MAIN CIRCULATOR DESIGN FEATURES FOR HTR 100, HTR 500 AND SPACE HEATING PLANTS

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Abstract

All design alternatives for modern high-temperature reactors have a common circulator concept: It is based on a vertical shaft design with a flying impeller. The circulators are equipped with active magnetic bearings and are driven by induction motors connected to variable-speed static converters.

Due to their multiple functions during normal reactor operation and under accident conditions, extremely high requirements are made to safety-relevant circulators, since with the reactor pressurized as well as under depressurized conditions specified delivery heads and flow rates have to be ensured.

The use of active magnetic bearings permits to obtain maintenance-free operation and functional safety to an extent which had not been achieved before. Magnetic bearings are therefore provided for the total range including primary gas circulators of a drive power of several MW as well as circulators for helium loops of reactor auxiliary systems.

The essential feature for using active magnetic bearings is the retainer bearing technology, preventing contact between rotor and static circulator parts upon unintended deenergisation of the magnets. Results of current experiments are reported.

Another aspect to be considered for reliable long-term operation for several decades is the effect of rotor dynamics. The various natural frequencies resulting from torsion and bending modes in view of a drive by a frequency-controlled induction motor have to be considered as well as the specific characteristics of the active magnetic bearings.

Special attention has to be directed to the internal cooling loop so as to ensure that reactor temperature excursions in the event of deviation from normal operation can be overcome without damage. For circulator components exposed to temperature fields the design characteristics are determined by combining experimental and analytical methods.

The coordination of all component parts is currently being optimized on a prototype circulator whose detailed design is underway. This circulator will be tested in a test stand designed for test runs of all different circulator sizes.

1 Preview to Future HTR Plants and Their Circulators

With the beginning of commercial power operation of the THTR-300 the pebble-bed high-temperature reactor is now at the threshold of maturity for the commercial market.

Safe and reliable reactor operation is directly related with the reliability of the coolant gas circulators. They are the only active components installed in the reactor. A failure of the circulators mostly necessitates a plant shutdown. In consequence stringent requirements reagarding availability and safe operation are to be complied by the circulator design.

The way how the coolant gas circulators are integrated in the reactor are of major importance for the overall arrangement of the nuclear section. As a consequence of the expenditure and the disadvantages involved in arranging the circulators at the side of the primary loop a new circulator concept was developed. Its features are as follows:

- A vertical arrangement of the circulators makes use of the existing openings in the prestressed concrete reactor vessel required for installing the steam generators.
- Use of active magnetic bearings for the circulators: this definitely precludes any possible contamination of the primary loop by oil.
- Actuation of the circulator shutdown valve in accordance with the "oil-free circulator operation" concept.

The circulators for the various reactor types have the following specific features:

HTR 500: there are no safety engineering requirements for the 6 main circulators since decay heat removal is taken care of by two additional NWA circulators. We are therefore developing at present design solutions for the safety-related NWA circulators which also cover the requirements for all other coolant gas circulators.

HTR 100 (Industrial Reactors and Modular Plants): here two systems, each consisting of steam generator and circulator, are used; thus a redundancy for decay heat removal exists which uses operational equipment.

GHR 10 Space Heating Reactor: Because of the low power density heat removal by natural convection does not involve any problems when decay heat has to be removed. No safety-engineering requirements exist.

Fig. 1 shows the main design parameters for the various coolant gas circulators in the different reactor types. An essential feature of our R & D activities is that the impeller of the NWA circulator for the HTR 500 has some of the largest dimensions used to date because of the different conditions "reactor under pressure" and " reactor de-pressurized".

Technical Data		Units	HTR 500 Main circulator	HTR 500 Circulator for decay heat removal R under press.	HTR 500 Circulator for decay heat removal R depressurized	HTR 100 Industrial Plant normal operation	HTR 200 Modular Plant normal operation	GHR 10 Heating Reactor normal operation
Mass Flow	M	kg/s	108	22,8	4,1	55,6	85,5	8,8
Helium Pressure	P	bar	55	55	1	70	61	15
Helium Temperature	T	°C	280	280	120	250	248	280
Pressure Rise	ΔP	bar	1,4	0,03	0,07	1,36	1,5	0,2
Helium Density	Ro	kg/m³	4,80	4,80	0,123	6,34	5,50	1,30
Impeller Diamet.	D	m	1,0	1,25		0,71	0,8	0,56
Speed Range	n	min⁻¹	700 to 4800	570	5280	580 to 5600	530 to 5300	1100 to 5880
Motor Power	P_K	kW	4100	25	430	1800	3100	200
Position	/	/	impeller down	impeller at the top		impeller down		
Rotor Mass	G	kg	3000	2100		1800	2500	1500
Number of Circulators per Reactor		/	6	2		2	2	1

FIG.1. Table of main data for the various cooling gas circulators.

2 Basic Requirements for Circulators

As rotating turbo-machines they are virtually not subject to wear. The shape of the impeller as the only active part has been a topic of theoretical consideration ever since Euler's equations were formulated two centuries ago. Despite this the devil is in the nuts and bolts, naturally, even today, and in the short time available for this paper it is not possible to refer to all the details which have to be considered in blower design.

2.1 Fluidic Boundary Conditions

Due to the different operating conditions of the reactor the coolant gas circulators operate over a wide speed range within the entire family of characteristics. Furthermore several circulators are arranged in parallel - except in the space heating reactor. The basic requirement to be derived from this is a characteristic as stable as possible without distinctive reversal points and without a pronounced peak.

Impellers with a higher degree of reaction are best for meeting this requirement. Although this means relatively large impeller dimensions, the diffusor does not require excessive attention. In addition impellers can be designed for high circumferential speeds, and because of their simple design a very long service life can be guaranteed.

2.2 Structural Boundary Conditions

All modern HTR concepts in Germany are now based on the use of coolant gas circulators with active magnetic bearings. Fig. 2 shows their principle mode of functioning. The figure also indicates by which physical parameters the bearing capability of an active magnetic bearing is determined. The order of magnitude of the specific bearing capability at the bearing faces controlled by the magnetic flux is around 50 N/cm^2.

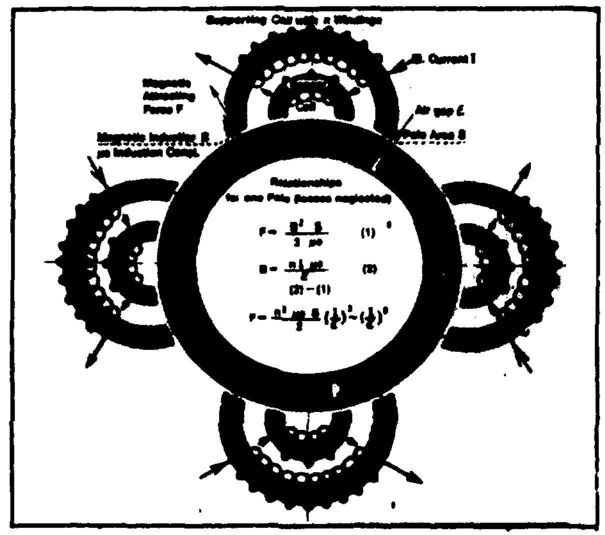

FIG.2. Active magnetic bearing principle.

To make the circulators repairable their design shall allow easy decontamination with simple assembly tools. In Germany one must assume that a contaminated coolant gas circulator can never be returned to the manufacturer's workshop. Any replacement of parts must be possible at the site of installation in the controlled area of the power plant.

3 Design Features of the Prototype Circulator

The new circulator technology is to be tested with the NWA circulator for the HTR 500. The impeller dimensions are determined by the decay heat removal operation with depressurized reactor. Since considerable quantities of helium at low pressure must be circulated in the reactor for this operating mode, only a big impeller running at high speed can cope with the task. During normal decay heat removal operation with pressurized reactor the circulator speed is smaller by one order of magnitude.

Fig. 3 is a cross section through the circulator. Its shape is determined by the circulator shutdown valve. This valve has only opening and closing function and prevents reactor core by-passes during normal operation. The actuator moves the valve mechanism from one end position to the other within 10 seconds.

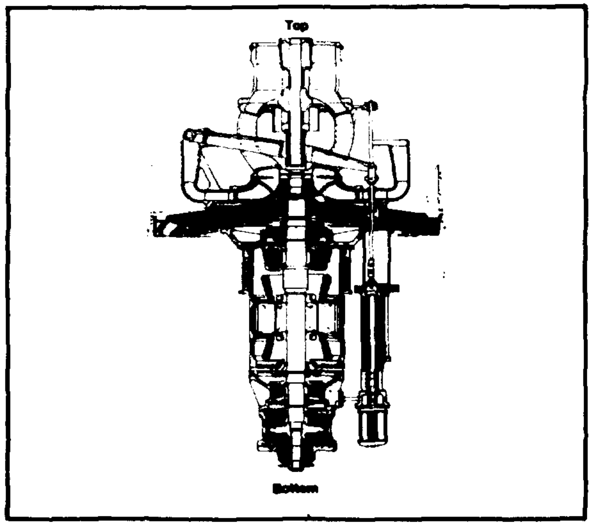

FIG.3. Cross-section of the NWA-circulator for the HTR 500.

The flow restrictor fitted with thermal shielding on the hot side, is additionally water-cooled on the motor side. Its design strength is sufficient to withstand the pressure differential which may arise when the reactor is de-pressurized. This differential will be built up because the helium enclosed in the circulator motor compartment can only flow into the primary loop through the shaft penetration.

The internal motor cooling circuit for removing the dissipation heat from the electrical components and the heat entering from the reactor is kept going by an auxiliary impeller and a water cooler.

3.1 Necessity and Functioning Mode of the Retainer Bearings

An essential prerequisite for the use of active magnetic bearings are retainer bearings preventing undesired contact between the rotor and stationary parts of the machine when the magnets are de-energized.

Fig. 4 depicts the functioning mode of our retainer bearing test facility, the overall view of which was already shown by Dr. Stölzl in his general paper. The locations shown in red and dark blue indicate the principle: if the active magnetic bearings fail the shaft will drop onto conical parts which themselves run in friction bearings.

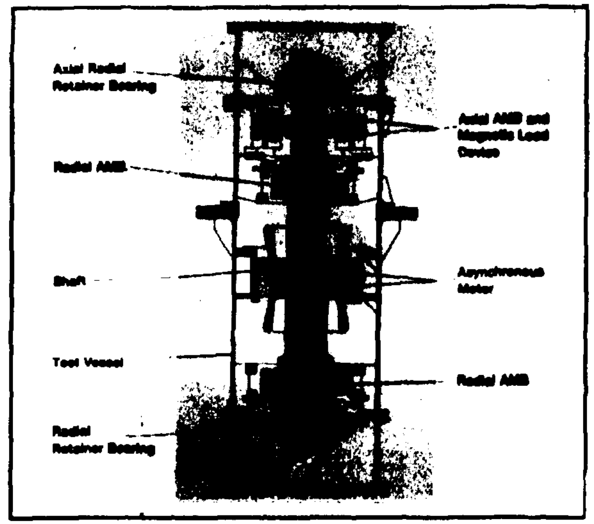

FIG.4. Arrangement for the retainer bearing test facility, schematic.

The retainer bearing will be accelerated to the shaft speed within a few hundred ms if the shaft is dropped. The shaft may then safely coast to a halt as a result of the power consumed by the impeller of the circulator or by the additional electric braking with the motor which happens in our test facility.

The advantage of the active magnetic bearing in the retainer bearing test facility is not only that shaft drops take place under realistic boundary conditions. It is possible in addition to make rotor loads associated with larger rotor dimensions act upon the retainer bearings via magnetic forces. And finally it is possible to re-energize the magnetic bearing during an experiment in the event of an impending failure of a retainer bearing. The rotor will then return to the levitation position and further damage of conical parts and retainer bearing components is avoided.

Nearly 100 rotor drops have been carried out to date. At the moment retainer bearings with dry lubrication are being optimized. Fig. 5 depicts the typical plot of a number of test parameters for a shaft drop from an initial speed of 6100 r.p.m.

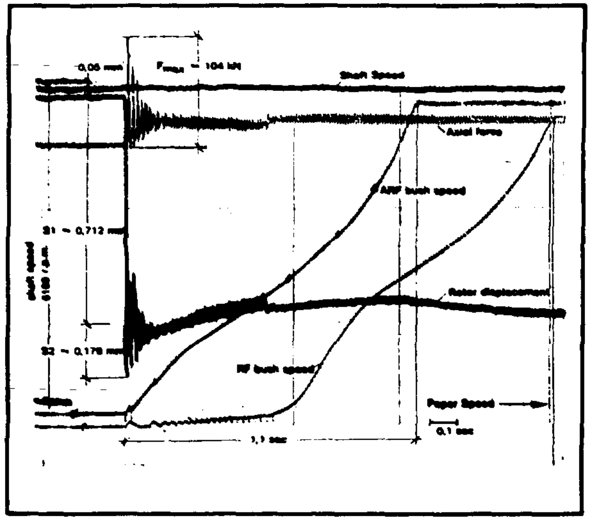

FIG.5. Test parameters at the beginning of a shaft drop.

Plot 4 shows that the running-up of the upper axial-radial retainer bearing (ARF) takes approx. 1.1 s. For the lower radial retainer bearing (RF) an analogous run-up takes place according to plot 5, however with a time delay of ca. 0.5 seconds.

The axial force taken up by the ARF is most interesting. With a rotor weight of 1320 kg in the test facility an additional magnetic load was applied. According to plot 2 an axial load of ca. 25 kN was measured after the dynamic processes accompanying the drop had died down. The shock load which occurs at the first moment of the drop, amounting to 104 kN, represents four times the quasi-static load appearing later on.

One of the focal points of the development activities is the design of the friction bearings and their lubrication. Since the coolant gas circulators are designed for operation in pure helium the unfavourable friction properties of ferrous materials involved in comparison with operation in air must be taken into consideration.

We provide special coatings e.g. molybdenum disulfide, and also supplementary structural measures for the configuration of the friction bearing guideways. In addition one must naturally prevent that the friction cones are welded together in the pure helium atmosphere when the retainer bearing is accelerating.

From the tests to date one can clearly see that a specific clearance in the friction bearings is a prerequisite for a reproducible functioning of the retainer bearings. This tolerance is partly disappearing during a drop due to friction-induced thermal expansion. In this context it is to be considered, too, that the heat flow from the impeller to the motor compartment which will occur during subsequent operation will also influence the bearing clearance.

3.2 Magnetic Bearing Technology

Fig. 6 is a view of a stator part for an active magnetic bearing, manufactured by BBC Brown Boveri and ready for installation. The winding and insulation techniques are very similar to that of electric motors. As far as possible the

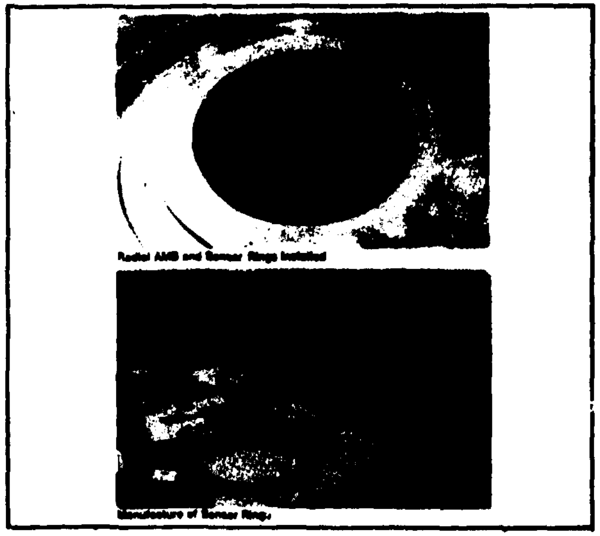

FIG.6. AMB components being assembled.

magnetic circuits of the magnetic flux are constructed with laminated cores to keep losses as low as possible.

The air gap between rotor and stator for the coils is in the order of 1 mm. The control system must be able to compensate the dynamic effects of imbalances, and in particular those caused by external impacts such as e.g. earthquakes.

As can be seen from the right-hand corner of Fig. 7, the dynamic fraction of the rotor loads is decisive for the dimensioning of the magnetic bearings' electronic control system, because the radial displacements involved require high coil currents very fast and these currents should be in phase with the shaft motion.

Fig. 7 furthermore shows that the positive bearing stiffness which exists automatically in conventional bearings can in the case of active magnetic bearings only be realized by means of current changes. For a current which is kept constant the position of the shaft in the active magnetic bearing is unstable.

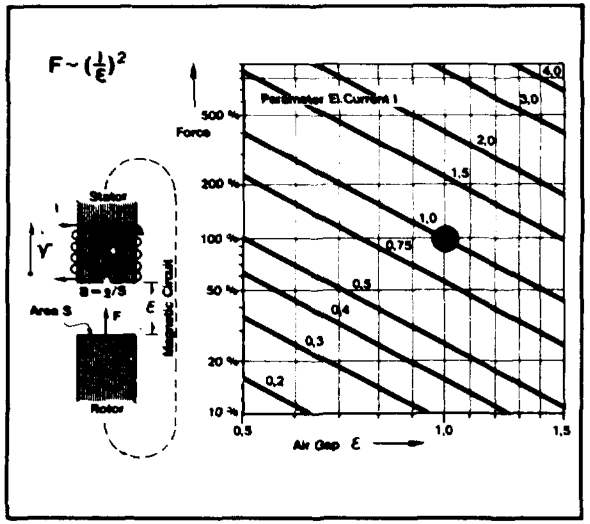

FIG.7. Interaction of current in AMB coil, bearing force and air gap, schematic.

The dynamic performance of the rotor with consideration of gyrostatic effects must also be taken into account for the design of the active magnetic bearings. Fig. 8 shows the major shaft vibration modes for a prototype rotor as a function of the bearing stiffness. Simultaneously the typical curve of the speed-dependent magnetic bearing stiffness has been entered which may be shifted within certain limits by the electronic control system. This also points out the principle how a coolant gas circulator can be operated over a wide speed range without being influenced by resonances.

In Fig. 8 the usual bearing stiffness of an oil-lubricated friction bearing has also been plotted. Active magnetic bearings are far removed in the less stiff range, where the concentration of the critical speed is no longer restricted to such narrow speed ranges, far removed from the actual processes, as in the case of the oil-lubricated bearing.

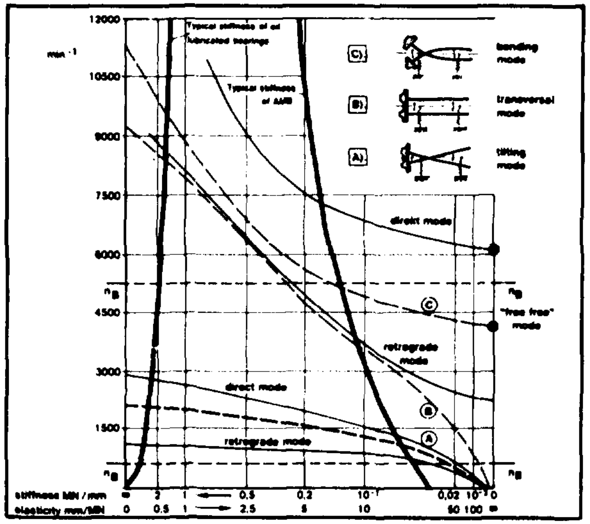

FIG.8. Shaft vibration modes of prototype circulator.

This and also the fact that with active magnetic bearings, contrary to oil-lubricated bearings, a but slightly damped retrograde mode may occur, underlines that the consideration of the dynamic natural modes of the rotor is a very important detail for the design of active magnetic bearings with decisive consequences for the electronics requirements, e.g. electric damping characteristics in certain speed ranges.

3.3 <u>Integrated Induction Motor</u>

In case of large machine capacities in particular a solid-state converter is much more easy to build for a synchronous machine than for an induction motor. Our decision in favour of an induction motor was mainly based on the following three arguments:

- Because of the poor accessibility of the encapsulated rotor parts during reactor operation in the course of an estimated service life of 40 years any type of motor with a minimum of insulated windings and components in the rotating part is preferable.
- To achieve a rotor rigidity as high as possible a compact design is to be aimed at. In case of synchronous machines excitation and damping devices which also have to rotate, would lead to an extension of the rotor.
- Trouble-free asynchronous startup when connected to the 50 Hz supply system and re-startup after system interruptions and switchovers must be possible.

For the insulation of live parts one must keep in mind that the equipment is exposed to a gamma dose rate of approx. 5 rad/h - apart from the considerably reduced insulation capability of helium gaps used as a dielectric. In addition any diffusion of gas into the winding insulation must be precluded, since the motor shall be designed for accidents involving depressurization rates of 3 - 5 bars/min. Furthermore electrically conductive deposits containing graphite will occur on the motor parts in the course of the long reactor operation period.

3.4 Circulator Cooling

Since the impeller is located in the primary circuit a non-negligible heat flow via the shaft into the motor compartment has to be considered. A possibility for compensation, especially when the circulator is at standstill and in case of accident-induced higher gas temperatures, has to be provided. One solution basically available is to feed in helium from the gas purification system. The helium will then search for a path to the primary loop through the non-contacting shaft seal in the flow restrictor wall. The annular clearance around the shaft subdivided by contactaless sealing strips acts as a heat exchanger and retains a major fraction of the heat flowing into the motor compartment. With the gas quantities available a cooling capacity of several KW for each circulator can be realized.

If this cooling concept is superimposed on the internal motor cooling circuit which is effective when the circulator is running, a slight overpressure against the primary loop will always prevail in the circulator blower compartment. The considerably reduced contamination of the circulator motor compartment which is then to be expected will very much enhance the ease of repairs.

4 Outlook

The development of retainer bearings and of the prototype of a vertically arranged coolant gas circulator with active magnetic bearings is sponsored by the Federal German Minister of Research and Technology. We wish to express our sincere gratitude for this support.

We hope to be able to complete the testing of the prototype by mid-1991. This date would still fit in with the existing time schedules for the planning of advanced high-temperature reactors.