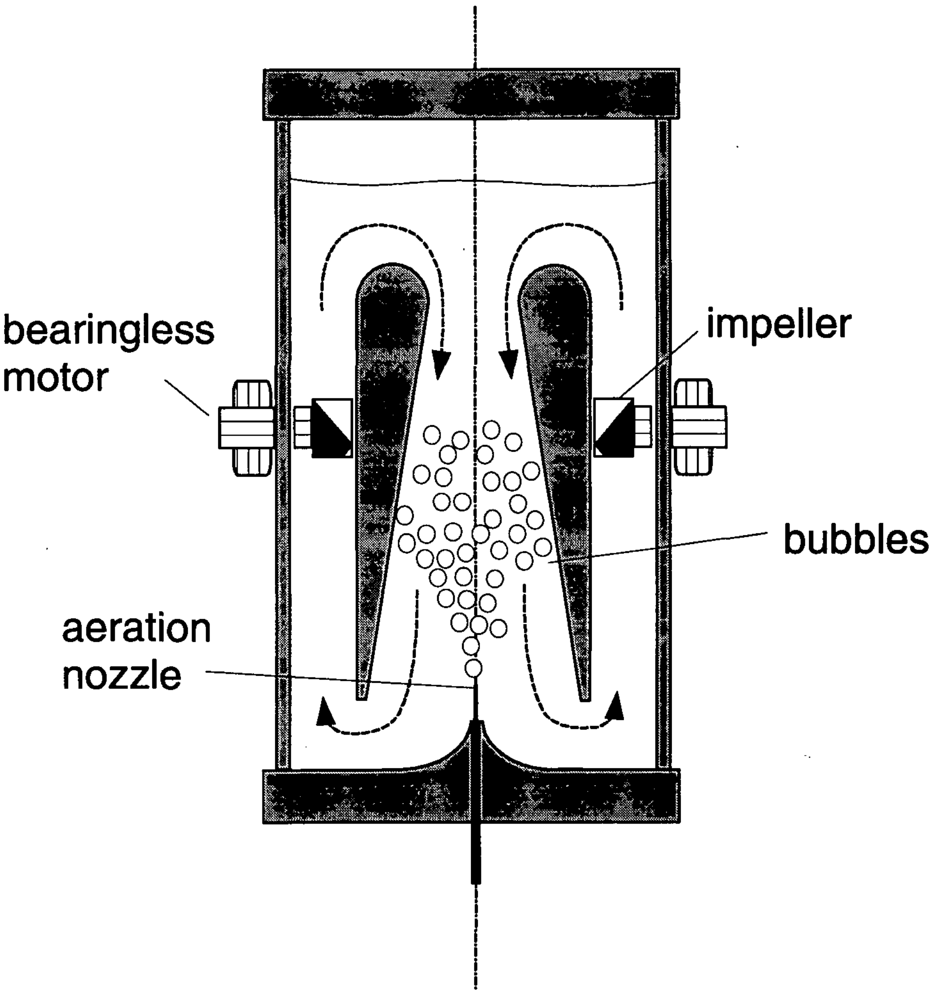


Fig. 4: Functional principle of the bearingless bubble bed reactor

MOTOR DESIGN

It was clear from the beginning that only a permanent magnet synchronous type bearingless motor would allow an air gap of 3 mm without producing excessive losses and requiring high inverter power. During the design of the motor it became obvious that the concept of the pump motor with its 45 mm rotor was not directly applicable to the 188 mm rin-shaped rotor. For the bubble bed reactor it is crucial that the inner bore of the rotor is as wide as possible in order to provide enough space for the impeller. The goal was to reach a bore of 160 mm. From a manufacturing point of view, the rotor magnet has to be divided into eight segments or more. Both general setups argue in favour of a high pole motor. It was found that due to the large rotor diameter already a small part of the circumference is sufficient to create the specified torque of 0,3 Nm. A high pole segment motor with 24 rotor poles but only 4 corresponding stator poles would be the most adequate drive. On the other hand, from the bearing point of view, the axial load capability (because of the rotor weight) and tilting stiffness were recognised to be the most critical design parameters. The problem was to combine a high pole segment motor which requires only about 60° active stator area with a magnetic bearing which has a large air gap (3mm), generates moderate actively controlled radial forces and relatively high passively stabilising axial forces and tilting stiffness.

One way to solve this optimization problem is shown principally in Figure 5. A permanent magnet biased homopolar magnetic bearing is combined with a high pole segment motor. In this arrangement, the bias flux path of the bearing is completely separated from the control flux path. The bias flux generates in interplay with the control flux controllable radial bearing forces. Beside exciting the bias flux, the permanent magnets form a passive magnetic axial bearing with additional excellent tilting stabilization. A similar arrangement has been proposed before in [11]. The idea is now to generate a high-pole modulated but rectified bias flux which interacts with motor segments of the same pole width. Especially simple motor configuration can be achieved by splitting the motor phases into different motor segments. Figure 5 shows the example of a two phase motor with two stator segments per phase and concentrated windings. Figure 6 shows the arrangement of the stator segments in relation to the rotor magnets. The stator segments of corresponding phases are arranged in opposite positions. This helps to balance the magnetic pull forces. The stator segments of different phases are shifted by half the pole distance.

SENSORS

For the control of the radial rotor position, it is crucial that the position is measured in the middle of the rotor. Otherwise there is a coupling between tilting of the rotor and the measurement of the radial position. This coupling can lead to instability. A simple solution to the problem is to measure the air gap flux and to calculate the rotor position from the air gap flux and the control current. However, with switching amplifiers, relatively noisy signals can result. Another method is to measure the rotor flux at two opposite positions somewhere between the stator teeth. By weighting the signals with the corresponding magnitudes and forming the difference, a good position signal can be gained. If this is done in two quadrants, the radial position of the rotor can be determined.

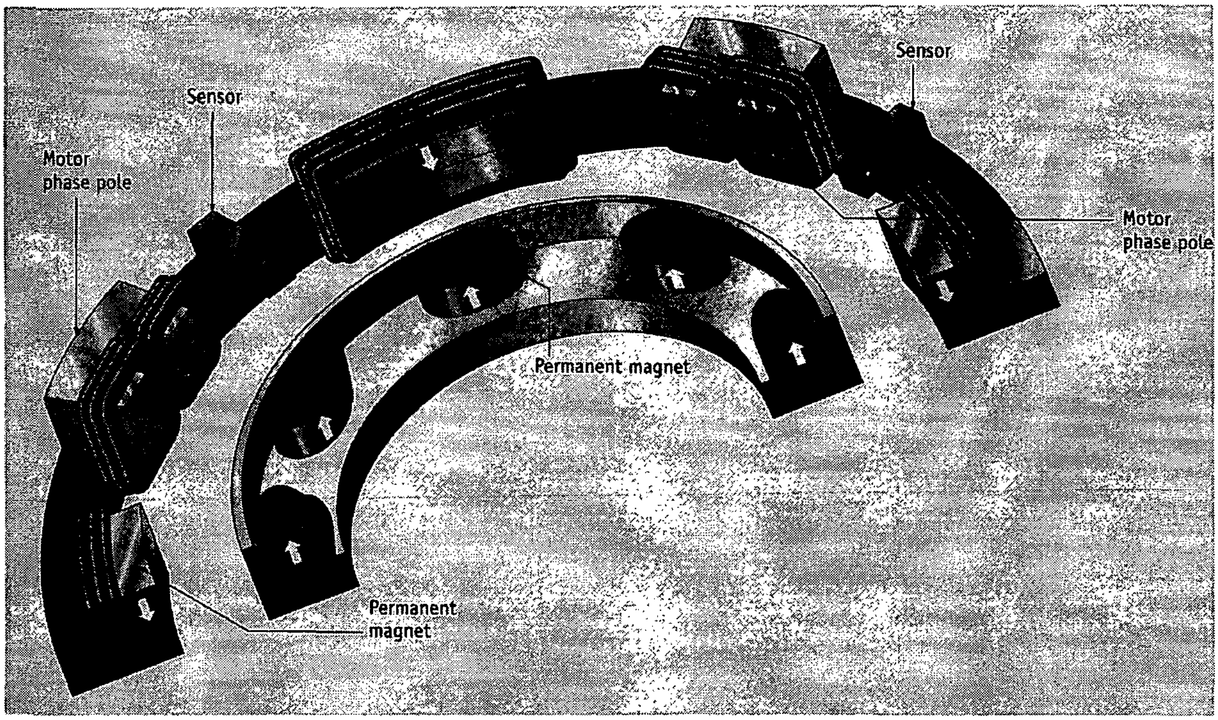


Fig. 5: Functional Principal of the combined motor-bearing
(Picture from Eureka March 1998 by courtesy of Findlay Publications)

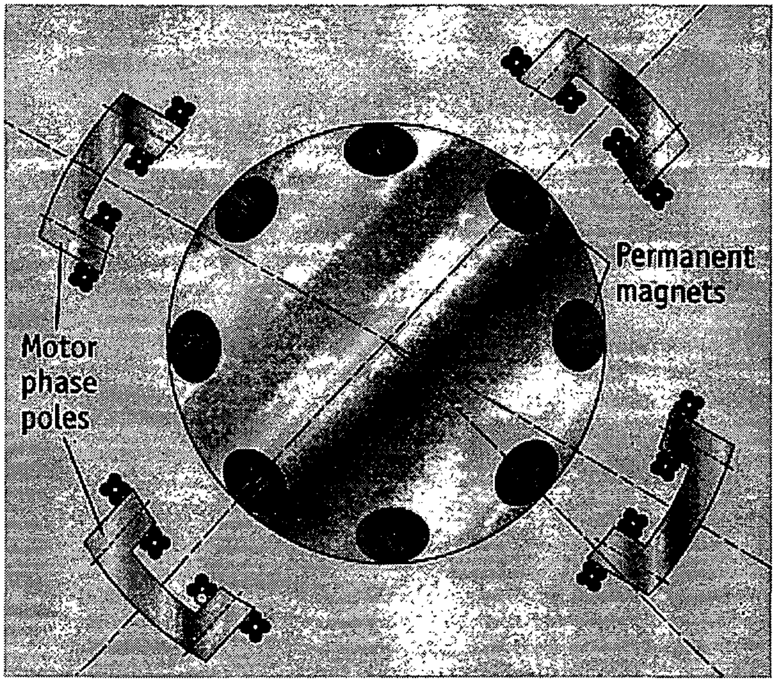


Fig. 6: Arrangement of the stator segments relative to the rotor magnets
(Picture from Eureka March 1998 by courtesy of Findlay Publications)

THE PROTOTYPE SYSTEM

Figure 7 shows the prototype bubble bed reactor with the control electronics. It has a diameter of 200 mm (without the motor), a height of 720 mm and a content of about 18 L. Due to the avoidance of a central shaft an aeration nozzle can be placed in the centre of the bottom. Figure 8 shows the central part of the reactor with the motor/bearing stator, the axial flow impeller and the pump stator. The impeller and the stator blades are designed to produce minimum hydraulic axial forces. Figure 9 shows a close up of the motor-bearing system with the impeller. The rotor has an outer diameter of 188 mm and a bore of 160 mm which contains the impeller. Its total weight is 2.2 kg. The stator has an inner diameter of 194 mm, an outer diameter of 266 mm and a height of 48 mm. The control electronics for the drive and the bearing windings is placed in a small cabinet with the dimensions 85x105x162 mm. It is based on our standard pump controller and incorporates an 80 MHz DSP TMS 320C50 with standard PC interface and CAN-BUS controller, a universal sensor interface for Hall sensors as well as for eddy current sensors and five 200 VA inverter channels.

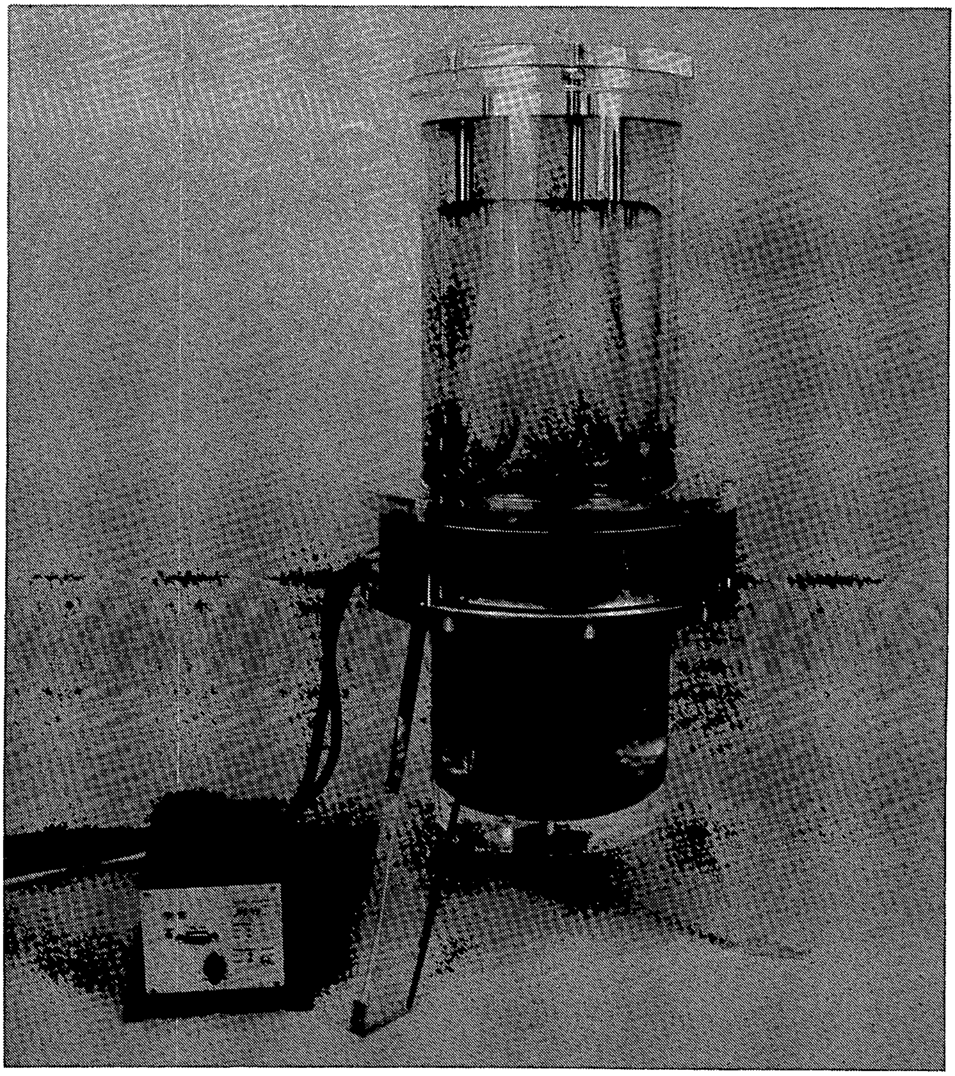


Fig. 7 : Prototype bubble bed reactor with the control electronics

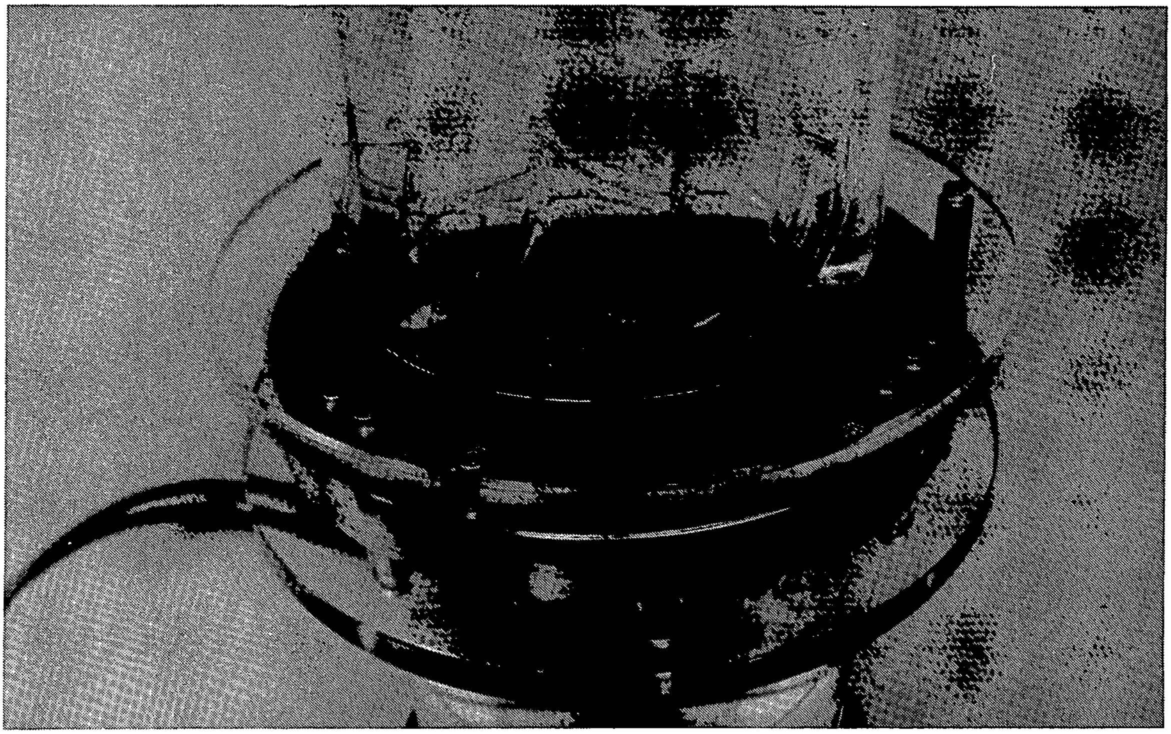


Fig. 8: Central part of the reactor with the motor/bearing stator, the axial flow impeller and the pump stator

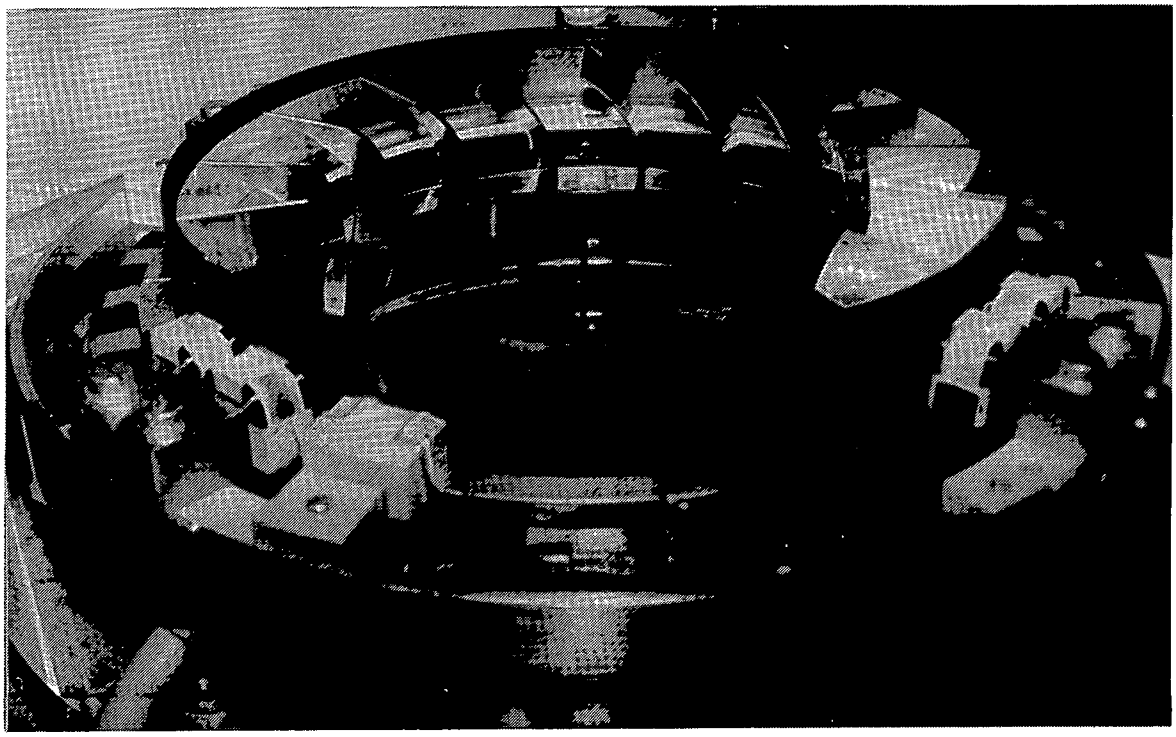


Fig. 9: Motor-bearing system with the impeller

TEST RESULTS AND OUTLOOK

The prototype is able to capture bubbles in the "bubble bed" very efficiently. This happens already at less then half the maximum speed of 300 rpm and requires a torque of less than 0.3 Nm, which is slightly more than half the peak torque. The bearing system is very robust. It can handle axial loads of up to 53 N and radial loads of 35 N, which is much more than what is required during operation. Also the passive bearing shows a relativ high axial stiffness of 22 N/mm and a tilting stiffness of 1.1 Nm/°. The power consumption of the whole system is only 78 W at the operating point. So far we have tested the system for more than half an year. During this time, the drive system showed not a single failure or operating problem. This makes us confident that the system can be successfully applied in an industrial environment. For this step we have designed a whole range of motor/bearing systems. The main parameters of these drives are summarized in table 1.

D_R [mm]	**d_R** [mm]	**h_R** [mm]	**D_S** [mm]	**h_S** [mm]	**L_R** [mm]	**F_{max} (axial)** [N]	**F_{max} (radial)** [N]	**M_{max} torque** [Nm]
188	160	20	266	48	3	50	35	0.5
188	150	40	274	88	3	90	70	1.2
350	300	30	450	64	3	90	70	2.7
350	290	50	460	118	3	160	140	6.5
500	440	50	660	112	3	130	150	4.8
500	420	80	680	190	3	220	300	12

Table1: Date of several bearingless motors

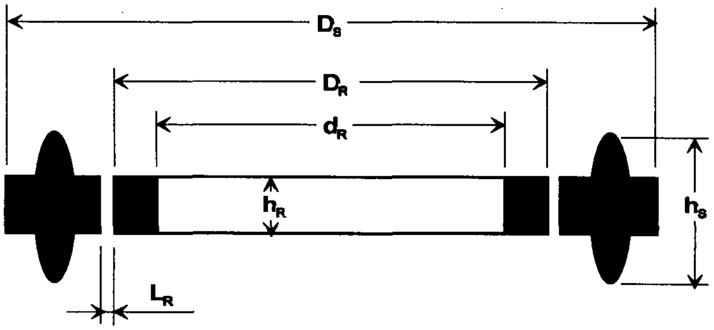


Fig. 10: Measures of drive parts summarized in table 1

With the prototype bubble-bed reactor we have shown that the bearingless motor offers exciting new options in the field of biotechnology. The outstanding features of the new system are:

- no rotating seals
- no wear

- absolutely hermetic system
- simple cleaning and sterilization (no narrow clearances and fissures)
- no cell damage by the drive
- no central shaft, which offers new options in the construction
- precise regulation of speed
- interesting price

What makes the system especially interesting is its moderate price which is absolutely comparable to magnetic coupling systems with speed control.

ACKNOWLEDGEMENTS

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