MULTICOMPONENT DISCHARGE DYNAMICS OF ADSORBED NATURAL GAS STORAGE SYSTEMS

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Introduction

Several operational problems hinder the success of Adsorbed Natural Gas (ANG) storage. The one of concern in this work is the adsorbent-capacity deterioration on extended operation due to the nature of NG composition. Besides methane, NG contains ethane, nitrogen, and a small proportion of alkanes ranging from C_3 to C_7. CO_2 may also be present in small quantities (0.04 to 1% molar), as well as water vapor in the concentration range 75–180 ppm (v/v), and sulfur-containing compounds at the ppm level [1].

These species, mainly the higher molecular-weight hydrocarbons, are more strongly adsorbed than methane, especially in the low-pressure region. If the higher molecular-weight hydrocarbons are allowed to enter the on-board storage system during charge, they adsorb preferentially and decrease the amount of gas that is actually deliverable by the storage system. This is driven by the unfeasibility of operating an on-board storage reservoir under sub-atmospheric pressure, since excessive compression hardware would be necessary to extract and boost the fuel pressure [2].

Problem formulation and theoretical model

The dynamic behavior of an on-board cylinder for ANG storage is modeled as a series of consecutive cycles. Each cycle is a two-step process whose characteristics are depicted in Fig. 1. Multicomponent adsorption equilibrium is predicted by an approach combining the Adsorption Potential and the Ideal Adsorbed Solution theories. The combined approach is sufficiently accurate to provide a reasonable description of how gas composition affects the dynamic behavior of the cylinder on cyclic operation. A detailed description of the theoretical model is given in [3].

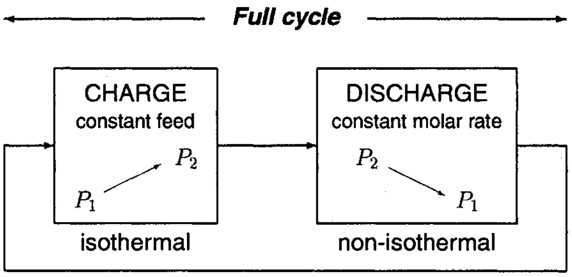

Figure 1. Simulated cyclic operation of an on-board storage system; P_1 = depletion pressure; P_2 = charge pressure.

Results and discussion

The gas mixture considered in this work is describe in Table 1, and characterizes the Algerian NG from the Hassi R'Mel well that supplies the author's country.

If the vehicle is always refueled with the same gas mixture, the cylinder will approach a cyclic steady state on extended operation. Under these conditions net charge capacity and net deliverable capacity are identical: the gas stored in the cylinder during charge is fully delivered during discharge. Furthermore, under cyclic steady-state operation the overall composition of the gas delivered by the cylinder is the same as that of the NG supplied by the refueling station. Thus, under cyclic steady-state operation the total amount of species i delivered by depressurizing the cylinder from P_2 down to P_1 is $z_i Q^{(\infty)}$, where $Q^{(\infty)}$ is the total amount of gas delivered in cyclic steady-state, and z_i is the species mole fraction in the NG supplied by the refueling station (Table 1). This fact suggests that the net deliverable capacity of an ANG cylinder is best measured by a dynamic efficiency, η, which for component i is defined as

$$\eta_i = \frac{\text{amount of species } i \text{ delivered under real conditions}}{(\text{amount of pure CH}_4 \text{ delivered isothermally}) \cdot z_i}.$$

With this definition, the η_is converge to a single point at the cyclic steady-state, whose value is

$$\eta^{(\infty)} = \frac{Q^{(\infty)}}{\text{amount of pure CH}_4 \text{ delivered isothermally}}.$$

This feature is depicted in Fig. 2. Note that η takes into account the loss in capacity due to both the composition of the gas mixture and the nonisothermal operation of the discharge step.

Regarding the NG considered in the present work, which has 90% methane, the results show that there is a drastic

Table 1. Composition of Algerian natural gas from the Hassi R'Mel Well that Supplies Portugal.

Component	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}	N_2
Mole fraction	0.840	0.076	0.020	0.007	0.003	0.054

reduction in net deliverable capacity with cyclic operation. Before leveling off, the total hydrocarbon capacity loss, defined as

$$\eta_{1-5} = \frac{\text{total amount of HCs delivered under real conditions}}{(\text{amount of pure CH}_4\text{ delivered isothermally}) \cdot \sum z_i},$$

depends linearly on the logarithm of the number of cycles. This is in qualitative agreement with experimental observations [4] for 1000 cycles of operation of a storage cylinder on a NG containing 2.6% impurities. The measured capacity decrease after 100 cycles of operation was 22%. According to Parkyns and Quinn [1], the latter author performed cyclic testing with a number of different carbons on Canadian NG and also observed significant losses in adsorption capacity. Furthermore, the leveling off of capacity was observed when the cyclic testing was prolonged sufficiently. This is experimental evidence of the cyclic steady-state operation.

In another experimental study [5], a capacity loss of more than 50% was measured on a NG with 8.9% impurities. Given that η represents a relative loss in deliverable capacity, its value should be more dependent on gas composition than on the adsorbent. Hence, although the carbon tested in [5] is different from the one considered here, both results can be compared roughly because the two NGs have nearly the same purity. When this is done, a fairly good agreement is obtained. Note that the storage system modeled here does not operate isothermally, this increases the loss in deliverable capacity by about 10%.

Figure 3 compares the histories of temperature and adsorbed-phase mole fractions, inside the cylinder during discharge, for the first cycle and for the cyclic steady state.

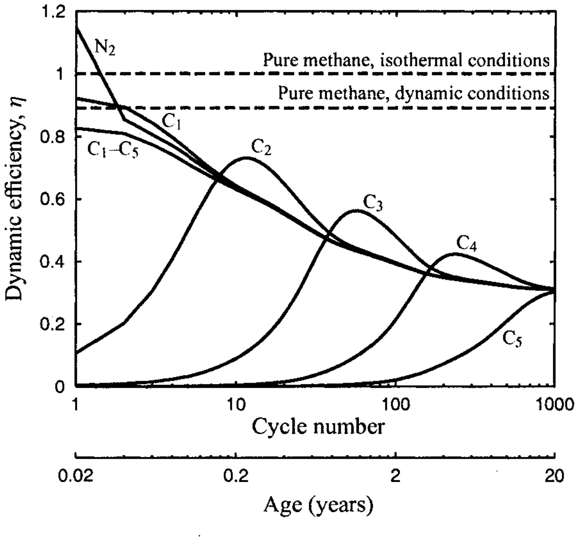

Figure 2. Dynamic efficiency, η, as a function of cycle number for the ANG storage cylinder.
C_1: methane; C_2: ethane; C_3: propane; C_4: butane; C_5: pentane; C_1–C_5 identifies the total hydrocarbon dynamic efficiency, η_{1-5}.

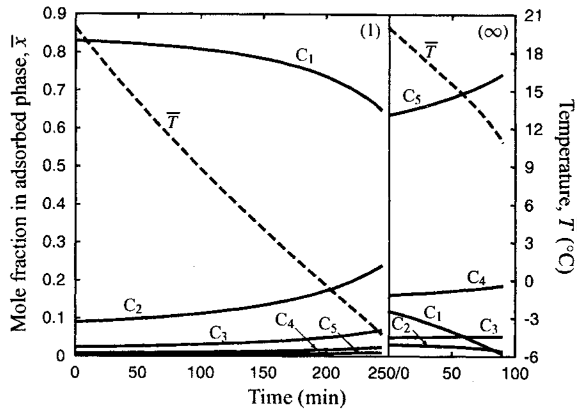

Figure 3. Histories of temperature and adsorbed-phase mole fractions in the ANG storage cylinder for the first cycle (1) and for the cyclic steady state (∞).
The curves correspond to lumped values obtained by averaging the variables over the cross section of the cylinder. C_1: methane; C_2: ethane; C_3: propane; C_4: butane; C_5: pentane.

The difference between the results for the first cycle and for the cyclic steady state is noticeable. If the discharge flow rate is held constant, discharge duration decreases with cycle number. When the cyclic steady state is reached, pentane is clearly the species that is more adsorbed. In fact, its mole fraction in the adsorbed phase is at the same level as that of methane in the first cycle.

Conclusions

Performance levels required for commercial viability of ANG storage have already been achieved with methane under isothermal conditions. There are, however, other species besides methane in a real NG. Although one carbon and a single gas composition have been studied here, other NG compositions give rise to the same qualitative behavior. The results demonstrate that any commercial mobile application of this storage technology must provide economical means of removing the higher molecular-weight hydrocarbons and other highly adsorbed species from the gas stream before charging the storage vessel.

References

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