Thermomolecular Accumulator for Touring Bicycle

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Abstract. The work presents an ecological vehicle, which is a touring bicycle with the compact hydraulic system based on the hydraulic / thermomolecular accumulator. Due to the hydrosystem, the cyclist has the ability to store mechanical / hydraulic energy by pedaling during downhill, which is used when moving uphill without pedaling. The prototype was designed some time ago at the Laboratory of Thermomolecular Energetics (TME) of the Igor Sikorsky Kyiv Polytechnic Institute. In order to improve the vehicle technical characteristics, it is proposed to replace the traditional pneumohydraulic accumulator (PHA) with the thermomolecular analogue. The comparative analysis of the vehicle operation with each type of accumulator is carried out.

1. Introduction
Bicycle as an ecological and clean energy vehicle has been and remains an attractive object for researchers and engineers to improve its technical and operational characteristics. As a result, the bicycle original design is updated by the new technical elements and systems, including energy storage and recovery systems: hydraulic, electrical, or hybrid. These systems enter into competition and reveal their strengths and weaknesses [1-3]. In this case, the bases of such systems are rechargeable battery devices: pneumohydraulic accumulators or electric batteries. This paper proposes a variant of the simple and compact hydraulic system for a touring bike, allowing accumulating the energy of pedaling and then using it at the right moment. At the same time, the possibility of replacing the traditional PHA with the TME analogue with better environmental attractiveness and higher specific energy capacity is being considered.

The fact is that for all types of PHAs there are three principal disadvantages that can not be eliminated within the traditional approach to designing a PHA: the hydraulic system pressure variability in accordance with the accumulated energy change, low specific energy capacity than in other branches of power engineering, explosion hazard due to the presence of the gas phase. Even the new technological improvements do not lead to a fundamental improvement. The problem is proposed to be solved by developing the new types of accumulators using the fundamentally new working media – the heterogeneous working media (HWM), developed at the Laboratory of Thermomolecular Energetics, Igor Sikorsky Kyiv Polytechnic Institute [4-8].

The TME-accumulator working medium is the heterogeneous liquid system (HLS) “liquid – porous matrix”, which uses micro-mesoporous materials: superhydrophobic zeolites with pore space of 0.2-0.3 ml/g and specific surface (1-2)·10³ m²/g. The TME-accumulator operating chamber is a volume filled with HLS, where the pore space remains free of fluid in the absence of external action due to the non-wetting of the porous body by the liquid.
The process of energy accumulation is the forced development of the interphase surface by forced intrusion of the liquid into the porous space under the external pressure, which is determined by the Laplace capillary pressure. The value of the accumulated energy is equal to the product of the surface tension of the liquid on the interphase surface area (the Gibbs work, surface energy capable of performing mechanical work).

Recuperation of energy is the spontaneous release of liquid from the pore space under the Laplace capillary pressure. For a synthesized matrix, the working pressure can be ~ 600 bars. Taking into account the designed matrix, the specific (volumetric) energy capacity can reach 25-30 MJ/m³ of HLS.

2. Touring bicycle hydromechanical circuit with PHA / TME-accumulator

The basic element of the proposed experimental unit, designed some time ago at the Igor Sikorsky Kyiv Polytechnic Institute is a traditional touring bicycle equipped with the accumulation hydrosystem (figure 1).

As an accumulator the PHA 24-5636-0 of the AN-24 aircraft hydraulic system is used [9]. Technical data of the PHA are presented in table 1.

| Name, unit                                           | Value       |
|------------------------------------------------------|-------------|
| Nominal capacity (gas volume), cm³                   | 4200        |
| Gas pre-charge pressure, kg/cm²                      | 60 ± 3      |
| Oil volume, cm³ (at a discharge of 150 to 120 kg/cm²) | 400         |
| Oil volume, cm³ (at a discharge of 150 до 85 kg/cm²) | 1800        |
| Oil volume, cm³ (at a discharge of 150 до 85 kg/cm²) | 2500        |
| Charging gas                                         | Nitrogen    |
| Hydraulic fluid                                      | AMG-10      |

As a hydromotor the reversible rotary-piston hydraulic motor GM36 of the AN-24 (Antonov) aircraft hydraulic system is used. Technical data are presented in table 2 [9].
Table 2. The GM36 general data.

| Name, unit | Value |
|------------|-------|
| Max speed of rotation, rpm | \( \leq 3000 \) |
| Max supplied pressure, kg/cm\(^2\) | \( \leq 160 \) |
| Specific flow rate of oil in cm\(^3\) per rev. | \( \leq 11.5 \) |
| Torque, kg·cm | \( \geq 190 \) |
| Mass (dry), kg | \( \leq 4 \) |

3. Basic operating modes of the bicycle hydraulic system
The accumulator system connection / disconnection is carried out by the cyclist with the hand lever. When the system is off, the bike functions in the classic mode. When connecting the system, the gearbox enters the gearshift on the rear wheel hub. The activated hydrosystem of the bicycle works in two basic modes (figure 2). The pump operating mode (the accumulator charging) is used when moving downhill by pedaling. The motor operating mode (the accumulator discharging) is used when moving uphill when pedaling is difficult.

![Diagram of bicycle hydraulic system](image)

(a) & (b)

1 – Hydraulic accumulator, 2 – Hydraulic pump-motor, 3 – Directional spool valve with hand lever, 4 – Check valve, 5 – Oil tank, 6 – Oil pressure gauge

Figure 2. Basic operating modes of the bicycle hydraulic system: (a) pump operating mode, (b) motor operating mode.

4. Dynamic integral indicators of cycling pedal technique (table 3) [10, 11]

Table 3. Indicators of cycling pedal technique.

| Pedal force (N) | Crank arm (mm) | Moment of pedaling (Nm) | Pedaling frequency (rpm) |
|----------------|---------------|-------------------------|--------------------------|
| Sportsman      |               |                         |                          |
| ● road cyclist | 700           | 170                     | 119                      | 90-110                    |
| ● sprinter cyclist | 165        | 170-175                 | 85                       | 110-125                   |
| ● middle-distance cyclist | 170         | 150                     |                          |                          |
| Non-sportsman  | 500           | 170                     | 85                       | 70                        |

5. Moment of pedaling and pedal force calculation
The average torque for the GM36 hydromotor in the pump operating mode is:

\[ T = \frac{1}{\pi} pfR\gamma \sin \gamma , \]

where: \( p \) - working pressure, kg/cm\(^2\), \( f \) - Gm36 piston square (\( d = 0.9 \) cm), \( R \approx 2.8 \) cm – radius of
GM36 cylinder centres circle, \( z = 9 \) - number of GM36 pistons, \( \gamma = 30^\circ \) - GM36 piston block tilt angle.

The required moment of pedaling is:

\[
M_{\text{ped}} \geq T_i \xi,
\]

where \( i_\xi \) - the total kinematic ratio.

The required pedaling force is:

\[
F_{\text{ped}} \geq M_{\text{ped}}/l,
\]

where \( l = 17 \text{ cm} \) – the crank arm length.

The total moment of pedaling (transfer torque \( T \)) is calculated according to the bicycle kinematic scheme, which includes: pedal (P), chain drive (Ch), rear wheel hub (Rwh), gearbox (Gb), GM36 working shaft (figure 1). For \( n_{\text{ped}} = 70 \text{ rpm}, M_{\text{ped}} = 85 \text{ Nm} \) (table 3) the results are next (table 4):

| Kinematic element | Rotation frequency \( n \) (rpm) | Kinematic ratio \( i \) | Torque \( T \) (Nm) |
|-------------------|----------------------------------|------------------------|---------------------|
| P                 | 70                               |                        | 85                  |
| Ch                |                                  | \( i_{\text{Ch}} = 2.5 \) |                     |
| Rwh               | 175                              |                        | 34                  |
| Gb                |                                  | \( i_{\text{Gb}} = 0.52 \) |                     |
| GM                | 90.3                             | \( i_\xi = 1.29 \)     | 65.9                |

The calculation results are presented in the form of the diagram (figure 3).

![Figure 3. Moment of Pedaling and Pedal Force Diagram.](image)

6. Calculation of PHA parameters

6.1. PHA charging

If the charge pressure is to take the actual PHA work pressure 150 kg/cm², all the charging process parameters can be seen in table 5.
Table 5. The PHA charge parameters.

| Parameter, unit                  | Value |
|----------------------------------|-------|
| Charge pressure \( P_{ch} \), bar | 150   |
| GM36 pistons diameter \( d \), cm | 0.9   |
| Radius of GM36 cylinder centres circle \( R \), cm | 2.8   |
| Number of GM36 pistons \( Z \) | 9     |
| GM36 piston block tilt angle \( \gamma \), grad | 30    |
| GM36 torque \( T \), Nm | 38.3  |
| Kinematic ratio \( i \) | 1.29  |
| Moment of pedaling \( M_{ped} \), Nm | 49.4  |
| Crank arm length \( l \), cm | 17    |
| Pedal force \( F_{ped} \), N | 290.4 |

Thus, according to the table 5 data, while moving, the cyclist can physically charge the PHA to the pressure of 150 kg/cm\(^2\) with the pedal force of 29 kg and having developed the moment of 50 Nm.

6.2. PHA discharging.

Due to the PHA data (table 1), we assume that the PHA discharge occurs from 150 to 80 kg/cm\(^2\), the hydraulic fluid volume is 2 liters.

Average pressure the PHA discharge:

\[
p_d = L/\Delta V = p_2 V_2 \ln(p_1/p_2),
\]

where \( L \) - work of the PHA discharge (isothermal expansion of nitrogen).

The GM torque:

\[
T_{GM} = p q_{GM} / (2\pi),
\]

where \( q_{GM} \) - GM36 specific flow rate.

GM36 rotation frequency:

\[
n_{GM} = Q_{Sv}^{nom} / q_{GM}, \ \text{rev/min}
\]

\[
\omega_{GM} = \frac{\pi n_{GM}}{30}, \ \text{c}^{-1}
\]

where \( Q_{Sv}^{nom} \) - spool valve flow rate, cm\(^3\)/min.

GM36 power \( N_{GM} \), kW:

\[
N_{GM} = T_{GM} \omega_{GM}.
\]

Rare wheel hub torque \( T_{RWH} \):

\[
T_{RWH} = T_{GM} i_{GB}.
\]

Rare wheel rotation frequency:

\[
n_{RW} = n_{GM} i_{GB}, \ \text{rev/min},
\]

\[
\omega_{RW} = \frac{\pi n_{RW}}{30}, \ \text{c}^{-1}.
\]

PHA energy capacity, kJ:

\[
E_{PHA} = p \Delta V,
\]

where: \( p \) - average PHA discharge pressure, \( \Delta V \) - hydraulic fluid volume.

PHA specific energy capacity, J/cm\(^3\):

\[
e_{PHA} = E_{PHA} / V_{NOM},
\]

where \( V_{NOM} \) - PHA nominal capacity.

The results of calculating the PHA discharge parameters are presented in table 6.
Table 6. The PHA discharge parameters.

| Parameter, unit | Value  |
|-----------------|--------|
| Average discharge pressure $P_d$, bar | 106.2  |
| GM36 specific flow rate $q_{GM}$, cm$^3$/rev. | 11.5   |
| Spool valve flow rate $Q_{SV(nom)}$, cm$^3$/min | 8000   |
| GM36 torque $T_{GM}$, Nm | 19.4   |
| GM36 rotation frequency $\omega_{GM}$, c$^{-1}$ | 73     |
| GM36 power $N_{GM}$, kW | 1.4    |
| Rare wheel hub torque $T_{RWH}$, Nm | 10.1   |
| Hub rotation frequency $\omega_{RWH}$, c$^{-1}$ | 38     |
| PHA energy capacity $E_{PHA}$, kJ | 214.4  |
| PHA specific energy capacity $e_{PHA}$, J/cm$^3$ | 51.1   |

7. Calculation of TME-accumulator parameters.

Taking into account the bicycle hydrosystem parameters and the correctness of the PHA-TME comparison, the TME-accumulator design is based on the PHA 24-5636-0 as pressure vessel from which the working piston has been removed. The PHA operating pressure is 16 MPa, but it can be higher due to the safety factor.

As a result, for the TME-accumulator two variants of the heterogeneous working medium are proposed: “Zif-67 + H$_2$O” and “Zif-8 + H$_2$O” with the following properties. ZIF-(8, 67, 71) is a metal-organic frameworks (MOF) class called Zeolite Imidazolate Frameworks (ZIF) - highly porous zeolite sorbents with exceptional stability.

Table 7 shows the characteristics of HWM on the basis of those porous structures [12, 13], where: $e^{ch}$ - specific energy capacity at charging, $e^d$ - specific energy capacity at discharging, $P_{int}$ - pressure of intrusion (charge), $P_{ext}$ - pressure of extrusion (discharge), $r$, $V_{pore}$ - pore size and pore volume.

Table 7. HWM characteristics.

| Porous matrix | Liquid comp. | $e^{ch}$ (J/g) | $e^d$ (J/g) | $P_{int}$ (MPa) | $P_{ext}$ (MPa) | $r$ (nm) | $V_{pore}$ (cm$^3$/g) |
|---------------|--------------|---------------|-------------|-----------------|-----------------|---------|---------------------|
| Zif-8 MOF     | H$_2$O       | 13.3          | 11.2        | 27              | 22              | 0.19    | 0.5                 |
| Zif-67 MOF    | H$_2$O       | 6.6           | 4.1         | 18.8            | 11.6            | 0.35    | 0.35                |

Consider first the work of the TME-accumulator on the “Zif-67 + H$_2$O”. As can be seen from table 7, the charge-discharge pressure of the HLS is, respectively, 188 and 116 kg/cm$^2$, which allows the use of the ready-made hydraulic system with PHA 24-5636-0 and GM36. To do this, remove the piston group elements from the PHA vessel, increasing the capacity of the working chamber to 4.5 liters. The technical characteristics of the TME-accumulator (Zif-67) are presented in the table 8.

Table 8. The TME-accumulator (Zif-67) basic parameters.

| Parameter, unit | Value  |
|-----------------|--------|
| Working chamber full capacity, cm$^3$ | 4500   |
| Charge pressure, MPa | 18.8   |
| Discharge pressure, MPa | 11.6   |
| Volume of liquid at discharge, cm$^3$ | 1500$^a$ |
| Working fluid specific volume, cm$^3$/g | 0.35   |
| Specific energy capacity at charging, J/g (per unit mass of porous matrix) | 6.6    |
| Specific energy capacity at discharging, J/g (per unit mass of porous matrix) | 4.1    |
Hysteresis of energy capacity, % 38
Working fluid H₂O
Hydraulic fluid AMG-10

*Calculated

Other calculating discharge parameters of the TME-accumulator (Zif-67) are presented in the table 9. Analyzing the results (tables 8 and 9) it should be noted that the TME accumulator (Zif-67) prevails at the hydraulic motor torque and shaft power, but loses on the specific energy capacity to the traditional PHA 24-5636-0 (table 6).

Table 9. TME-accumulator (Zif-67) discharge parameters.

| Parameter, unit | Value |
|-----------------|-------|
| Average discharge pressure $P_d$, bar       | 106.2 |
| GM36 specific flow rate $q_{GM}$, cm³/rev.  | 11.5  |
| Spool valve flow rate $Q_{SV}(nom)$, cm³/min | 8000  |
| GM36 torque $T_{GM}$, Nm                      | 21.2  |
| GM36 rotation frequency $\omega_{GM}$, c⁻¹    | 73    |
| GM36 power $N_{GM}$, kW                      | 1.55  |
| Rare wheel hub torque $T_{RWH}$, Nm          | 11.0  |
| Hub rotation frequency $\omega_{RWH}$, c⁻¹    | 38    |
| PHA energy capacity $E_{ZIF67}$, kJ           | 174.0 |
| PHA specific energy capacity $e_{ZIF67}$, J/cm³ | 38.7  |

Now consider the work of the TME-accumulator on the “Zif-8 + H₂O”. Technical data (table 7) show that the charge-discharge pressure of that HLS is 270 and 220 kg/cm² respectively, which no longer allows the use of the ready-made hydraulic system with PHA 24-5636-0 and GM36. To analyze the work of that working medium and compare it with the work of the corresponding traditional PHA, it is proposed to replace the main units of the bicycle hydraulic system with the following, more modern: bladder PHA HAB4-350-6X/0G and the hydromotor A2FM12/61W by Bosh Rexroth AG. Their basic parameters are presented in table 10 [14, 15] and table 11 [16, 17]. The work of these aggregates is similar to the previous models; the volume of hydroaccumulators is approximately the same, as well as the specific volume rate of hydromotor fluids. The difference lies only in higher working pressures of the new models (table 10 and table 11). The operating characteristics of the updated hydrosystem are given below (table 12 and table 13).

As we can see, the force and the moment of pedaling are only slightly higher than the parameters that are typical for a non-sportsman cyclist (table 3). Therefore, we can conclude that the use of the hydrosystem updated elements is correct.

Table 10. The HAB4-350-6X/0G general data.

| Name, unit             | Value   |
|------------------------|---------|
| Nominal volume, liters | 4       |
| Max operating pressure, bar | 350     |
| Gas pre-charge pressure, kg/cm² | 70⁴     |
| Oil volume, cm³        | 2604⁴   |
| (at a discharge of 270 to 80 bar) |         |
| Charging gas           | Nitrogen|
| Hydraulic fluid        | Hydraulic oil|

⁴Calculated
Table 11. The A2FM12/61W general data.

| Name, unit                        | Value |
|-----------------------------------|-------|
| Max speed of rotation, rpm        | 8000  |
| Nominal pressure, bar             | 315   |
| Max pressure, bar                 | 350   |
| Specific flow rate of oil in cm³  | 12    |
| Torque, Nm                        | 67    |
| Mass (approx.), kg                | 5.4   |

Finally, let us evaluate the operation of the hydrosystem with the TME-accumulator on “Zif-8 + H₂O”. To do this, also remove the bladder and oil valve from the PHA HAB4-350-6X/0G, increasing the capacity of the working chamber to 4.5 liters. The technical characteristics of the TME-accumulator (Zif-8) are in the table 14.

Table 12. The updated PHA charge parameters.

| Parameter, unit                      | Value |
|-------------------------------------|-------|
| Charge pressure $P_{ch}$, bar       | 270   |
| GM A2FM12/61W pistons diameter $d$, cm | 0.9   |
| Radius of GM A2FM12/61W cylinder centres circle $R$, cm | 2.8   |
| Number of GM A2FM12/61W pistons $Z$ | 9     |
| GM A2FM12/61W piston block tilt angle $\gamma$, grad | 30    |
| GM A2FM12/61W torque $T$, Nm        | 68.9  |
| Kinematic ratio $i_\Sigma$          | 1.29  |
| Moment of pedaling $M_{ped}$, Nm     | 88.9  |
| Crank arm length $l$, cm             | 17    |
| Pedal force $F_{ped}$, N             | 522.8 |

Table 13. The updated PHA discharge parameters.

| Parameter, unit                      | Value |
|-------------------------------------|-------|
| Average discharge pressure $P_d$, bar | 270   |
| GM A2FM12/61W specific flow rate $q_{GM}$, cm³/rev. | 11.5  |
| Spool valve flow rate $Q_{SV}(nom)$, cm³/min | 8000  |
| GM A2FM12/61W torque $T_{GM}$, Nm     | 26.4  |
| GM A2FM12/61W rotation frequency $\omega_{GM}$, c⁻¹ | 70    |
| GM A2FM12/61W power $N_{GM}$, kW      | 1.84  |
| Rare wheel hub torque $T_{RWH}$, Nm   | 13.7  |
| Hub rotation frequency $\omega_{RWH}$, c⁻¹ | 36    |
| PHA energy capacity $E_{PHA}$, kJ      | 340.6 |
| PHA specific energy capacity $e_{PHA}$, J/cm³ | 85.1  |

7.1. TME-accumulator (Zif-8) charging

Taking into account the characteristics of the TME-accumulator (Zif-8) working medium, the charge pressure should be 270 kg/cm². Elements of the updated bicycle hydrosystem allow working with that pressure. All parameters of the charge process to the pressure of 270 kg/cm², including force and moment of pedaling, already calculated earlier. They can be seen in table 12. Thus, during the movement the cyclist can physically charge the TME-accumulator to the pressure of 270 kg/cm², putting the force of 523 N and developing the torque of 89 Nm (the result is only slightly higher than for a non-sportsman cyclist, table 3).
### Table 14. The TME-accumulator (Zif-8) basic parameters.

| Parameter, unit                              | Value   |
|---------------------------------------------|---------|
| Working chamber full capacity, cm$^3$       | 4500    |
| Charge pressure, MPa                        | 27      |
| Discharge pressure, MPa                     | 22      |
| Volume of liquid at discharge, cm$^3$       | 1500    |
| Working fluid specific volume, cm$^3$/g (per unit mass of porous matrix) | 0.5     |
| Specific energy capacity at charging, J/g (per unit mass of porous matrix) | 13.3    |
| Specific energy capacity at discharging, J/g (per unit mass of porous matrix) | 11.2    |
| Hysteresis of energy capacity, %            | 16      |
| Working fluid                              | H$_2$O  |
| Hydraulic fluid                            | AMG-10  |

*Calculated

7.2. TME-accumulator (Zif-8) discharging

The discharge pressure of the TME-accumulator (Zif-8) is 22.0 MPa (table 7). The rest of the discharge characteristics after the calculation are presented in table 15.

### Table 15. TME-accumulator (Zif-8) discharge parameters.

| Parameter, unit                              | Value   |
|---------------------------------------------|---------|
| Average discharge pressure $P_d$, bar        | 270     |
| GM A2FM12/61W specific flow rate $q_{GM}$, cm$^3$/rev. | 11.5    |
| Spool valve flow rate $Q_{SV}$ (nom), cm$^3$/min | 8000    |
| GM A2FM12/61W torque $T_{GM}$, Nm            | 42      |
| GM A2FM12/61W rotation frequency $o_{GM}$, c$^{-1}$ | 70      |
| GM A2FM12/61W power $N_{GM}$, kW             | 2.93    |
| Rare wheel hub torque $T_{RWH}$, Nm          | 21.8    |
| Hub rotation frequency $o_{RWH}$, c$^{-1}$   | 36      |
| PHA energy capacity $E_{PHA}$, kJ            | 380.8   |
| PHA specific energy capacity $e_{PHA}$, J/cm$^3$ | 95.2    |

8. Conclusions

1. The work deals with an ecological vehicle, which is a touring bicycle with the compact hydraulic system in which the traditional PHA with oil as a working fluid is replaced with the thermomolecular accumulator with water as the fluid component of the working medium. This replacement allows to increase the environmental attractiveness and cleanliness of the energy used.

2. During the movement in the charging mode the basic parameters of the updated hydrosystem with PHA/TME-accumulator, namely the force and the moment of pedaling, are 523 N and 89 Nm, which is practically in the range of physical capabilities of a non-sportsman.

3. When driving in the discharging mode the hydromotor shaft power and the moment on the drive wheel hub have the following values:

   - for traditional HAB4-350-6X/0G $N_{HM}$=1.84 kW, $M_{DWH}$=13.7 Nm, $e_{PHA}$=85.1 J/cm$^2$
   - for TME-accumulator with HLS “Zif-8+H$_2$O” $N_{HM}$=2.93 kW, $M_{DWH}$=21.8 Nm, $e_{PHA}$=95.2 J/cm$^2$. 
4. Within the same working volume, the specific energy capacity of TME-accumulator by 11.8% exceeds the PHA, the developed moment - by 59%. These results indicate the validity of replacing the traditional PHA with a TME accumulator in the hydraulic system of the bicycle.

9. References

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