CFD-subset-FVM-based MATLAB-simulation of Heat Transfer in High Grade Cold Storage Augmenting Cryogenic Energy Storage System by Circulating Natural Gas as Working Fluid

A. Kanni Raj
Professor,
School of Basic and Advanced Sciences, Veltech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology (University), Avadi, Chennai, Tamil Nadu, India
Email: drakanniraj@veltech.edu.in
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Abstract
Cryogenic energy storage (CES) improves power grid application with renewable intermittent power sources. In CES, off-peak excess electricity liquefies air or natural gas. Cryogenic fluid so obtained is stored in large Dewar tanks for long periods of time. Whenever electricity need is in peak, work available in cryogen is recovered by thermodynamic cycle using hot storage waste heat (HSWH) that has been generated by liquefier’s compressor. Many researchers focus on liquid air energy storage (LAES). But, natural gas (NG) is good working substance for CES liquefaction process. This paper reviews NG-CES containing high grade cold storage (HGCS). Cold stored HGCS is utilized to raise CES efficiency and hike liquefier yield. This paper models HGCS unit and compares output with experimental data. Impact of cold recycling is analyzed for liquefier yield and storage efficiency.

Keywords: Computational fluid dynamics, cold storage, cryogenic energy storage, exergy, finite volume method, MATLAB, natural gas

INTRODUCTION
Theoretical Review of Energy Storage and Cryogenic Technologies
More and more share of renewable energy sources in electricity power grid is good for eco-friendly sustainable energy strategy. Renewable sources are intermittent as weather influencing solar and wind power production. Therefore, energy by renewable sources shows more match with demand. So, developing energy storage methods becomes very important to increase electrical power grid stability [1, 2]. CES is very good alternative storage technique to currently available techniques, viz., compressed air energy storage (CAES), Lithium-ion batteries, etc. Though CAES and Li-ion battery provide large storing capacities, they are highly specific to site topology and geology. CES is free from such drawbacks. CES principle is: application of off-peak electricity to liquefy air or natural gas (NG), storage of cryogen in large Dewar tank, and recovery of cryogenic exergy via thermodynamic cycle to produce power to meet high demand. Regularly researched and used CES is LAES as atmospheric air is widely available. But, NG-CES is highly efficient. Also, NG is also available plentifully in industrially advanced countries [3, 4]. Current review is CES using NG as working fluid.

Brief Review of Natural Gas based Cryogenic Energy Storage System
Modeled and analyzed NG-based-CES system example is shown in Fig.1. It applies Linde’s method of liquefaction via reverse Carnot cycle for charging. It again applies direct expansion system with a
two-stage expander for discharging. Charging and discharging processes are coupled with high grade cold storage (HGCS) unit [5]. In this method, medium pressure NG (6bar or 0.6MPa) is compressed to high pressure (100bar or 10MPa). Very high compression rises NG temperature sharply. Hot NG is cooled in recuperator (or recuperative heat exchanger) with the help of HGCS cold and CES regasification. Cold high pressure NG so obtained is throttled in expansion valve (follows Joule-Thomson effect), which liquefies only a part of it. Cryogenic liquid that is formed by throttling is sent to storage (Dewar tank). Extra vapour available is then sent through recuperator to LP-NG pipe line (Fig.1).

Compressor work is given by the formula: $w_c = T_a(s_l - s_H) - (h_l - h_H)$, where $T_a$ – air temperature (K), $s$ – specific entropy (J/kg/K), $h$ – specific enthalpy (J/kg). Liquefaction yield ($y$) can be derived from energy balance (boundary: red dash line): $\dot{m} h_H - y \dot{m} h_{IV} - (1 - y) \dot{m} h_V - \dot{m} q$, $y = \frac{h_{IV} - h_H}{h_V - h_{IV}}$, where $\dot{m}$-NG entry mass flow rate (kg/s), $q$- delivered cooling load per unit mass of NG (J/kg). So, work to liquefy unit mass of NG is $g$: $w_l = \frac{w_c}{y}$, $w_l = \frac{h_{IV} - h_H}{h_V - h_{IV}} [T_a(s_l - s_H) - (h_l - h_H)]$.

Direct expansion components are: LNG pump, heat exchangers (HEs) and Hot expanders. LNG is pumped till pressure rises to HP. It evaporates and gets heated in HE. HGCS is cooled in liquefaction. Warm HP-NG expands in I Expander to release stored power. After I Expansion, NG is reheated and then sent to II Expander [1]. So, CES network done is: $w_{net} = w_{exp_1} + w_{exp_2} - w_p = (h_3 - h_4) + (h_5 - h_6) - (h_2 - h_1)$.

Energy storage efficiency is: $\eta = \frac{w_{net}}{w_l}$. CES parameter values are shown in Table 1.

### Table 1: Inputs for CES thermodynamic calculation.

| Parametric variable                      | Numerical input values for variables |
|------------------------------------------|--------------------------------------|
| MP pipe line – NG pressure              | 6bar                                 |
| LP pipe line – NG pressure              | 1.1bar                               |
| discharge pressure – compressor (p$_t$,or Pc) | 100bar                              |
| exergy recovery system - network (w$_{net}$) | 313 kJ kg$^{-1}$                      |
| exergy recovery system- power output (P) | 350kW                                |
| LNG - mass stream ($\dot{m}_{LNG}$)     | 1.12 kg s$^{-1}$                     |
| liquefaction - charging time            | 6h                                   |
| Expansion – discharge time              | 2h                                   |

**MATERIALS AND METHODS**

**Modeling Cold Storage That Augments Cryogenic Energy Storage**

HGCS is packed with spheres made up of quartz or quartzite rock. Parameters considered for heat transfer analysis are...
given in Table 2. Conceptualization of HGCS is in Fig.2. Heat (cold) is stored as sensible heat within quartz spheres. During discharging of CES, cool air formed by LNG vaporization process is sent to HGCS by cooling its packed spheres to 140 K. During liquefaction in CES, warm air flows into cold HGCS bed and is then sent to recuperative heat exchanger (recuporator) of liquefier [6].

![Conceptualization – HGCS bed.](image)

**Table 2:** Parameters for HGCS conceptualization.

| Parameter                          | Value                        |
|------------------------------------|------------------------------|
| Diameter of Storage Dewar Tank (D) | 2.5m                         |
| Length of Storage Dewar Tank (L)   | 10m                          |
| HGCS packing spheres size (d)      | 15mm                         |
| HGCS packing material              | Quartzite Rock               |
| Volume fraction of voids (ε)       | 0.38 (or 38%)                |
| HGCS fluidic medium                | Air with 1.5bar (0.15MPa) and at 140-273K |

**Heat Transfer Calculations by Finite Volume Method Manipulation**

For modeling of high grade cold storage (HGCS) packed bed unit, a one-dimensional model is assumed. It is formed as per usual conductive, convective and transient heat transfer methods [7]. Equations 1 and 2 are fundamental PDEs those are solved by FVM-CDS schemes / TDMA-IM solution, respectively for fluidic air and solid packing material-quartzite rock.

\[
\begin{align*}
\rho_f C_{p,f} \frac{\partial T}{\partial t} + \rho_f C_{p,f} u_x \frac{\partial T}{\partial x} &= \frac{\partial}{\partial x} \left( k_f \frac{\partial T}{\partial x} \right) + h_v \frac{1-\varepsilon}{\varepsilon} (T_a - T) \\
 k_f \frac{\partial^2 T}{\partial x^2} - \rho_f C_{p,f} u_x \frac{\partial T}{\partial x} - \rho_f C_{p,f} \frac{\partial T}{\partial t} + h_v \frac{1-\varepsilon}{\varepsilon} (T_a - T) &= 0
\end{align*}
\]

where \( \rho_f \) – density of fluid air (kg/m\(^3\)), \( C_{p,f} \) – heat capacity of fluid air (J/kg/K), \( u_x \) – fluid velocity (m/s), \( k_f \) – thermal conductivity of fluid air (W/m/K), \( \varepsilon \) – volume fraction of voids, \( h_v \) - convective heat transfer coefficient (W/m\(^2\)/K), and \( T_a \) – air temperature (K).

\[
\begin{align*}
\rho_b C_{p,b} \frac{\partial T_b}{\partial t} &= \frac{\partial}{\partial x} \left( k_b \frac{\partial T_a}{\partial x} \right) + h_v (T - T_b) - U_v (T_b - T_a) \\
 k_b \frac{\partial^2 T_a}{\partial x^2} - U_v (T_b - T_a) \rho_b C_{p,b} \frac{\partial T_a}{\partial t} + h_v (T - T_b) &= 0
\end{align*}
\]

where \( \rho_b \) – density of quartzite rock (kg/m\(^3\)), \( C_{p,b} \) – heat capacity of packing rock (J/kg/K), \( k_b \) – thermal conductivity of quartzite, \( U_v \) – volumetric heat transfer coefficient (W/m\(^3\)/K), i.e., heat in-leaks from air, and \( T_b \) – HGCS bed temperature.
(K). Convective heat transfer coefficient \( (h_v) \) is calculated from Colburn factor for gas flowing through bed of spheres, i.e.,

\[
h_v = \frac{2.06Re^{-0.575}GPr}{\epsilon Pr^{1/3}}, \text{ where } G - \text{ fluid air mass flow rate per surface unit (kg/m²/s)}, \text{ Re - Reynold's number, and } Pr - \text{ Prandtl’s number.}
\]

**RESULTS AND DISCUSSION**

**Computational Fluid Dynamics Simulation in MATLAB software**

Aforesaid model is solved in MATLAB by well-prepared solution scheme involving partial differential equations (PDEs). In current CES research, it is used to solve PDEs by FVM. It applies Central Difference Scheme (CDS) of discretization, implicit method of solution finding and Thomas Tri-Diagonal Matrix Algorithm (TDMA) for simplifying calculation [8]. Residual tolerance setting is \( 10^{-6} \) for all time steps. Computational domains length 10m, which are divided into 1000 equi-spaced computational nodes of 0.015mm, with the time step set to 0.5ms. Thermodynamic properties needed for heat transfer of fluidic air is taken from internet data bases [9]. Calculations compares well with experimental data as shown in Fig.3.

**Numerical Outputs Showing Temperature Profiles and Hiking Yield**

Calculations are initiated for HGCS charging (air temperature at inlet is 140 K, i.e., -133°C), and then for its discharge (air inlet temperature is 273 K, i.e., 0°C). Temperature profile at beginning of HGCS discharge is assumed to be same as end of charge cycle (heat in-leaks from surrounding during time between cycles is omitted). T profiles during charging HGCS and HGCS discharge are presented in Fig.4 and 5. Cold storage is always in neither fully charged nor fully discharged condition. Cooling power stored in HGCS is:

\[
Q_{bed} = \int_{x_0}^{x_f} \rho_b c_{pb} A [T_a - T_b (x)] dx.
\]

Cooling power used in liquefaction cycle is assumed to be different from that of discharging. HGCS influences on CES efficiency and liquefier’s yield (Fig.6). Minimal work is also manipulated. Table 3 shows these findings. Computer aided thermodynamic tables are used to get enthalpy and entropy values, from pressure and temperature data, in turn to calculate exergy and efficiency [5, 10].

![Figure 3: HGCS validation - T versus t.](image)

![Figure 4: Bed T after HGCS fully charged.](image)

![Figure 5: Bed T after HGCS discharged.](image)

![Figure 6: Cold recycle on liquefier yield.](image)
Table 3: HGCS influence on CES efficiency.

| Parametric variable                  | Numerical output, when cold recycling is done | Numerical output, when there is no cold recycling |
|--------------------------------------|-----------------------------------------------|--------------------------------------------------|
| Liquefier’s minimum work requirement | 1383kJ/kg                                    | 1612kJ/kg                                       |
| Current storing efficiency of CES system | 23%                                           | 19%                                             |

CONCLUSION
Application of recycling cold improves efficiency of liquefier. It also improves efficiency of overall CES system. HGCS bed is not 100% charged and 100% warmed up during assumed cold recycles. Due to intermittency of CES system, HGCS charging is short to 100% cool down. Heat transfer or exchange between warmer HGCS and liquefier’s recuperator causes a large drop in liquefaction yield. By properly arranging and operating HGCS unit is opened for further research to increase liquefaction yield. Concept of HGCS unit utilizing waste latent heat is also under further development. Modification of model incorporating equations for phase change materials (PCM) is another HGCS newly opened research area.

REFERENCES
1. Kanni Raj A (2019), “Analytical modeling of exergy and efficiency of cryogenic energy storage plant using various working fluids to identify best one for load shifting of nuclear power plant and renewable energy sources”, Journal of Modern Thermodynamics in Mechanical Systems, Volume 1, pp.36–41.
2. Kanni Raj A (2019), “Simulation of thermodynamic efficiency and plant equipment finance for cryogenic energy storage systems as applied to medium to large scale liquid-air electricity-storage”, Journal of Statistics and Mathematical Engineering, Volume 5, pp.18–27.
3. Markides CN (2014), “Role of pumped, and waste heat technologies in a high efficiency and sustainable energy future for UK”, Applied Thermal Engineering, Volume 53, pp.197–209.
4. Markides CN (2015), “Low-concentration solar-power systems based on organic Rankine thermodynamic cycles for distributed-scale applications: and overview, and further development”, Frontiers in Energy Research, Volume 3, pp.1–16.
5. Franco A, Casarosa C (2014), “Thermodynamics and heat transfer analysis of LNG energy recovery for power production”, Journal of Physics - Conference Series, Volume547, pp.1–10.
6. Wojcieszak P, Malecha Z (2018), “Cryogenic energy storage system coupled with packed-bed cold storage”, Web of Conferences, Volume44, pp.1–8.
7. Versteeg VK, Malalasekera W (2007), “An introduction to CFD: The FVM”, Pearson Education, New York, USA.
8. Kanni Raj A(2015), “CFD: Brief Notes”, CreateSpace Indie Publishing, North Charleston, USA.
9. Bergman TL (2011), “Introduction to Heat Transfer”, John-Wiley and Sons, New Jersey, USA.
10. Howe TA, Pollman AG, Gannon AJ (2018), “Operating range for a combined, building - scale LAES and expansion system: energy and exergy analysis”, Entropy, Volume 20, pp.1–17.