Accumulators with sorbent material – an innovative approach towards size and weight reduction

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Utilizing accumulators in hydraulic systems with the purpose of energy storage, temporal changes in state of the storage medium must be considered during design and prospectively also monitored during operation. High efficiency aside, the reduction of weight and size is of high interest, especially in mobile applications. Regarding these objectives, accumulators with sorbent material are an innovative and promising development. The herein introduced generic physical model enables the consideration of sorption processes in the description of such accumulators. The results are discussed by means of time response analysis and compared to the behaviour of conventional accumulators. Potential use cases are investigated and the model application to a practical duty cycle is shown.

Keywords: accumulator, size reduction, sorbent material
Target audience: mobile hydraulics, design process, component manufacturer

1 Introduction

Accumulators are utilized in hydraulic systems for various functionalities. They serve as energy storage, supply of demanded volume flow, compensation of leakage or as capacitive element of a Helmholtz-Resonator for absorption of pressure pulsation. In this paper we focus on the accumulator as energy storage. The stored energy serves as coverage for the peak load of a rotating or linear hydro motor (boosting). When reversing the power flow the motor serves as a pump, so braking energy can be recuperated. Boosting and recuperation enables downsizing of the drive unit and, as a result, the reduction of energy consumption.

Aside from energy consumption, the reduction of weight and size is a primary objective in mobile applications. Given this background, recent development of accumulators involves employing sorbent material, utilized e.g. as vehicle air springs /1/ and gas pressure tank /2/. The physical phenomenon of adsorption and desorption is exploited for an only ostensible volume increase. An agglomeration of gas molecules takes place on the inner surface of a highly porous solid material, called sorbent, due to Van-der-Waals-forces. The transition from gas to adsorbed phase is an exothermic process, which means energy is released as adsorption heat. Desorption denotes the inverse process to adsorption. These sorption processes are described by means of sorption isotherms, the functional correlation between capacity of the sorbent and system state (pressure, temperature) /3/ /4/.

The theoretical part of this paper is close to the recent work of the third author published in german /5/, which presents an axiomatic model for hydraulic accumulators with sorbent material. The conservation equations for mass and energy are extended by appropriate terms representing the sorption processes and discussed in detail. This is followed by an in-depth analysis of the dynamic storage behaviour. New is the concluding part of this article in section 5, which discusses potential applications of accumulators with sorbent material and shows the model application on a practical duty cycle. These studies are carried out in context of the CRC 805 'Control of uncertainty in load carrying structures in mechanical engineering' (SFB 805) at the Technische Universität Darmstadt. The research project is funded by the German Research Foundation (DFG).

2 Conventional hydraulic accumulators

The following section describes the state transitions of a conventional hydraulic accumulator (c.f. Figure 1 a). During expansion the gas pressure drops and at the same time, if the expansion happens fast enough, the gas temperature. This process is reversed during compression. Transitions are called fast if they occur in time frames much shorter than the thermal relaxation time of the system. The thermal relaxation time τ is the ratio of gas heat capacity at constant volume $V_0\varrho_0 c_v$ with respect to the thermal conductivity kA: $\tau = V_0\varrho_0 c_v/kA$. Assuming that the thermal resistance is dominated by the heat transfer on the inner surface of the accumulator, the heat transmission coefficient is $k = \mathrm{Nu}\,\lambda\,S$, where $\mathrm{Nu} \approx 3$ is the Nusselt number, /6/, /7/. Here, λ is the coefficient of thermal conductivity and $S = A/V_0$ the volume specific surface of the accumulator. With the results of Pelz et al. /6/, /7/ the thermal relaxation time can be obtained by the equation

$$\tau = \frac{V_0\varrho_0 c_v}{kA} = \frac{\varrho_0 c_v}{\mathrm{Nu}\,\lambda S^2} = \frac{1}{\gamma\,\mathrm{Nu}\,a\,S^2}\,. \tag{1}$$

where $a = \lambda/(c_p\,\varrho_0)$ is the thermal diffusivity of the gas and $\gamma = c_p/c_v$ is the isentropic exponent obtained by the ratio of the specific heat capacities. The isentropic exponent has a value of $\gamma = 7/5 = 1.4$ assuming the gas is diatomic.

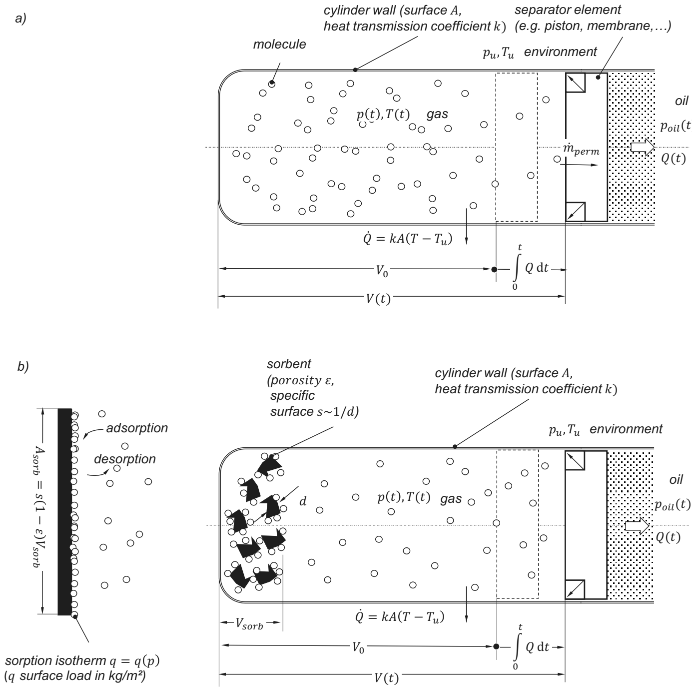

Figure 1: Hydraulic accumulators based on two different physical mechanisms: a) mere gas expansion, b) parallel setup of porous sorbent as accumulator in addition to gas expansion.

The earliest studies concerned with thermal equilibrium processes in hydraulic accumulators were conducted by Otis /8/, who introduced the thermal relaxation time as a significant quantity. A spheric accumulator with a diameter D has the specific surface $S = 6/D$, yielding the thermal relaxation time $\tau \approx D^2/(151.2\ a)$. Assuming $D = 0.2$ m and $a = 34 * 10^{-7}\ \mathrm{m^2/s}$ (applicable for air at 7 bar and 20 °C) results in the thermal relaxation time $\tau \approx 78$ s. This result is a typical value, confirmed by measurements of air springs /6/. With increasing precharge pressure and change of the volume specific surface, oil hydraulics applications typically achieve values up to $\tau \approx 100$ s. With $D = 1$ mm the relaxation time decreases by four orders of magnitude down to $\tau \approx 0.3$ s. The changes in state inside small oscillating gas bubbles in liquids are for example usually isothermal /7/, /9/, /10/. To summarize: All processes taking place in timeframes significantly shorter than $\Delta t \ll \tau$ are adiabatic and thus isentropic. All changes in state occurring in significantly longer timeframes than $\Delta t \gg \tau$ are isothermal. In thermodynamics, processes are usually categorized into isentropic, isothermal, isochoric and isobaric processes. As is apparent in the discussion above, this classification is associated with the consideration of characteristic timescales. This distinction into isentropic and isobaric processes is not possible for changes in state occurring in timeframes of $\Delta t \sim \tau$. Thus, the goal is to predict the temporal behaviour of the gas state for timescales of $\Delta t \sim \tau$. This is achieved by means of evolution equations based on axioms, namely the continuity equation and the energy equation.

3 Dynamic model of an hydraulic accumulator with sorbent material

The following assumptions are made for the modelling:

(i) *zero-dimensional model:*
The thermodynamic states are only considered to be functions of the time t, but not of the location. Especially the gas pressure $p(t)$ as well as the gas temperature $T(t)$ inside the cylinder volume are considered spatially averaged. The spatial resolution of impulse- and temperature boundary layer is possible /7/, /9/, but is not considered in this paper.

(ii) *equations of state*
The gas is assumed to be caloric and thermally ideal. Therefore the caloric equations of state for the internal energy $e = c_v T + const$, and enthalpy $h = c_p T + const$ are applicable, as well as thermal equation of state $p = \varrho R T$, with the density ϱ and the specific gas constant $R = c_p - c_v$. The adaptation for real gas is possible by means of applicable equations of state.

(iii) *sorption*
The sorbent is geometrically characterized by the porosity $\varepsilon \coloneqq \lim_{\Delta V_{sorb} \to 0} \Delta V_{void}/\Delta V_{sorb}$ and the specific surface $s \coloneqq \lim_{\Delta V_{sorb} \to 0} \Delta A_{sorb}/[(1-\varepsilon)\Delta V_{sorb}]$, as figure 1 b) illustrates. Assuming spherical bulk material or nonwoven material with an average sphere- or thread-diameter d this results in $s = s_+(\varepsilon)/d$ for dimensional reasons. During adsorption of gas molecules bond energy is released. The needed bond energy for desorption is conducted to the surface from the environment. At the equilibrium, while assuming the sorption isotherm to be linear, the surface specific mass of agglomerated molecules q is proportional to the $q = q'p$, with the pressure specific sorbent load $q' \coloneqq \partial q/\partial p|_T$. The model design could also account for separated gas components by means of partial pressures. Likewise it is possible to replace the linear sorption isotherm with a non-linear isotherm (eg. Langmuir-isotherm), /4/, /11/, /12/.

The continuity-, energy- and state equations in conjunction with the above assumptions (i) through (iii) yield the evolution model for the thermodynamic state of the gas inside the accumulator, and thus the work capacity. The model is an extension of the simulation model for air springs and dampers ADASS (Air Damping Air Spring Simulation), developed by the third author. This simulation model is employed by the companies Vibracoustic and Daimler to aid the design of pneumatic suspension systems /13/.

The following section shows continuity equation, energy equation and equation of state for the discussed processes. The continuity equation yields the evolution equation

$$V \frac{\mathrm{d}\varrho}{\mathrm{d}t} + \varrho Q + \dot{m}_{perm} = -A_{sorb} \frac{\mathrm{d}q(p,T)}{\mathrm{d}t} \tag{2a}$$

where $\dot{m}_{perm}$ considers a mass flow due to permeation through membrane or seal. The impact of an associated loss of mass is only noticeable in significantly longer timeframes compared to the relaxation time τ. The right-hand term of the continuity equation describes the behaviour of the sorbent. The structure of the equation implies the analogy with a capacity: The flow (here the mass flow) is obtained by multiplication of capacity and time derivative of the potential (here the surface specific mass of agglomerated molecules). In this context the sorbent takes the role of an additive capacity.

The energy equation includes a term on the right-hand side, describing the heat source that results from the sorption processes, in addition to the heat flow. During adsorption the bond energy E_A is released and conducted to the gas, during desorption the bond energy is drawn from the gas of molar mass M:

$$V \frac{\mathrm{d}\varrho c_V T}{\mathrm{d}t} + \left(\varrho Q + \dot{m}_{perm}\right) c_p T = -kA(T - T_0) + \frac{A_{sorb} E_A}{M} \frac{\mathrm{d}q(p,T)}{\mathrm{d}t} \tag{2b}$$

Usually, the sorbent's change of inner energy is negligible due to the low mass of the sorbent. To complete the system, the thermal equation of state (alternatively a compressibility factor can be employed)

$$p = \varrho R T \tag{2c}$$

is needed, as well as the sorption equilibrium

$$q = q(p,T). \tag{2d}$$

The system can be solved for a known initial state

$$p(0) = p_0, T(0) = T_0 = T_u \tag{2e}$$

given a diffusion model for the permeation flow is established. The unknown quantities are gas pressure p, gas temperature T, gas density ϱ and gas volume V. The equations (2a) through (2d) are sufficient to solve this system. For example given a kinematic stimulation of the volume flow $Q(t)$, the first term of the continuity equation and the energy equation with the time integral $V(t) = V_0 + \int_0^t Q(t)\,\mathrm{d}t$, yield the accumulator volume V.

4 Analysis of the dynamic behaviour of a hydraulic accumulator with sorbent material

This section shows a more detailed consideration of the developed model in the specific case of negligible permeation $\dot{m}_{perm} = 0$ and a linear sorption isotherm $\dot{q} = q'\dot{p}$:

$$V\dot{\varrho} + \varrho Q = -A_{sorb} q' \dot{p} \tag{3a}$$

$$\dot{p}\, V + Q\gamma p + (\gamma - 1)kA(T - T_0) = (\gamma - 1)A_{sorb} \frac{E_A}{M} q' \dot{p} \tag{3b}$$

$$p = \varrho R T \tag{3c}$$

$$p(0) = p_0, T(0) = T_0 = T_u \tag{3d}$$

The dimensional analysis /14/ for a harmonic stimulation with the cycle time $2\pi/\Omega$ motivates the introduction of the dimensionless quantities

$$p_+ \coloneqq p/p_0,\ T_+ \coloneqq T/T_0,\ \varrho_+ \coloneqq \varrho/\varrho_0,\ V_+ \coloneqq V/V_0,\ Q_+ \coloneqq Q/(V_0 \Omega),\ t_+ \coloneqq t\,\Omega, \tag{4}$$

As well as the dimensionless form of the equation system (3):

$$V_+\dot{\varrho}_+ + \varrho_+ Q_+ + q'_+\dot{p}_+ = 0, \tag{5a}$$

$$\dot{p}_+ V_+ + \gamma Q_+ p_+ + \frac{T_+ - 1}{\Omega_+} = E_{A+}\, q'_+\, \dot{p}_+, \tag{5b}$$

$$p_+ = \varrho_+ T_+, \tag{5c}$$

$$p_+(0) = 1, T_+(0) = 1. \tag{5d}$$

The following four dimensionless parameters resulting from the dimensional analysis characterize the accumulator explicitly:

$$\Omega_+ \coloneqq \Omega\tau = \Omega\frac{V_0\varrho_0 c_v}{kA}, \quad q'_+ \coloneqq \frac{m_{0,\text{adsorbiert}}}{m_{0,\text{frei}}} = q' R T_0 \frac{A_{sorb}}{V_0}, \quad E_{A+} \coloneqq \frac{E_A}{M R T_0}(\gamma - 1) = \frac{E_A}{M\, c_v T_0}, \quad \gamma, \tag{6}$$

The dimensionless frequency Ω_+ is the product of relaxation time τ and stimulation frequency Ω and quantifies the temporal behaviour ($\Omega_+ \gg 1$ implies isentropic behaviour, $\Omega_+ \ll 1$ an isothermal one). The dimensionless sorbent charge q'_+ describes the sorbent material and represents the ratio of adsorbed gas mass $m_{0,\text{adsorbed}}$ and free gas mass $m_{0,\text{free}}$ at initial state. Thus, it quantifies the sorption capability of the accumulator and can be easily obtained by measurement. The dimensionless bond energy E_{A+} represents the ratio of bond energy and inner energy at initial state and therefore quantifies the inner heat source of the accumulator. γ denotes the isentropic exponent of the gas.

The dynamic behaviour of the accumulator can be derived from the model (5) using ‘pen and paper’, by linearizing the non-linear initial value problem by means of perturbation theory and transforming it into the frequency domain, with the ansatz $p_+ = 1 + \tilde{p}_+ = \mathrm{Re}(1 + \hat{p}_+ \exp \mathrm{i}\Omega t)$, $\varrho_+ = 1 + \tilde{\rho}_+ = \mathrm{Re}(1 + \hat{\varrho}_+ \exp \mathrm{i}\Omega t)$, $T_+ = 1 + \tilde{T}_+ = \mathrm{Re}(1 + \hat{T}_+ \exp \mathrm{i}\Omega t)$, $V_+ = 1 + \tilde{V}_+ = \mathrm{Re}(1 + \hat{V}_+ \exp \mathrm{i}\Omega t)$, where $\mathrm{i} = \sqrt{-1}$. Originating from the initial value problem (5), results the algebraic formulation for the system’s steady state

$$\hat{\varrho}_+ + \hat{V}_+ + q'_+\, \hat{p}_+ = 0, \tag{7a}$$

$$\hat{p}_+ + \gamma\, \hat{V}_+ + \frac{1}{\mathrm{i}\,\Omega_+}\hat{T}_+ = E_{A+} q'_+\, \hat{p}_+, \tag{7b}$$

$$\hat{p}_+ = \hat{\varrho}_+ + \hat{T}_+, \tag{7c}$$

The model described by the equations (7a) through (7c) can be represented in form of a linear system of equations

$$\begin{pmatrix} q'_+ & 0 & 1 \\ 1 - E_{A+}q'_+ & 1/\mathrm{i}\Omega_+ & 0 \\ 1 & -1 & -1 \end{pmatrix} \begin{pmatrix} \hat{p}_+ \\ \hat{T}_+ \\ \hat{\varrho}_+ \end{pmatrix} = \begin{pmatrix} -1 \\ -\gamma \\ 0 \end{pmatrix} \hat{V}_+. \tag{8}$$

The complex and dimensionless stiffness $\hat{p}_+/\hat{V}_+$ is obtained by means of Cramer’s rule

$$\frac{\hat{p}_+}{\hat{V}_+} = \frac{\det\begin{pmatrix} -1 & 0 & 1 \\ -\gamma & 1/\mathrm{i}\Omega_+ & 0 \\ 0 & -1 & -1 \end{pmatrix}}{\det\begin{pmatrix} q'_+ & 0 & 1 \\ 1 - E_{A+}q'_+ & 1/\mathrm{i}\Omega_+ & 0 \\ 1 & -1 & -1 \end{pmatrix}} = -\frac{1 + \gamma\mathrm{i}\Omega_+}{1 + q'_+ + \mathrm{i}\Omega_+(1 - E_{A+}q'_+)} \tag{9}$$

derived from the system of equations (8) and characterizes the behaviour of the accumulator. We conduct a parametric study of the sorbent load q'_+ to investigate the accumulators characteristics. Figure 2 shows the respective resulting dynamic stiffness as a function of the frequency. Initially, the following two edge cases are considered. For $\Omega_+ \to 0$ (first edge case $\Delta t \gg \tau$, i.e. isothermal behaviour) the dimensionless stiffness has the value $1/(1 + q'_+)$. A conventional accumulator (fig. 1a) on the contrary has the asymptote one. The stiffness of an accumulator with sorbent material decreases due to the adsorption of gas molecules. Such behaviour verifies the above presumed role as additional parallel capacity. An equally stimulated accumulator with sorbent material delivers lower pressure levels. For $\Omega_+ \to \infty$ (second edge case $\Delta t \ll \tau$, i.e. isentropic behaviour) the dimensionless stiffness is $\gamma/(1 - E_{A+}q'_+)$. Therefore an accumulator with sorbent material has a higher dimensionless stiffness compared to a conventional accumulator, which has a dimensionless stiffness of asymptotically γ.

The transition range between both edge cases is found for the dimensionless frequencies $0.1 < \Omega_+ < 100$. The above results show, that this transition range of an accumulator with sorbent material has a higher gradient as well as an increased phase shift.

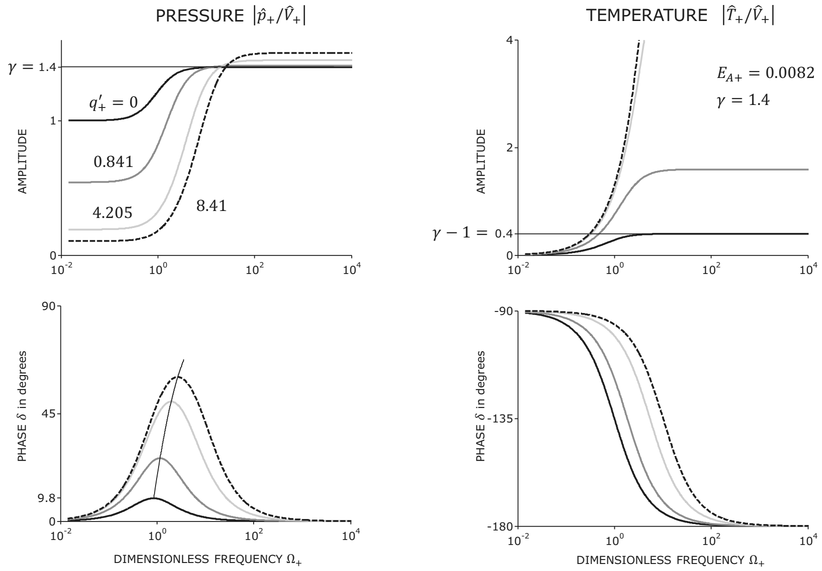

Figure 2: Dynamic behaviour (transmission behaviour) of an accumulator partially filled with sorbent material.

Aside from the dynamic stiffness, figure 2 additionally shows the temperature behaviour for various dimensionless sorbent charges q'_+ as a function of the dimensionless frequency Ω_+. The temperature behaviour is analogously computed by means of Cramer’s rule:

$$\frac{\hat{T}_+}{\hat{V}_+} = -\mathrm{i}\Omega_+ \frac{\gamma q'_+ + \gamma - (1 - E_{A+}q'_+)}{1 + q'_+ + \mathrm{i}\Omega_+(1 - E_{A+}q'_+)}. \tag{10}$$

For $\Omega_+ \to 0$ the accumulator shows isothermal behaviour, as above mentioned. For $\Omega_+ \to \infty$ the gas temperature of an accumulator with sorbent material increases compared to a conventional accumulator. This temperature increase is largely dependent on the sorption characteristics q'_+ and E_{A+}, as equation (8) implies. These observations emphasize the sorbent’s role as a heat source.

As an alternative to solving the non-linear differential equation system (5) by means of the ‘pen and paper’ method, numeric methods can be employed. The pressure- and temperature-response of the accumulator is numerically computed as a result of a given stimulation, for example a volume flow.

Figure 3 shows the behaviour of the stiffness as known from figure 2. The scatter plots represent the corresponding numeric solution of the non-linear differential equation system (5). It is clearly recognizable that the results obtained by means of linearization match the numeric results very well, especially for lower dimensionless stimulation frequencies. The transition range between purely isothermal and purely isentropic behaviour is represented appropriately as well. For higher dimensionless stimulation frequencies however, the results diverge significantly. These discrepancies can be attributed to the non-linear terms of the model (4), which become increasingly important at higher stimulation frequencies.

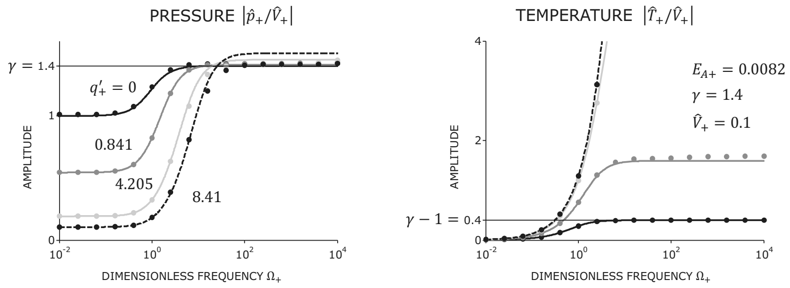

Figure 3: dynamic behaviour (transmission) behaviour of an accumulator partially filled with sorbent material. Comparison of linearization and numeric computation of the model.

In the following section the behaviour of the accumulator is discussed by means of a p-V-diagram, for the four sorbent charges ($q'_+ = 0, 0.841, 4.205$ and 8.41) shown above. Figure 4 shows the typical hysteresis curves of the accumulators for a dimensionless frequency of $\Omega_+ = 1$. The dotted curves depict isotherms, the dashed curves depict isentropic behaviour. The known behaviour of a conventional accumulator is represented by $q'_+ = 0$. Examining accumulators with sorbent material ($q'_+ > 0$), the isentropic pressure amplitude (dashed curve) increases slightly with increasing sorbent portion. In contrast, the isothermal pressure amplitude decreases with increasing portion of sorbent. Such behaviour was already evident in figure 2. At $\Omega_+ = 1$ two aspects of the accumulator's behaviour are significant. First, the slope of the hysteresis decreases with increasing sorbent portion and converges towards isothermal behaviour, as was already evident in figure 2 as well. Secondly, the area of the hysteresis decreases with increasing sorbent portion. Since the area of the hysteresis quantifies the dissipation due to heat transfer into the environment, this result motivates the consideration of the efficiency η as a function of the dimensionless frequency and dimensionless sorbent charge. Otis /15/ was the first to make the connection between efficiency and dimensionless frequency in 1975. He defined the efficiency as the ratio of emitted work W_{21} and absorbed work W_{12} (cf. figure 5) of the accumulator

$$\eta = \frac{W_{21}}{|W_{12}|}. \tag{11}$$

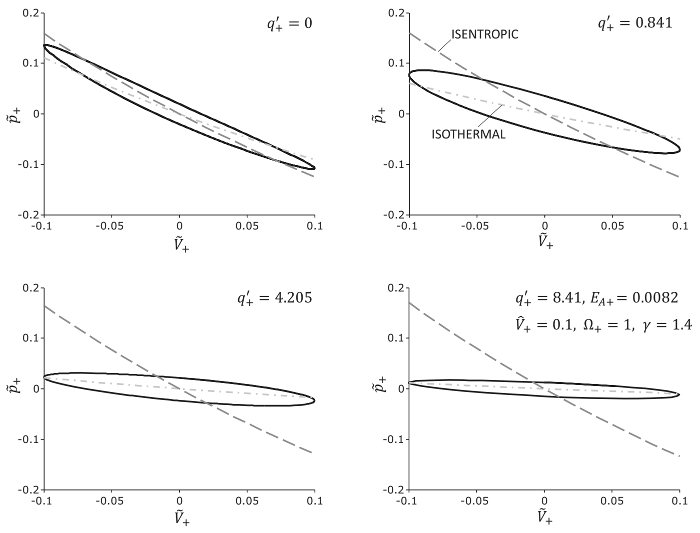

Figure 4: Hysteresis curves for four different accumulators. The dashed curve represents the isentropic change in state, the dotted curve the isothermal change in state and the continuous curve represents the change in state at $\Omega_+ = 1$.

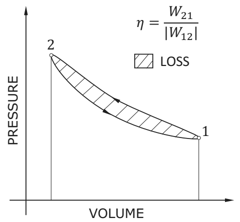

Figure 5: Efficiency in a p-V-diagram /14/.

Figure 6 accordingly shows the behaviour of the efficiency as a function of the dimensionless frequency for accumulators with and without sorbent material. The conventional accumulator reaches an efficiency minimum at $\Omega_+ = 1$, as already shown by Otis /15/. Examining accumulators with sorbent material, the following three important insights can be obtained: (i) The efficiency minimum decreases with increasing sorbent portion. (ii) The efficiency minimum occurs at higher dimensionless frequencies with increasing sorbent portion. (iii) The efficiency characteristics of accumulators with sorbent material and the efficiency characteristic of conventional accumulators intersect due to the displacement towards higher dimensionless frequencies (cf. figure 6). The accumulator with sorbent material therefore achieves higher efficiency compared to the conventional accumulator towards the left of this intersection. In the examined steady state of $\Omega_+ = 1$ this is the case for a dimensionless sorbent charge of 8.41 (cf. figure 6).

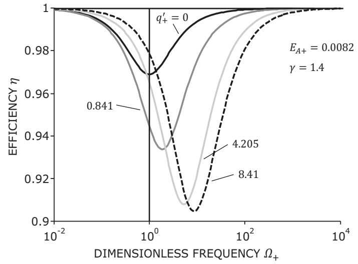

Figure 6: Efficiency characteristic as a function of dimensionless frequency for different configurations.

5 Model application on a practical duty cycle

The following section discusses the application of accumulators with sorbent material more detailed. First, it is essential to summarize the assumptions for the model design and the above findings. Secondly; it is important to consider the design restrictions imposed by the objective and the state transition characteristics of possible applications.

Assumptions

1. Zero-dimensional model design, i.e. all state variables are only functions of time.
2. The heat capacity of the sorbent is assumed to be negligibly small compared to the heat capacity of the gas. An extension of the equation (2b) is readily possible.
3. The permeation is neglected (not a general restriction imposed by the model).
4. Ideal gas characteristics are assumed (no general adjustment of the model needed).
5. A linear sorption isotherm is assumed, which does not include saturation of the sorbent material (no general adjustment of the model needed).

Findings

1. At low dimensional frequencies the sorbent acts as an additive capacity, which results in a reduction of the stiffness of the accumulator. This behaviour motivates the application of hydraulic accumulators with sorbent material in the context of an assembly size reduction.
2. The heat build-up of the accumulator as well as the increase of the stiffness at higher dimensionless frequencies is to be considered by the end user.

The design of a hydraulic accumulator is highly dependent on the system's objectives and the corresponding operating parameters. The generally most important design criterion is the required displacement volume or the hydrostatic discharge energy, while the operating pressure range is mostly determined by the hydraulic system. Additional restrictions are imposed by safety requirements or other basic system conditions /16/.

Applications are usually categorized by the time scale of their duty cycle and the corresponding state transition. In practice, a process is considered slow (and thus isothermal) for charge and discharge cycles taking place in time frames $\Delta t > 3$ min, for example in leakage compensation applications. Duty cycles recognized as fast (and thus isentropic) processes have typical timeframes of $\Delta t < 1$ min. Application examples are shock absorbers or suspension systems /16/.

As can be conducted from Figure 2, the deployment of accumulators with sorbent material is only favorable for applications of isothermal behaviour, else the accumulator characteristic converges towards that of a conventional accumulator. Therefore, applications with generally faster duty cycles like pulsation dampeners for displacement pumps, blow molding or pressure injection machines and suspension systems cannot benefit from the utilization of accumulators with sorbent material.
Reasonable application objectives with generally longer duty cycles are leakage compensation as mentioned above, but also lubricant supply and maintaining system pressure over long time periods. Examples for the latter are clamp systems, throttle valves, hydraulic bearings or rolling mills /16/ /17/ /18/.

Given this background, we will exemplary examine the potential of an accumulator with sorbent material on the practical duty cycle of a hydraulic molding press. This is an application where the accumulator is used as a leakage compensator under isothermal conditions, hence the dimensionless frequency can be assumed to be $\Omega_+ \ll 1$. The maximum permitted leakage is 2 cm³/minute over a time period of 60 minutes. The target pressure level is 200 bar with a minimum of 198 bar. This specification results in an initial volume of 13.3 l and a displacement volume of 0.12 l. These are typical conditions and operating parameters for this type of application /19/ /20/. We again study the system characteristics as a function of the remaining influencing parameter for the system q'_+. To solve the dimensionless equation system (5) of our model numerically, we use the volume as a function of time

$$V = V_0 - \Delta V \, \frac{1}{2}\left[1 + \sin\left(t_+ + \frac{3}{2}\pi\right)\right] \tag{12}$$

in the dimensionless form

$$V_+ = \frac{V}{V_0} = 1 - \Delta V_+ \, \frac{1}{2}\left[1 + \sin\left(t_+ + \frac{3}{2}\pi\right)\right]. \tag{13}$$

As figure 7 shows, the operating pressure levels of the original conventional accumulator can be retained by increasing the dimensionless displacement volume $\Delta V_+ = \Delta V / V_0$. Since the displacement volume in this application is significantly smaller than the initial volume ($\Delta V \ll V_0$), we can on the one hand interpret the increase of the dimensionless displacement volume as a reduction of the initial volume and therefore the assembly size, while retaining the discharged volume and amount of energy (left-hand side of figure 7). On the other hand this can represent an increase of the achievable amount of discharge energy in an existing system with unchanged size by means of utilizing a sorbent material (right-hand side of figure 7).

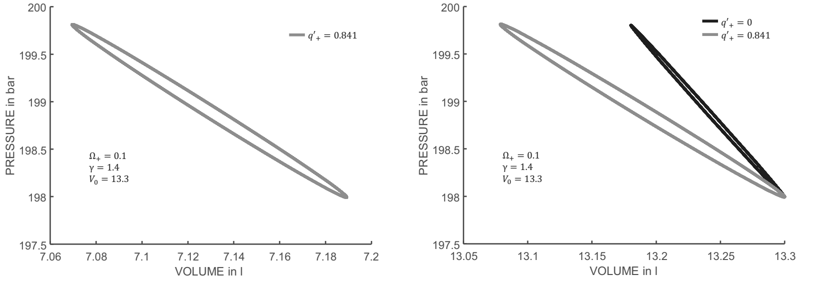

Figure 7: Duty cycle of a conventional accumulator and an accumulator with sorbent material.

Further applications with the purpose of covering a higher volume demand ($\Delta V \sim 0.5\, V_0$) over a long period of time are plausible. However, the ratio of $\Delta V / V_0$ must be considered properly. It restricts the achievable size reduction or gain of discharge energy and more importantly the ability to retain the original operating pressure level. The latter might not be an obstacle if a reduction of the operating pressure levels is acceptable or even desired.

In the context of energy storage for emergency supply or kinetic energy recovery, the duty cycle time with respect to the relaxation time of typical accumulators cannot be considered ‘slow’ as clear-cut as the above mentioned examples. Both the expected charge and discharge cycle time, as well as the relaxation time may vary greatly depending on each particular use case. Many applications utilizing hydraulic accumulators for this purpose today are represented by dimensionless frequencies of $\Omega_+ = 10$ and above. Typical duty cycle times range from 1 second to 1 minute, with accumulator volumes from 20 l to several 100 l and operating pressure levels of 100 bar to 400 bar /21/ /22/ /23/.

Nonetheless, accumulators of smaller size and lower pressure levels have decently low relaxation times /24/, which in conjunction with peak load coverage occurring over longer time periods results in the desired slow state transition process.

6 Conclusion and future research

In regard to the achievable reduction of mass and size of hydraulic systems, hydraulic accumulators with sorbent material are an innovative and promising development. This paper introduces a generic model description for these novel accumulators. The results show, that an accumulator with sorbent material is softer at low dimensionless frequencies (i.e. in the isothermal edge case) and stiffer at high dimensionless frequencies (i.e. in the isentropic edge case) compared to conventional accumulators. Furthermore, the heat build-up of an accumulator with sorbent material at high dimensionless frequencies has to be considered.

A relevant application of accumulators with sorbent material is the deployment at low dimensionless frequencies, allowing a considerable reduction in size compared to a conventional accumulator. The operation of an accumulator with sorbent material in the transition range between isothermal and isentropic behaviour generally is to be avoided. In this range, small changes of the stimulation frequency can lead to increasing pressure- and temperature amplitudes, due to the high gradients in the transition behaviour. Thus, reasonable application examples are leakage compensation, lubricant supply or maintaining system pressure. The sorption model assumes quasi-stationary behaviour, diffusion processes as a time determining aspect are not considered here. Achievable improvements over conventional accumulators depend on the sorbent characteristics which are unknown thus far. The applicability of accumulators with sorbent material for the purpose of energy storage or recuperation remains an open question for future research.

The next research step is the development of a prototype accumulator with sorbent material – corresponding to the outlined idea - for the validation of the model design. Characterizing applicable sorbent materials imposes an additional challenge and will require experimental investigations. These investigations are to be conducted in the scope of the Collaborative Research Center 805 ‘Control of uncertainty in load carrying structures in mechanical engineering’ (SFB 805) at the Technical University Darmstadt.

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Nomenclature

The first column of the following table shows the symbols utilized for physical and mathematical quantities. The second column shows the meaning of each quantity. The dimension of each physical quantity is denoted in the third column as a product of power terms, based on the generic quantities length (L), mass (M), time (T), amount of substance (N) and temperature (Θ). Dimensionless quantities are denoted by a plus symbol in the index, disturbing variables are marked by tilde or circumflex.

Variable	***Description***	***Dimension***
a	thermal diffusivity coefficient	L^2T^{-1}
A	cylinder surface	L^2
A_{Sorb}	sorbent surface	L^2
c_p	specific isobaric heat capacity	$L^2T^{-2}\Theta^{-1}$
c_v	specific isochoric heat capacity	$L^2T^{-2}\Theta^{-1}$
d	characteristic diameter of sorbent material	L
δ	phase angle	1
D	diameter of the accumulator	L
e	inner energy	L^2T^{-2}
E_A	bond energy	$L^2M\,T^{-2}N^{-1}$
η	efficiency	1
h	enthalpy	L^2T^{-2}
i	Imaginary number	1
k	heat transmission coefficient	$MT^{-3}\Theta^{-1}$
M	molar mass	MN^{-1}
$\dot{m}_{perm}$	mass flow due to permeation	MT^{-1}
n	polytropic exponent	1
Nu	Nusselt number	1
p	pressure inside the accumulator	$L^{-1}MT^{-2}$
p_0	referenced pressure	$L^{-1}MT^{-2}$
$p_{Öl}$	oil pressure	$L^{-1}MT^{-2}$
p_u	ambient pressure	$L^{-1}MT^{-2}$
q	sorbent charge, surface specific mass of agglomerated gas molecules	$L^{-2}M$
Q	volume flow	L^3T^{-1}
$\dot{Q}$	heat flow	L^2MT^{-3}
R	specific gas constant	$L^2T^{-2}\Theta^{-1}$
s	specific surface of the sorbent material	L^{-1}
S	specific surface of the accumulator	L^{-1}

t	time	T
T	gas temperature inside the accumulator	Θ
T_0	referenced temperature	Θ
T_u	ambient temperature	Θ
V	volume of the accumulator	L^3
V_0	referenced volume, volume of the accumulator at operation state	L^3
V_{Sorb}	solid state volume of the sorbent material	L^3
V_{void}	cavity volume of the sorbent material	L^3
γ	isentropic exponent	1
ε	sorbent porosity	1
λ	thermal conductivity coefficient	$LMT^{-3}\Theta^{-1}$
ϱ	density	$L^{-3}M$
ϱ_0	referenced density	$L^{-3}M$
τ	thermal relaxation time	T
Ω	stimulation frequency	T^{-1}

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