FR 2 676 374 A1 discloses a continuously operated magnetically enhanced particle bed, wherein the particles of the bed are replaced in an ongoing method by said particles being removed from the particle bed by suction and fresh particles being supplied to the particle bed.

EP 0 115 684 A1 discloses a method for carrying out reactions in a magnetically enhanced particle bed with a controlled reaction rate profile. The particles are magnetizable, can exhibit catalytic properties and are used for supply or removal of heat. To enhance conversion, reactivity and/or product yield, the particle bed is conveyed through the reactor in the form of a plug flow, optionally regenerated after emerging from the reactor and recycled into the reactor.

EP 0 021 854 A1, US 4294688 and US 4292171 each provide methods in which magnetizable, in some cases catalytically active, particles are continuously withdrawn from a magnetically enhanced fluidized bed and also regenerated and recycled.

DE 29 50 621 A1 describes a catalyst composition of passivated magnetic alloys for use in magnetically stabilized fluidized beds for high-temperature applications. The catalyst composition comprises aluminum, silicon and/or chromium, has a high Curie temperature and is stable in a corrosive environment.

The magnetically enhanced fluidized beds and magnetic field-based separation methods disclosed in the prior art documents do not take advantage of the dependence of the magnetic properties of a solid on the temperature or composition for self-regulation of a system, wherein transport of magnetizable and/or magnetic particles is used for temperature management or reaction management. For example in the method for temperature management described in EP 0 115 684 A1, a high level of process engineering complexity and outlay is required which externally controls the establishment of a desired temperature level by determining conveying rates. In US 4354856, DE 696 03 270 T2 or DE 3642557 A1 for example, the change in the magnetic properties is brought about by changes outside the system in order that a separation principle is realizable at all. Although overheating by inductive supply of heat is prevented in DE 10 2007 059 967, it is, however, not possible to exert a self-regulating influence over the composition of the mixture in the reaction space here, in order to prevent overheating for reasons other than the inductive supply of heat.

It is an object of the present invention to provide a method for self-regulation of a system, wherein the composition of a mixture in a control volume is adjusted according to prevailing temperature conditions and/or prevailing reaction progress without being reliant upon an external closed loop control means, i.e., peripheral equipment outside the control volume.

The object is achieved by a method for self-regulation of a system comprising the steps of:

(I) utilizing a magnetic field to transport magnetizable and/or magnetic particles out of a control volume or to localize said particles in the control volume,

wherein the magnetizable and/or magnetic particles

a. are localized in the control volume by the magnetic field, when said particles have ferromagnetic properties, and transported out of the control volume by a flowing fluid or gravity, when said particles have paramagnetic properties, or

b. are transported out of the control volume by the magnetic field, when said particles have ferromagnetic properties, and are localized in the control volume, when said particles have paramagnetic properties,

(II) changing magnetic properties of the magnetizable and/or magnetic particles, which are ferromagnetic or paramagnetic, in the control volume by changing a temperature Tp of the magnetizable and/or magnetic particles or by changing the composition of the magnetizable and/or magnetic particles, wherein at least one chemical reaction is carried out in the control volume.

The magnetic field is preferably an external magnetic field generated by various arrangements of coils, in particular electrical coils, known to those skilled in the art. In this connection, external means that the magnetic field is not generated in the control volume but the magnetic field exists in the control volume. Depending on the arrangement and configuration of the coils, the magnetic field exhibits different orientations, field strengths and homogeneities. The strength of a magnetic field H can be described by the following equation:

$$H = I \cdot \frac{n}{L}, \qquad (1)$$

where I is current, n is the number of loops and L is the length of the coil. The unit of magnetic field strength H is A/m. Magnetic field strength is linearly correlated with magnetic induction B:

$$B = \mu_0 \cdot \mu_r \cdot H, \qquad (2)$$

where μ_0 is the magnetic field constant, i.e., the magnetic permeability of a vacuum, and μ_r is relative permeability which is a measure of the influence on the magnetic field of the material comprised in the magnet.

The magnetic field exerts a magnetic force F_m on magnetic or magnetizable particles which depends on the particle properties and the properties of the external field:

$$F_m = \mu_0 \cdot V_p \cdot M_p \cdot \nabla H, \qquad (3)$$

where μ_0 is the magnetic field constant, V_p is the particle volume, M_p is the magnetization of the particle and ∇H is the gradient of the magnetic field strength at the location of the particle. The magnetization of the particle in turn depends on the magnetic field strength H of the external magnetic field:

$$M_p = \kappa \cdot H \qquad (4).$$

Magnetic susceptibility κ is a measure of the magnetizability of material in an external magnetic field. In the case of ferri- and ferromagnetic materials, magnetic susceptibility κ depends, inter alia, on particle size, particle shape and field intensity. For diamagnetic and paramagnetic materials, magnetic susceptibility κ is constant.

transported into the control volume. For example, a catalyst in the synthesis of styrene has different magnetic properties in deactivated form to the same catalyst in non-deactivated form, for example iron in different oxidation states. In a further example, organic sulfur compounds and hydrogen sulfide can be cleaved in a first method step as follows:

$$FeS + R\text{-}SH \rightarrow FeS_2 + R\text{-}H$$

$$FeS + H_2S \rightarrow FeS_2 + H_2.$$

The first method step can be carried out in a fluidized bed or in another solid conveying reactor for example. A liquid phase and/or a gas phase comprising a desulfurized product can subsequently be removed from the solid FeS_2 and the FeS_2 can be conveyed into a regenerator. Retrocleavage to FeS can be effected in the regenerator at high temperatures. Elemental sulfur S can be removed and FeS can be recycled into the first method step.

In an alternative embodiment, the magnetizable and/or magnetic particles are a reactant or product of the chemical reaction and the magnetic properties of the reactant are distinct from the magnetic properties of the corresponding product and, in each case, one is ferromagnetic and the other is paramagnetic. In this case too, the change in the magnetic properties of the magnetizable and/or magnetic particles can be linked to the change in oxidation state due to the chemical reaction of at least one component of the magnetizable and/or magnetic particles. This makes it possible, for example, to localize a ferromagnetic reactant in the control volume using the magnetic field until it is converted into the paramagnetic product and then transported out of the control volume as product on account of the abovementioned forces. This optimizes the residence time of the reactant in the control volume such that the reactant remains in the control volume until it has been converted to the product.

Alternatively, a paramagnetic reactant can be converted into a ferromagnetic product in the control volume, said product then being transported out of the control volume by a magnetic field outside the control volume or by a moving magnetic field in the control volume. One advantage of this embodiment is that the reaction is directly combined with a separation method and an often required subsequent separation of product and unconverted reactant is rendered unnecessary. It is, moreover, possible to increase the conversion as a paramagnetic reactant remains in the control volume until it has been converted and is only then under the influence of the magnetic field and is not discharged from the control volume prematurely while still in the form of a reactant. It is assumed here that reaction-promoting conditions prevail in the control volume, for example in terms of temperature and the presence of a catalyst.

In a further embodiment, once transported out of the control volume the magnetizable and/or magnetic particles are cooled or heated and/or regenerated and then optionally recycled into the control volume. The magnetizable and/or magnetic particles can consequently serve as heat-transfer medium or can enhance process stability or catalyst productivity as deactivated catalyst can be selectively removed from the control volume and activated catalyst can be supplied to the control volume.