Applied Innovative Research
Vol. 2, June 2020, pp. 148-151

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
Vel Tech Rangarajan Dr Sagunthala R&D Institute of Science & Technology, Avadi 600 062, India

Received 4 September 2019; Accepted 20 March 2020

Cryogenic Energy Storage (CES) improves power grid with renewable intermittent power sources. In CES, off-peak excess electricity liquefies air or natural gas. Cryogen is stored in large dewar tanks for long periods of time. Whenever electricity need is in peak, work is recovered from cryogen by a power cycle using waste heat. Many researchers focus on liquid air energy storage (LAES). But, natural gas is promising working fluid for CES. This paper reviews a natural gas-based CES system, coupled with a high grade cold storage (HGCS) unit. Cold that is stored at a low temperature has been used to raise efficiency and hike yield of liquefier. This paper models HGCS unit and compares output with experimental data. Impact of cold recycling has been analyzed for liquefier yield and storage efficiency.

Keywords: Cold storage, FVM, CFD, MATLAB, Cryogenic energy storage, Natural gas, Energy

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. Solar and wind power rely strongly on the weather. Therefore, energy by renewable sources shows more match with demand. So, developing energy storage methods becomes very important to improve stability of electrical grid[1,2]. Cryogenic energy storage (CES) are potential alternatives to existing less efficient technologies, such as compressed air energy storage (CAES), Lithium-ion batteries, etc. CAES systems and Li-ion batteries can provide large storage capacities, but their usage is restricted to specific sites (based on 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 until discharge of storage system is required, and then, part of cryogen-bearing exergy is recovered during a power cycle. Most available research on CES systems is focusing on liquid air energy storage (LAES), as atmospheric air is widely available and so location of energy storage plant is not restricted. Nevertheless, NG is promising working fluid for CES system because of higher efficiency. NG is also widely available in industrially advanced countries, due to well-developed gas-supply pipe-line system[3,4]. This paper reviews CES using NG as working fluid.

Brief review of natural gas based cryogenic energy storage system

Modelled and analysed 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, gas from 6bar (0.6MPa) medium pressure pipeline is compressed until it reaches high pressure. Gas with 100 bar (10MPa) pressure is then directed to the recuperator (heat exchanger). There, gas is cooled by vapor return stream and using cold stored from

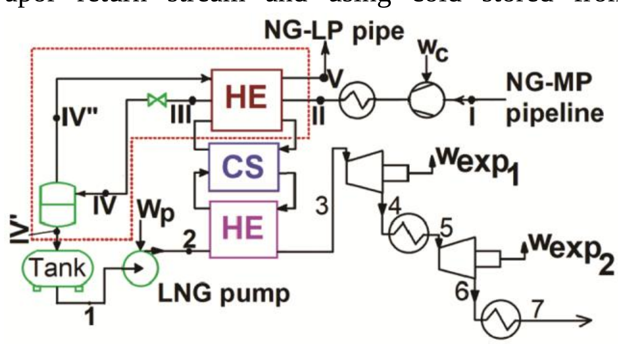

Fig. 1 – Analysed CES with HGCS bed

*Corresponding author: (E-mail: drakanniraj@veltech.edu.in)

regasification process. Cold, high pressure natural gas is throttled in expansion valve (follows Joule-Thomson effect), and part of stream is liquefied. Cryogen liquid is separated during separation phase and then directed to storage vessel (dewar tank). Vapour is then directed through recuperator to low pressure gas line (Fig. 1).

Compressor work is : $w_c = T_a(s_I - s_{II}) - (h_I - h_{II})$, where Ta – ambient temperature (K), s – specific entropy (J kg^{-1}K^{-1}), h – specific enthalpy (J kg^{-1}). Liquefaction yiled (y) can be derived from energy balance (boundary: red dash line): $\dot{m}h_{II} - y\dot{m}h_{IV'} - (1-y)\dot{m}h_V - \dot{m}q$, $y = \frac{h_V - h_{II} + q}{h_V - h_{IV'}}$, where $\dot{m}$ is the mass stream of natural gas at entry state (kg s^{-1}), q is the cooling power delivered per unit of NG mass flow rate (J kg^{-1}). Therefore, work required to liquefy 1 kg of natural gas can be calculated using formula: $w_l = {}^{w_c}/_{y} = \frac{h_V - h_{IV'}}{h_V - h_{II} + q}[T_a(s_I - s_{II}) - (h_I - h_{II})]$. Direct expansion components are: pump, heat exchanger, and expanders (with reheating between stages). LNG from tank is pumped until it reaches high pressure, and then it is evaporated and heated in heat exchanger. HGCS unit is cooled down for liquefaction cycle. Warm NG at high pressure is then directed to first expander, where mechanical power is produced. After first expansion, NG is then reheated and directed to second expander[1]. Specific net work of CES system 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 defined as a ratio of specific work recovered during LNG expansion, to work required for liquefaction of 1kg of a cryogen: $\eta = {}^{w_{net}}/_{w_l}$. Parameters of CES are listed in Table 1.

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. Conceptualisation 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 recuperator of liquefier[6].

Table 1 − Parameters for CES thermodynamics

Parameter	Value
medium pressure pipeline – gas pressure	6 bar
low pressure pipeline – gas pressure	1.1 bar
discharge pressure – compressor (p_{II}or Pc)	100 bar
exergy recovery system - net work (w_{net})	313 kJ kg^{-1}
exergy recovery system- power output (P)	350 kW
LNG - mass stream ($\dot{m}_{LNG}$)	1.12 kg s^{-1}
liquefaction - charging time	6h
Expansion – discharge time	2h

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].

$$\rho_f C_{p,f}\frac{\partial T}{\partial t} + \rho_f C_{p,f} u_x \frac{\partial T}{\partial x} = \frac{\partial}{\partial x}\left(k_f \frac{\partial T}{\partial x}\right) + h_V \frac{1-\varepsilon}{\varepsilon}(T_a - T) \quad \ldots(1)$$

$$k_f \frac{\partial^2 T}{\partial x^2} - \rho_f C_{p,f} u_x \frac{\partial T}{\partial x} - \rho_f C_{p,f}\frac{\partial T}{\partial t} + h_V \frac{1-\varepsilon}{\varepsilon}(T_a - T) = 0 \quad \ldots(2)$$

where ρ_f – density of fluid (kg m^{-3}), Cp,f – heat capacity of fluid (J kg^{-1}K^{-1}), u_x – velocity (m s^{-1}), k_f – thermal conductivity of fluid, ε - void fraction of bed (ratio of empty volume to total volume of bed), h_v - convective heat transfer coefficient (W m^{-2}K^{-1}), and Ta – temperature of ambient air (K).

$$\rho_b C_{p,b}\frac{\partial T_a}{\partial t} = \frac{\partial}{\partial x}\left(k_b \frac{\partial T_a}{\partial x}\right) + h_V(T - T_b) - U_v(T_b - T_a) \quad \ldots(3)$$

$$k_b \frac{\partial^2 T_a}{\partial x^2} - U_v(T_b - T_a)\rho_b C_{p,b}\frac{\partial T_a}{\partial t} + h_V(T - T_b) = 0 \quad \ldots(4)$$

where ρ_b – density of packed bed(kg m^{-3}), Cp,b – heat capacity of packed bed (J kg^{-1}K^{-1}), k_b – thermal

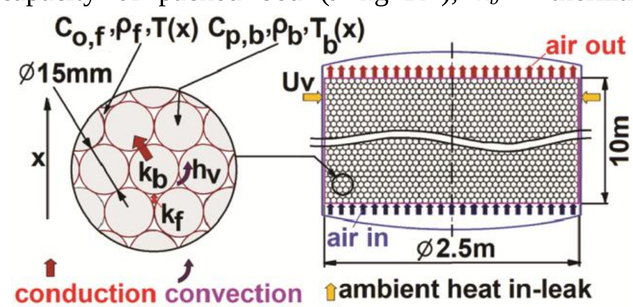

Fig. 2 – Conceptualisation – HGCS bed

Table 2 − Parameters for HGCS conceptualisation

Parameter	Value
Storage Dewar Tank Diameter (D)	2.5m
Storage Dewar Tank Length (L)	10m
Storage Spheres/Particle Diameter (d)	15mm
Cold Storage Material - Spheres	Quartzite Rock
Void Volume Fraction (ε)	0.38
Working Fluid – HGCS bed	Air (p=1.5bar, T=140-273K

conductivity of packed bed, *Uv* – volumetric heat transfer coefficient (W $m^{-3}K^{-1}$ – heat in-leaks from an ambient environment), and Tb – temperature of packed bed (K). Convective heat transfer coefficient (h_v) is calculated from Colburn factor for gas flowing through bed of spheres, ie., $h_v = \frac{2.06Re^{-0.575}GC_{p.f}\,6(1-\varepsilon)}{\varepsilon Pr^{2/3}}$, where G - mass flow rate per surface unit (kg $m^{-2}s^{-1}$), *Re* - Reynolds number, and *Pr* - Prandtl number.

Results and Discussion

Computational fluid dynamics simulation in MATLAB software

Aforesaid model is solved in MATLAB by well-prepared solution scheme involving PDEs. It solves Partial Differential Equations (PDEs) in Arbitrary Geometries, by Finite Volume Method (FVM). It applies Central Difference Scheme (CDS) of discretization, Implicit Method of solution finding and Thomas Tri-Diagonal Matrix Algorithm for simplifying calculation. Diffusion, Advection and Source Terms discretize by implicit method. Explicit method of discretization of source term is also considered, for comparison purpose. Implicit treatment of the diffusion terms permits unconditional stability during diffusion process, and provides tri-diagonal contribution to resulting algebraic linear equations[8]. Finally, discretization of PDEs results in sparse algebraic system solvable in MATLAB. Residual tolerance is set to 10^{-6} for all time steps. Computational domains are with lengths of L = 13 m and 10 m, and are divided into 1000 equi-spaced computational nodes, resulting in dx = 0.013 mm and 0.01 mm, with the time step set to dt = 0.0005 s. Above discretization is checked and confirmed by performing a mesh independence study. Thermodynamic properties of the heat transfer fluid (air) are 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 ºC), and then for its discharge (air inlet temperature is 273 K, i.e., 0 ºC). 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). HGCS temperature profiles at end of both charging and discharge cycles are shown in Figs. 4 & 5. Cold storage is always in neither fully charged nor fully discharged condition. Cooling power stored in HGCS is: $Q_{bed} = \int_0^L \rho_b C_{p,b} A[T_a - T_b(x)]\,dx$. Cooling power used in liquefaction cycle is assumed to be different from cooling power stored at beginning and also at end of discharge cycle. Influence of cold recycling on the efficiency of CES and liquefaction yield is verified by liquefaction both with and without cold recycle (Fig. 6). Minimal work of liquefaction and energy

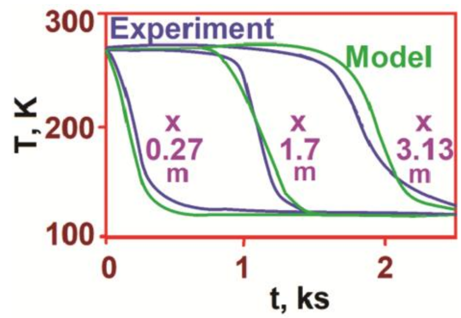

Fig. 3 – HGCS validation - T versus t for varying x

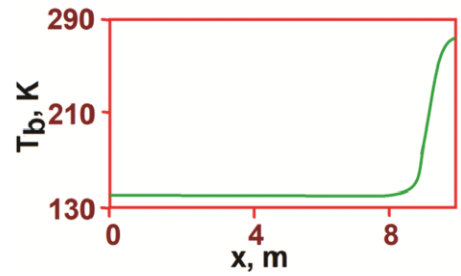

Fig. 4 – Bed T after HGCS fully charged

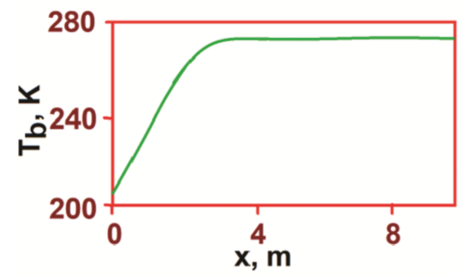

Fig. 5 – Bed T after HGCS discharged

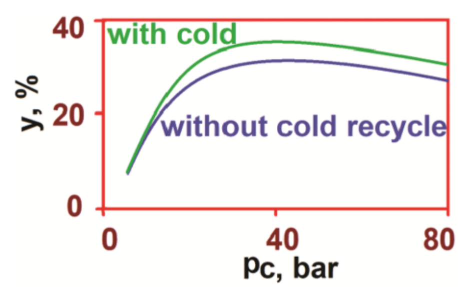

Fig. 6 – Cold recycle effect on liquefier yield

Table 3 − CES with and without cold recycle

Parameter	With cold recycle	Without cold recycle
Minimal work of liquefaction	1383 kJ kg^{-1}	1611.6 kJ kg^{-1}
Storage efficiency	22.6 %	19.4%

storage efficiency is also calculated for CES both with and without cold recycle. These findings are listed in Table 3. 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].

Conclusions

Application of cold recycle improves efficiency of liquefaction cycle. 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, charge cycle time of cold storage unit is too short to cool down packed bed 100%. Heat exchange between warm 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 Kanniraj A, *J Mod Thermo in Mech Sys,* 1 (2019) 36.
2 Kanniraj A, *J Statis & Math Engg*, 5 (3) (2019) 1.
3 Markides C N, *Appl Ther Engg*, 53 (2014) 197.
4 Markides C N, *Frontiers in Energy Research*, 3 (2014) 1.
5 Franco A & Casarosa C, *Journal of Physics : Conference Series*, 547 (2014) 1.
6 Wojcieszak P & Malecha Z, *Web of Conferences*, 44 (2018) 1.
7 Versteeg V K & Malalasekera W, An Introduction to Computational Fluid Dynamics: The finite volume Method, Pearson Education, New York, USA (2007).
8 Kanniraj A, CFD: Brief Notes, Create Space Indie Publishing, North Charleston, USA, (2015).
9 Bergman TL, Introduction to Heat Transfer. John-Wiley and Sons, New Jersey, USA, (2011).
10 Howe T A, Pollman A G & Gannon A J, MDPI : Entropy, 20 (2018) 1.