HEFAT2007
5th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
Sun City, South Africa
Paper number: CE1

INFLUENCE OF THERMODYNAMIC BEHAVIOUR ON HLA SYSTEM PERFORMANCES

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ABSTRACT

In the recent years, a new interest on kinetic energy recovery (KER) of vehicles arose. In USA, car manufacturers (Ford, Sheep et al.) developed research programs on the use of hydraulic devices to achieve KER, also with economical support of government body (EPA). In 2002 Ford built a very interesting prototype (Ford Tonka) using such recovery system (HLA, Hydraulic Launch Assist), achieving improvements better than 20 % on fuel consumption and pollution, besides increasing of acceleration. At present time, also DIMEG is working about HLA systems, carrying on two work lines: one (based on the building of a simulation program) to verify operation limits and system performances and another experimental (to study particular thermodynamic aspects of cyclic operation of hydro-pneumatic accumulators).

In previous works the authors studied application of HLA system on small vehicles, emphasizing the influences of mechanical parameters and kind of mission profile. Here they mean to treat the influences of some thermodynamic characteristics on performances and operation field of such system. The nitrogen behaviour is described by BWR state equation. Particular attention will be devoted to analyze, from a global point of view, the penalties introduced by using a more simple state equation for describing nitrogen, the influences on global performances of the efficiency of expansion and compression transformations and of heat exchange between gas and outside. The analysis will be performed for a commercial vehicle with mass of about 2000 kg.

INTRODUCTION

As widely underlined in the press and communication campaigns, the atmospheric pollution in urban areas becomes every day more relevant, and this is even more critical in large cities. The air conditions are often above the limit values established as dangerous (due to the presence of NOx and or fine particulate PM10). Therefore, the local administrations – considering that most of the urban pollution is produced by vehicles – are forced to intervene with acts that limit vehicle

NOMENCLATURE

D	[m]	Diameter
E	[J]	Energy
E_{HLA}	[J]	Energy delivered by HLA system to power shaft of vehicle
E_{sd}	[J]	Energy wasted in slow down motion
E_t	[J]	Energy required for vehicle motion
H_H	[J/m^2/s]	Heat flux through accumulator head
H_L	[J/m^2/s]	Heat flux through accumulator lateral surface
K_i	[W/m^2/K]	Heat exchange coefficient
Q_{oil}	[m^3/s]	Volumetric oil flow rate
R	[m^{3}Pa/kg/K]	Nitrogen constant
S_i	[m^2]	Surface
T	[K]	Temperature
T_∞	[K]	Temperature of external ambient.
V	[m^3]	Volume
c_v	[J/kg/K]	Specific heat at constant volume
f	[-]	Reduction factor
k	[-]	Coefficient of adiabatic transformation
m	[kg]	Mass
m_g	[kg]	Mass of gas in accumulator
n	[-]	Coefficient of polytropic transformation
p	[bar]	Pressure
u	[J/kg]	Internal energy
v	[m^3/kg]	Specific volume
Θ_{HLA}	[-]	Motion factor of HLA
η_{exp}	[-]	Efficiency of expansion transformation
η_{HLA}	[-]	Conversion efficiency of HLA

circulation. Consequently, it is important to observe that a great portion of vehicle kinetic energy is dissipated during slow down and stop driving: the accumulation and successive use of such kinetic energy during acceleration may lead to high energy savings (also above 20 % in stop-and-go traffic condition). This would allow a reduction of all the pollution factors and the possibility of downsizing the engine. Similar advantages, even if of lesser magnitude, are possible in extra urban journeys, where it is also possible to recover the kinetic energy that would be, otherwise, dissipated to maintain constant velocity over downhill slopes.

There are several types of device, operating according to different physical principles, that have been developed in the past years to operate as described above. Three different types of ESS (Energy Storage Systems) are generally considered and, for each of them, the perspectives of utilization are characterized with reference to hybrid and electrical vehicles: they are FES (Flywheel Energy Storage), SMES (Super-Magnetic Energy Storage) and HES (Hydro-pneumatic Energy Storage). Hydro-pneumatic systems and their principal components, either for using on vehicle, either as simple storage devices, were studied by numerous authors; let us remember the papers of Beachly [4,6], which regard the use on vehicles, and those of Pourmovahed [1,2,3], which diffusely treat the behavior of accumulators from thermodynamic point of view. In any case, even with the use of accumulators made of composite material of high resistance and small mass, HES systems are characterized by low energy density (nowadays range is 2 – 13 kJ/kg, but perspective of strong increment exists).

The poor storage capacity of HES systems determines the necessity of modifying their configurations going towards applications characterized by short storage times (and therefore by small quantities of accumulated energy) and equally short release time: these systems are then mainly oriented to the energy assistance during acceleration. These configurations, nowadays named in the literature as HLA (Hydraulic Launch Assist), have recently originated very interesting applications [7,8,9,10,11].

The authors, after some general consideration on the involved amount of energy, consider the application of HLA system to a vehicle with mass of 2000 kg with driving conditions typical of an urban environment (ECE15 is chosen as reference cycle). They analyze advantages and disadvantages involved by using an equation describing real gas behaviour and they also evaluate the influence of heat exchange. These considerations are always related with several values of efficiency of expansion/compression transformations of nitrogen in hydro-pneumatic accumulators.

HLA SYSTEMS

A HLA device (see Figure 1, from [7]) consists of: two bladder hydro-pneumatic accumulators (1, 2), respectively named high (HP) and low (LP) pressure accumulator; one electro-hydraulic valve (3) that controls and inverts the flow between the two accumulators; one reversible hydraulic pump/motor (4) with variable displacement operating between the accumulators. The pump/motor is mechanically linked to the main transmission line (6) – connecting engine and wheels – by means of a clutch (5), controlled by an appropriate electronic system. There are two different operating procedures: *assisted acceleration* and *slow down* with kinetic energy recovery. During each phase of assisted acceleration the clutch is engaged, the pump/motor unit operates as motor, hydraulic fluid is flowing from the HP accumulator to the LP accumulator and energy is transferred from HP accumulator to the transmission line. During each phase of slow down, the clutch is still engaged, and due to the valve operation, the pump/motor unit is operating as pump (absorbing power from the transmission line and decelerating the vehicle) and the hydraulic fluid inverts direction moving from the LP to the HP accumulator. During the phase of no operation the clutch is disengaged and, therefore, there is no mechanical link between the pump/motor and the transmission line; consequently there is no flow of hydraulic fluid between the two accumulators. The performances obtained are very interesting, [7]: the fuel consumption has been reduced of more than 20 % with respect to the original propulsion system, the emissions have been reduced between 20 % and 30 % and the accelerations have been increased of 30 %.

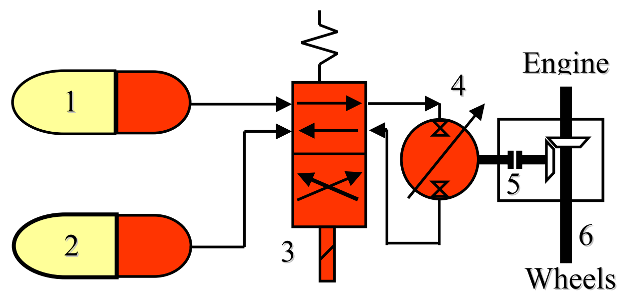

Figure1 Sketch of a HLA system

ENERGY CONSIDERATION AND SIMULATION MODEL

If we consider a vehicle which is driving an urban cycle (for example ECE15 as above told), we may verify that the energy E_{sd} – wasted by braking or by slowing down – is about 50 % of the traction energy E_t, necessary for the motion. In other words, about 50 % of motive energy is wasted during the portion of motion in which the kinetic energy of vehicle is reduced. Consequently, KER (Kinetic Energy Recovery) may be very useful if it is coupled with an efficient system of using the stored energy, as HLA device is. In fact, with HLA, a consistent fraction of motive energy may be substituted by recovered kinetic energy, saving energy and pollution of the prime mover of the vehicle.

The energy delivered by a hydro-pneumatic accumulator may be computed as the work connected with the expansion between minimum and maximum volume of the mass of gas contained in the bladder, i.e:

$$E = m_g \int_{v_1}^{v_2} p\,dv = m_g \frac{p_2 v_2 - p_1 v_1}{1-n} = f \cdot p_1 V_2 \qquad (1)$$

with

$$f = \left(e^{-n \cdot \ln \frac{V_2}{V_1}} - \frac{V_1}{V_2} \right) \Big/ (1-n) \qquad (2)$$

where sub-index 2 represents the end point of expansion (where the pressure reaches its admissible minimum value and the total volume of gas is about equal to the nominal volume of hydro-pneumatic accumulators) and sub-index 1 represents the beginning of expansion (where the pressure reaches its admissible maximum value). As pointed out in [11], it results that f has maximum value (of about 0.3) when the volumetric expansion ratio is about 2.3 (in the case of polytropic expansion coincident with adiabatic transformation, i.e. with $n \equiv k$), while the maximum delivered energy is realized with a pressure expansion ratio about 3.2. This values are used for defining pressure range of HP hydro-pneumatic accumulators.

Certainly, besides the above considerations, the energetic performances of a HLA system are affected by numerous mechanical parameters, diffusely detailed in [11]. Further, nature of the used gas (gas different from nitrogen may even be considered) and related thermodynamic properties have influence on HLA performances. In this report, the authors principally investigate about the differences on behaviour and performances induced by: i) using real or perfect gas state equation; ii) considering not unitary thermodynamic efficiency of expansion and compression transformations of the used gas (nitrogen); iii) involving inside-outside thermal exchanges.

Finally, the utility of mounting a HLA system may be easily evaluated in a global way if we refer to specific indicators as those defined in [10]. In particular, observing that the maximum energy that may be ideally introduced into hydro-pneumatic accumulators is E_b, calling E_{HLA} the net energy returned by HLA system to the drive line of the vehicle, we can define Θ_{HLA} (*HLA motion factor*) as the per cent ratio between energy returned by HLA (used for vehicle motion) and total energy requested for the motion, i.e.:

$$\Theta_{HLA} = \frac{E_{HLA}}{E_t} 100 . \quad (3)$$

In the same way, we may define η_{HLA} (*HLA conversion efficiency*) as the per cent ratio between the energy returned by HLA and the maximum energy, ideally introduced into hydro-pneumatic accumulators, i.e.:

$$\eta_{HLA} = \frac{E_{HLA}}{E_b} 100 . \quad (4)$$

For what concerns the simulation model, we use a particular computer program, detailed in [10,11]. The vehicle is defined by means of its main characteristics and only its longitudinal stability is considered under the influences of aerodynamic, rolling and gravitational losses. HLA system is modelled by means of two subsystems: one reversible hydraulic machine, using the traditional relations between torque, flow rates, volumetric and mechanical efficiency; two deformable closed volumes (bladder or cylinder-piston assembly) in which expansion and compression of nitrogen is realized. The mission profile is chosen between normalized reference cycles and it is divided into steps of 1 second, characterized by constant kinetic parameters. When the kind of mission step requires the use of HLA system, each step is further partitioned into ten subdivisions.

In this report, we consider a vehicle with mass of 2000 kg (incremented of HLA system mass when the device is mounted), and we fix ECE15 cycle as mission profile. The minimum pressure of HP accumulator is 107 bar, while its maximum values is 350 (the consequent expansion ratio assure optimal energetic response of HLA system); the minimum pressure of LP accumulator is 5 bar. The here reported simulation results are referred at ambient temperature of 25 °C, and the initial pressure of HP accumulator is 350 bar.

Thermodynamic Properties of Nitrogen

As told, the used gas is nitrogen and its behaviour is described by state equation of Benedict-Webb-Rubin, i.e.:

$$p = \frac{RT}{v} + \left(B_0 RT - A_0 - \frac{C_0}{T^2} \right) \frac{1}{v^2} + \left(bRT - a \right) \frac{1}{v^3} + a\alpha \frac{1}{v^6} + \frac{c\left(1 + \frac{\gamma}{v^2}\right) e^{-\frac{\gamma}{v^2}}}{v^3 T^2} . \quad (5)$$

From this equation, as shown in [1,2,3], specific heat at constant volume may be deduced:

$$c_v = c_{v_0} + \frac{6}{T^3} \left(\frac{c_0}{v} - \frac{c}{\gamma} \right) + \frac{3c}{T^3} \left(\frac{2}{\gamma} + \frac{1}{v^2} \right) e^{-\frac{\gamma}{v^3}} \quad (6)$$

where

$$c_{v_0} = R\left[\frac{N_1}{T^3} + \frac{N_2}{T^2} + \frac{N_3}{T} + \left(N_4 - 1\right) + N_5 T + N_6 T^2 + N_7 T^3 + N_8 \cdot e^{\frac{N_9}{T}} \left(\frac{\frac{N_9}{T}}{e^{\frac{N_9}{T}} - 1} \right)^2 \right] . \quad (7)$$

The values of constants of equations (5,6,7) are reported in [1,3].

The internal energy may be expressed by the relation:

$$du = c_v \, dT - \left[T \left(\frac{\partial p}{\partial T} \right)_v - p \right] dv \quad (8)$$

that may be numerically integrated using (5) and (6). For computing purpose a suitable look up table may be constructed, with temperature and specific volume as entries.

Expansion and compression transformation of nitrogen

The expansion and compression transformations of nitrogen in hydro-pneumatic accumulators are caused by volume changes imposed by oil flow rate. The transformations are assumed adiabatic, but not isentropic; so transformation efficiency is less than unit. Consequently, using energy equation, we can derive the value of internal energy at the end of expansion transformation:

$$u_2 = u_1 - \eta_{\exp} \left(u_1 - u_{2,is} \right) . \quad (9)$$

A similar relation may be used for compression.

As the specific volume is known by oil flow rate transferred between the two accumulators (imposed by pump/motor capacity and value of vehicle power shaft speed, see Figure 1), using the above look up table, the value of temperature at the end of expansion (or compression) may be evaluated. This procedure is applied, both for HP and LP accumulators, to the subdivisions of each temporal step of vehicle mission (during slowing down and accelerating motion, when HLA system is involved).

Heat exchange model

When heat exchange is involved, a piston type accumulators is used, as sketched in Figure 2. We suppose the nitrogen temperature is spatially distributed in a uniform way. Further, let us consider adiabatic the piston surfaces, so that heat exchange between nitrogen and oil is null.

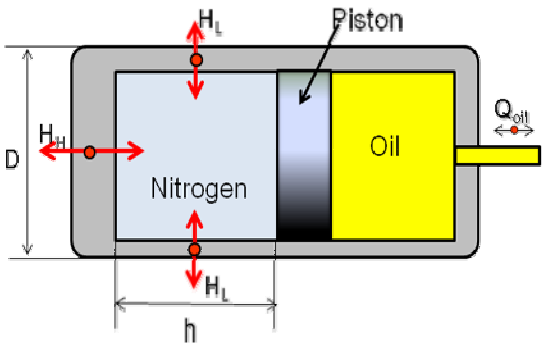

Figure 2 Sketch of piston type hydro-pneumatic accumulator

Consequently the heat exchange is only the sum of heat H_L, that flows through the cylindrical surface of nitrogen side of accumulator (height h of this surface is function of the volume of gas), and heat H_H, that flows through the head of accumulator. Then, the consequent variation of nitrogen temperature may be expressed as:

$$m\,c_v \frac{dT}{dt} = -\sum_{i=1}^{2} K_i \cdot S_i \left(T - T_\infty\right)$$

where each K_i is the global heat exchange coefficient, function of three contribution: convection between nitrogen and internal accumulator surface, conduction of accumulator wall and convection between outside accumulator surface and ambient. The assumed values in simulation are respectively 5, 50, 10 $W/m^2/K$.

For sake of simplicity, in computing, the heat exchanges are involved only when hydro-pneumatic accumulators are in stationary conditions, i.e. when the vehicle is stopped or its velocity is constant.

SIMULATION RESULTS

As above told, the simulations carried out are first of all oriented to investigate if, from a practical point of view, there are strong differences using the perfect gas state (PGS) equation (considering in any case specific heat function of temperature) instead of BWR state equation [1,2,3], which introduces strong penalties in computing time. Secondly, they are performed to evaluate the influence of efficiency of compression/expansion transformation of nitrogen in the accumulators; in such analyses the effects of heat exchanges are also involved.

In any case, the initial pressure in HP accumulator is fixed at 350 bar, which also represents the operational limit. To avoid damage on accumulator, two temperature limits are introduced: when the temperature of HP or LP accumulators becomes greater than 580 K or lower than 170 K, the operation of HLA system is stopped.

Comparison between BWR and PGS equations

Figure 3 and 4 show the evolution of motion factor and conversion efficiency as function of number of missions, when heat exchanges are not considered (fully adiabatic operation) and the efficiency of expansion/compression is fixed at 90 or 95 %. The use of PGS equation gives results in defect at the beginning of motion, but in excess with the increasing of carried out missions. The differences appears relevant during the first and last possible missions. Another important discrepancy is the number of missions at which the temperature limits are reached and HLA cannot further operate.

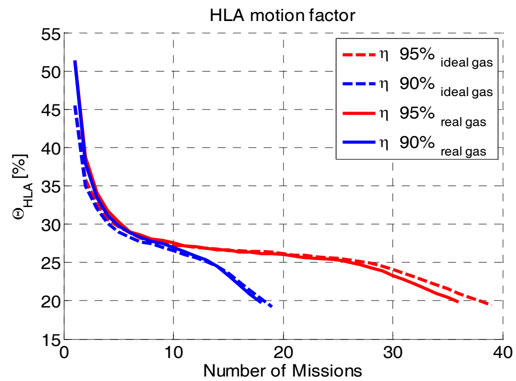

Figure 3 Comparison between the use of BWR equation and perfect gas state equation (Motion factor)

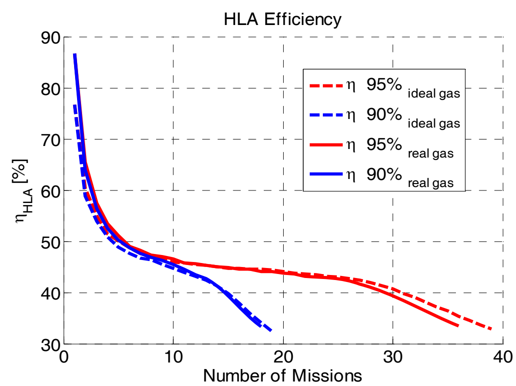

Figure 4 Comparison between the use of BWR equation and perfect gas state equation (Conversion efficiency)

This behaviour is emphasized in Figure 5, which represents the evolution of temperature at the end of each mission. For both efficiencies considered (90 and 95 %), it is clearly shown that using PGS equation determines a more slow increment of temperature than the real behaviour; consequently, LP vessel – which is the accumulator with the fast temperature raising – reaches later the upper temperature limit. In figure 6, which shows the evolution of pressure at the end of each mission, we may observe that, associated with reaching limit temperature, HP accumulator pressure reaches its maximum value, while LP pressure does not reach its minimum value, as consequence of the different speed of temperature raising in the two vessels and the same volume variation imposed by oil flow rate. Further, we may observe that BWR and PGS equations give pressure evolution with different values, but with the same tendency.

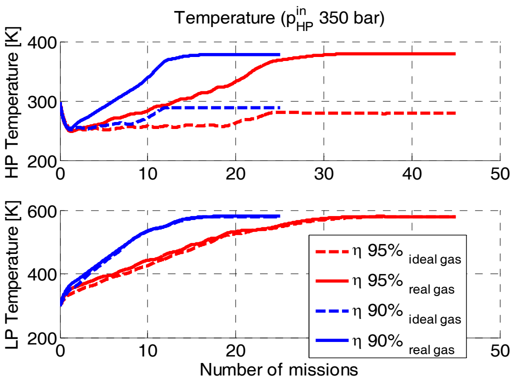

Figure 5 Comparison between the use of BWR equation and perfect gas state equation (Temperature evolution)

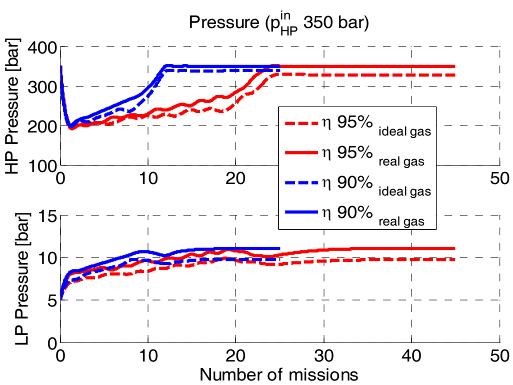

Figure 6 Comparison between the use of BWR equation and perfect gas state equation (Pressure evolution)

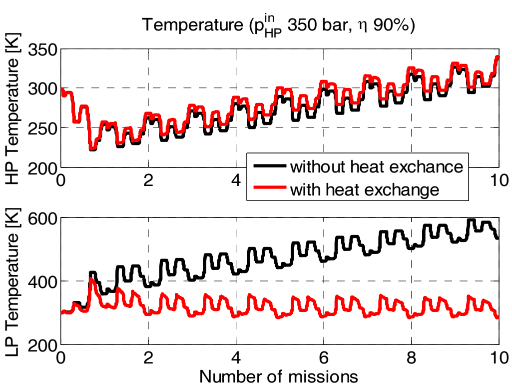

Figure 7 Effect of heat exchange in temperature evolution in HP and LP hydro-pneumatic accumulators

From the above considerations, clearly results that to have a good prediction of HLA performances it is necessary to apply BWR equation and to accept the strong increment of computing time. Consequently, ameliorating computational program will be necessary.

Effects of heat exchange and of expansion/compression efficiency

The heat exchange between nitrogen and the outside (with a fixed temperature of 25 °C) is more effective in LP hydro-pneumatic accumulator, as nitrogen mass is much smaller in LP vessel than in HP one, while the exchange surfaces are the same. This is clearly shown in Figure 7, where HP and LP pressure evolutions for the first ten consecutive missions are compared. As direct and important consequence, we can verify that the temperature operational limits may be reached only after a greater number of missions or they are not reached at all. In other words, a good heat exchange produce benefits on operation of HLA system. Figure 8 clearly shows this improvement as it puts in evidence that the temperature at the end of each mission, in both HP and LP vessels, reaches stable value well inside operational limits.

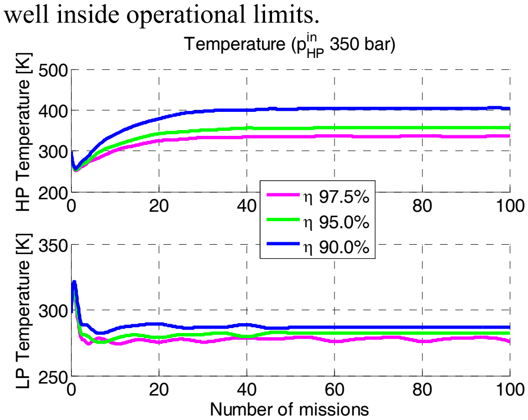

Figure 8 Effect of heat exchange in evolution of end mission temperature in HP and LP hydro-pneumatic accumulators

For what concern HLA motion factor and recovery efficiency, we may refer respectively to Figure 9 and 10. We may observe that heat exchange produces stabilized values for both indicators as mission number increases; the achievement of a stable value happens as soon, as high the efficiency is. In any case the obtained motion factor assures the utility of using a HLA system. The values of conversion efficiency also appear very interesting.

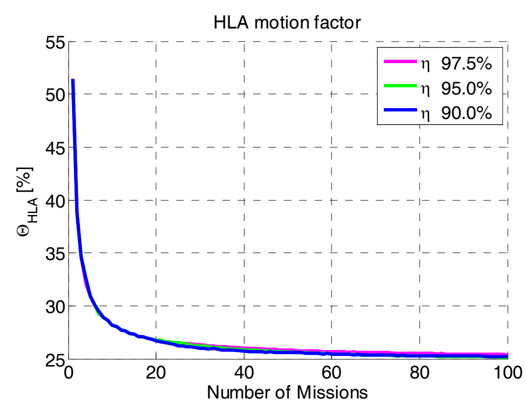

Figure 9 Effect of heat exchange in HLA motion factor with different values of expansion/compression efficiency

The high values of the two indicators at the beginning of motion are related with the initial pressure of HP accumulator, fixed at its maximum.

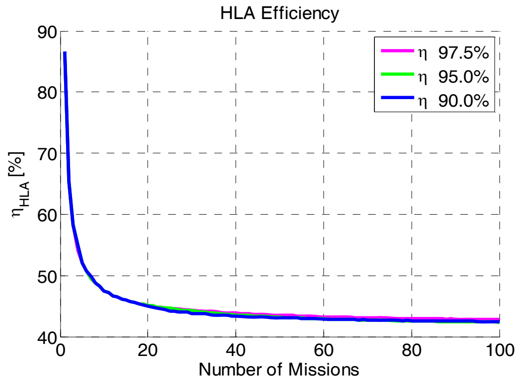

Figure 10 Effect of heat exchange in HLA recovery efficiency with different values of expansion/compression efficiency

Influence of initial pressure of HP accumulator

Finally, as further details, we may observe Figure 11 where it is shown the influence of the initial pressure value of HP accumulator, which represents the quantity of energy present in HLA system at the beginning of motion. The influence is relevant only in the first mission; but, when the number of missions becomes great, the effect is dramatically reduced and there are not practical incidences on the values of HLA motion factor and recovery efficiency.

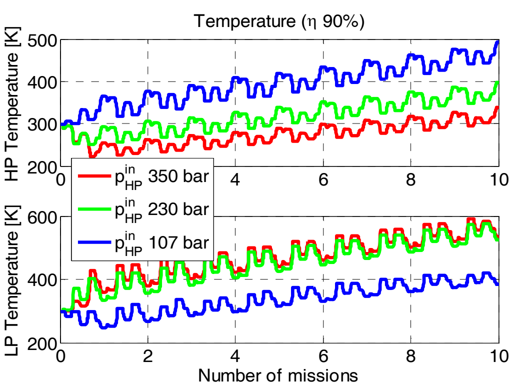

Figure 11 Effect of initial pressure of HP hydro-pneumatic accumulator (absence of heat exchange)

CONCLUSION

In present work, after a brief description of HLA system and of its way of operation, the authors quantify the amount of energy involved by a vehicle when perform a mission in an urban contest. To evaluate the utility of using a HLA system, a simulation model is described, putting particularly in evidence the aspects, relevant from a thermodynamic point of view.

The numerical tests performed show that, the use of BWR equation to represent the behaviour of nitrogen in hydro-pneumatic accumulator, is fundamental for a good description of HLA performances, even if the use of PGS equation would be very profitable for computing time. In fact, as shown by figures 3-6, strong differences (also about 10 %) appear between the results obtained by using PGS and BWR equation, but the use of PGS equation may be dangerous as, for example, a greater number of missions seems possible.

The advantage of having a heat exchange between nitrogen and outside is assessed. In fact, in a situation of natural convection, great improvements are achieved in terms of containment of temperature between the operational limits (imposed by vessel material integrity) and the consequent great increasing of allowed mission number. Consequently, realizing accumulators for HLA systems by a material with high conductivity and defining a layout that assure at least a good natural convection are good practices. Further, good heat exchange appears to strongly reduce the negative effects of poor thermodynamic efficiency, as shown by figures 9 and 10.

The values obtained for HLA and motion factor assure that, in an urban contest, about 20-25% of motive energy may be delivered by the braking energy stored in HLA system, realizing correspondent saving of fuel and reduction of pollution (without taking into account the increasing of durability of braking system). Further, HLA recovery efficiency achieves acceptable but not optimal values (35-42%) and, with more deep studies and analyses, it may be certainly improved.

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