

ADIABATIC-LIQUEFACTION TEMPERATURE OF LNG MAIN CRYOGENIC HEAT EXCHANGER APPLYING FIRST LAW OF THERMODYNAMICS

WORDU, A . A & UZONO, R . I

Department of Chemical/Petrochemical Engineering
Rivers State University, Nkpolu, Port Harcourt,
Rivers State- NIGERIA
E-mail: wordu.animia@ust.edu.ng

ABSTRACT

This research centered on the development of thermodynamic model equations to simulate the adiabatic-liquefaction temperature of natural gas (methane 86%) into liquefied natural gas. The thrust model is derived from the first law of Thermodynamics maintaining adiabatic process operation; the model predicted perfectly the liquefaction temperature of natural gas as $-159\text{ }^{\circ}\text{C}$, and was validated with plant data to a maximum deviation of -3.91 . This study gave industrial applicability of first law of thermodynamics to real plant operations.

Keywords: Liquefaction process, thermodynamic model, adiabatic process, Simulation, main cryogenic heat exchanger (special reactor).

INTRODUCTION

Natural gas has grown to be an important source of energy in the global mix; the demand is steadily increasing and statistics show that from 2004-2005 there was 2.5% increase in natural gas demand [BP Statistical review of world energy, 2006]. The liquefaction of natural gas serves to reduce natural gas volume for economic transportation since LNG takes about 1/600th the volume of natural gas. Liquefaction of natural gas is energy intensive and is achieved by cooling natural gas below $-160\text{ }^{\circ}\text{C}$ using main cryogenic heat exchanger (MCHE special reactors). The basic principles for cooling and liquefying natural gas using refrigerants involves matching as closely as possible the cooling/heating curves of the process gas and the refrigerant resulting in a more efficient thermodynamic process the Joule-Thomson effect or adiabatic expansion, which is the act of reducing the temperature of the gas below its critical value. While, the adiabatic expansion method relies on the fact that an expanding gas doing work against an external pressure cools down, if the system is insulated against heat gain or loss.

The relation between pressure and temperature in an adiabatic expansion (Chadwick, 1974), is given as

$$\left(\frac{T_1}{T_2}\right)^r = \left(\frac{P_1}{P_2}\right)^{r-1} \quad (1)$$

where,

r = ratio of molar heat capacities of the gas at constant pressure and constant volume.

$$\left(\frac{T_1}{T_2}\right) = \left(\frac{V_1}{V_2}\right)^{(k-1)} \quad (2)$$

Equation (2) stands for liquefaction process (Yunus & Michael, 2006).

The natural gas liquefaction plant technology is currently dominated by the propane precooled mixed refrigerant cycle (C₃-MR) licensed by Air Products and Chemicals Inc. (APCI) (Finnet, 1999, Busman & Navelwort, 2009). (Wordu & Peterside, 2013) quantified

the boil off gas (BOG) losses in LNG plant in Bonny, to the tune of \$16,636.88 per hour @ \$9 per MMBtu of LNG.

Liquefaction of natural gas is a physical change process converting natural gas to LNG by cooling natural gas to about -160°C and thus reducing the volume the gas occupies to about 600 times its original volume (Jose *et al*, 2007). This conversion of natural gas to LNG is carried out in extremely low temperature thus this makes it cryogenic. Generally, substance which are -100°C (-48°F) or less are considered cryogenic and requires special technology for handling. Hence, the design of special process unit called cryogenic reactor is developed for the purpose of liquefaction of C_1 -gas.

LNG plant (NLNG) plant in Bonny was built 1999, which consists of parallel units called LNG trains.

Acid gas removal unit

The dehydration unit

Mercury removal unit

The liquefaction unit

Fractionating unit

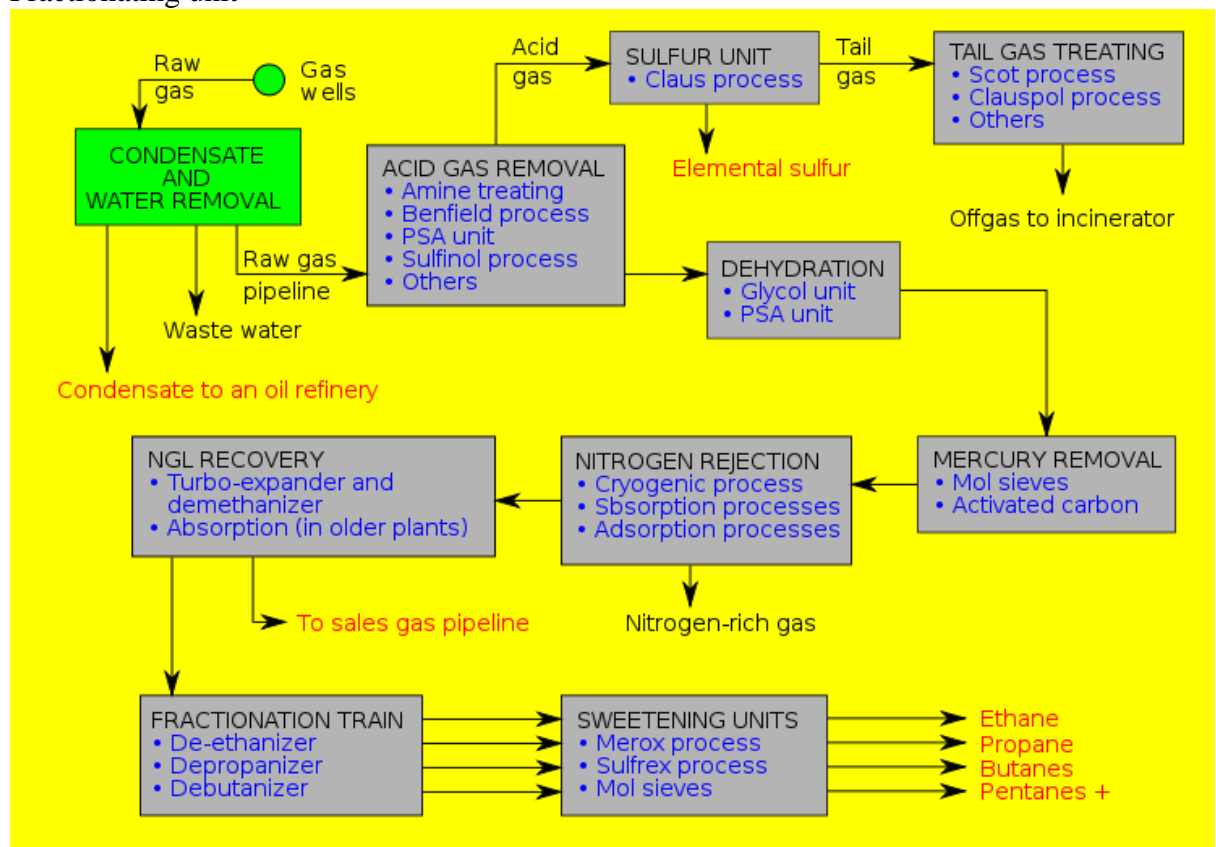


Figure 1 Process flow scheme of LNG plant

MATERIALS and METHOD

The principles of first law of thermodynamics (i.e conservation of energy), liquefaction work functions, and accessing reference plant data from LNG plant Bonny; Table 1 contains literature and reference data fundamental materials.

Table 1 Natural gas composition

Species	Low	High
Methane	86.3	95.2
Ethane	2.5	8.1
Propane	0.6	2.8
Butane	0.13	0.66
Pentanes	0	0.44
Hexanes plus	0	0.09
CO ₂	0	1.1
N ₂	0.31	2.47
H _e	0.01	0.06
Heating value MJ (m ³ Btu/ft ³)	38.15(1024)	40.72(1093)
specific gravity Ref: Air at 288k (60°F)	0.586	0.641

*LNG Bonny, Rivers State-Nigeria, 1999.***Table 2. Chemical composition of natural gas.**

CHEMICAL	CHEMICAL FORMULA	LOW	HIGH
Methane	CH ₄	87%	99%
Ethane	C ₂ H ₆	<1%	10%
Propane	C ₃ H ₁₀	>1%	5%
Butane	C ₄ H ₁₀	>1%	>1%
Nitrogen	N ₂	0.1%	1%
Other Hydrocarbons	Various	Trace	Trace

Table 3 Nigerian LNG process plant data and constant for liquefied Natural gas

Plant Data and Constant	Values
Minimum feed flow rate, M _{min}	8000mtonnes/day
Maximum feed flow rate, M _{max}	9500mtonnes/day
Inlet temperature of feed	25.3°C
Specific heat capacity at constant pressure	2.2266kj/Kgk
Minimum outlet flow rate	340mtonnes/day
Maximum outlet flow rate	405mtonnes/day
Density of natural gas	0.717kg/m ³
Thermal conductivity of ambient air	0.27W/m°K
Safety factor	1.05

Source: Nigerian LNG plant design data (1999).

Fundamentally, thermodynamics is the transformation of energy that accompanies any physical process change. A process of liquefaction or compression of methane gas gives rise to a change in state variable of a system i.e in pressure, temperature, volume or changes in physical state, gas to liquid which implies change in volume; of which the research model developed from the first law concept will predict the effects on the system variables.

The first law of thermodynamics is the law of conservation of energy of a system (Tarik, 1999); (Yunus & Michael, 2006).

Mathematically;

$$dw = pdv \quad (1)$$

And, change in internal energy of a system is given as

$$du = dq + PdV \quad (2)$$

Thermodynamics process in which there is no heat transfer in or out of the system is called adiabatic process ($Q = 0$) i.e. the system is perfectly insulated as expressed in equation (1).

The mathematical derivation process considers fundamental principles of compression work functions in main cryogenic heat exchanger vessel containing methane gas for liquefaction.

If the piston exerts a force \mathbf{P} through an incremental distance dx the work done to compress the gas is the force-distance expression, given as:

$$dW = FdX \quad (3)$$

$$\text{Since, } F = PA \quad (4)$$

$$dW = PAdX \quad (5)$$

$$dW = PdV \quad (6)$$

Equation (5) depicts the First law of thermodynamic under adiabatic process. Also, change in internal energy of a system is mathematically given as,

$$du = CvdT = dw \quad (7)$$

Combine equations (6) and (7) yields,

$$PdV = C_v dT \quad (8)$$

For 1 mole of the gas,

$$PV = nRT$$

$$P = \frac{nRT}{V} \quad (9)$$

Substituting equation (9) into equation (8) gives

$$c_v dT = nRT \frac{dV}{V}$$

Rearranging

$$C_v \frac{dT}{T} = nR \frac{dV}{V} \quad (10)$$

Integrating equation (10) using the boundary conditions from final to initial state of the system, yields

$$\int_{T_1}^{T_2} c_v \frac{dT}{T} = \int_{V_1}^{V_2} nR \frac{dV}{V} \quad (11)$$

Where,

C_V , Specific heat capacity at constant volume.

R , Gas constant

n is a constant,

Equation (11) becomes

$$C_V \int_{T_1}^{T_2} \frac{dT}{T} = nR \int_{V_1}^{V_2} \frac{dV}{V} \quad (12)$$

Integrating equation (12) yields (13)

$$C_V \ln \frac{T_2}{T_1} = nR \ln \frac{V_2}{V_1} \quad (13)$$

For 1mole of a gas, $C_p - C_v = nR$

$$C_V \ln \frac{T_2}{T_1} = (C_P - C_V) \ln \frac{V_2}{V_1} \quad (14)$$

$$\ln \frac{T_2}{T_1} = \left(\frac{C_P - C_V}{C_V} \right) \ln \frac{V_2}{V_1} \quad (15)$$

From thermodynamics, the ratio of specific heats at Constant pressure and volume is given as

$$\frac{C_P}{C_V} = r$$

Therefore, equation (15) becomes

$$\ln \frac{T_2}{T_1} = (r - 1) \ln \frac{V_2}{V_1} \quad \frac{T_2}{T_1} = \left(\frac{V_2}{V_1} \right)^{(r-1)} \quad (16)$$

$$T_2 = T_1 \left(\frac{V_2}{V_1} \right)^{(r-1)} \quad \text{But change in temperature;} \quad \Delta T = T_2 - T_1 \quad (17)$$

Insert equation (17) into (18), yields

$$\Delta T = T_2 - T_1 = T_1 \left(\frac{V_2}{V_1} \right)^{(r-1)} - T_1 \quad (19)$$

$$T_2 = T_1 \left[\left(\frac{V_2}{V_1} \right)^{(\gamma-1)} - 1 \right] \tag{20}$$

Equation (20) model with index (r-1) ratio of specific heat capacities is applied to simulating the liquefaction temperature of liquefied natural gas.

RESULTS AND DISCUSSION

Table 4.1 shows the model predictions of the LNG liquefaction temperature, percentage deviation of model and actual plant data for the LNG production (m³/hr.). The model prediction and its deviation in terms of percentage were obtained from equations (3.6) and (3.1.9 respectively. The Maximum % deviation of the model predictions from the actual liquefaction temperature is -0.52%. The deviation in mode prediction from the plant liquefaction temperature is due to the assumptions made when calculating the liquefaction temperature i.e. assumption that the feed gas composition and LNG composition are constant for all data points. But in reality there is a difference between the LNG composition and feed gas composition and the LNG production rate and feed gas supply rate due to NGL extraction in the scrub column to remove heavy stuff from the feed gas stream. During NGL extraction a significant amount of methane lost in the NGL stream. Although, the main cryogenic heat exchanger and propane kettles and their associated piping are insulated, there are usually some heat leaks into the process from the surroundings (Wordu & Boma, 2013).

$$\% \text{ deviation} = \frac{\text{model prediction} - \text{actual liquefaction temperature}}{\text{actual plant liquefaction temperature}} \times \frac{100}{1}$$

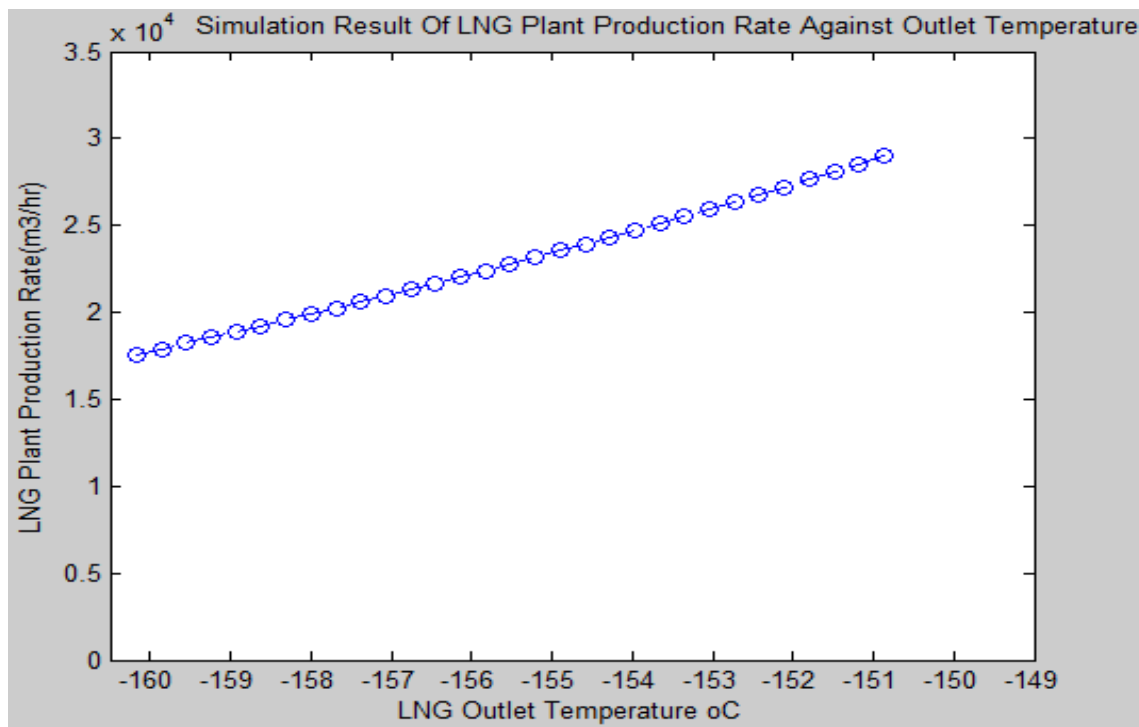


Figure 1 Plot of LNG production against LNG outlet temperature

Figure 1 shows the plot of LNG production against the LNG outlet temperature. The LNG production rate decreases linearly with decreasing outlet temperature. For an average of

0.32°C decrease in LNG outlet temperature results in a 3900m³/hr. decrease in LNG production. A decrease in LNG outlet temperature decreases the LNG production rate because the refrigeration duty required to achieve a much lower temperature is increased. This suggests that cooling the LNG beyond its design temperature of 461°C is not advantageous. It is important to note that higher LNG temperatures also results in LNG losses due to increased boil off gas production rates in the LNG storage tanks and during loading operations. And losses of BOG was estimated 3545&20 kg/hr. Wordu & Boma (2013).

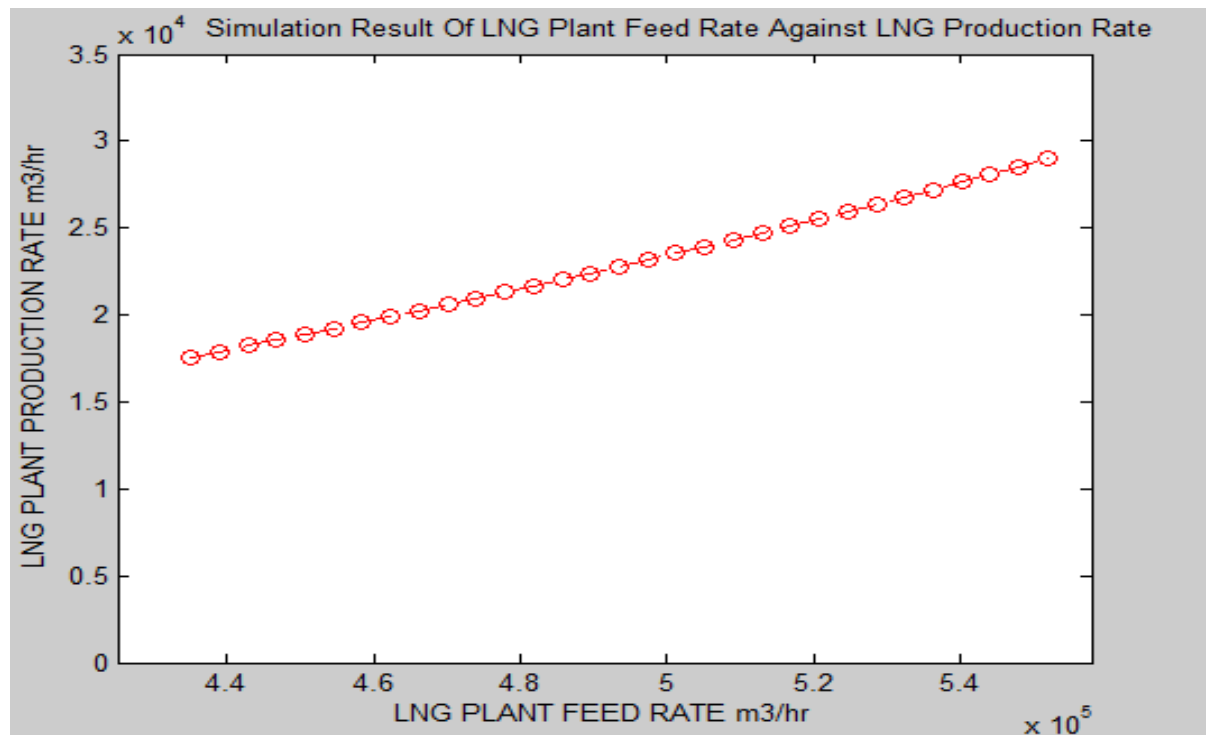


Figure 2 Plot of LNG production against LNG plant feed rate

Figure 2 shows the plot of LNG production rate and the methane feed rate of the LNG plant. The LNG production rate varies inversely with feed gas rate of the plant, i.e. the amount of feed gas charged into the plant reduces at the outlet stream. This reduction is due to compression of the gas as compression implies reduction in volume as earlier stated in this work. Various factors affect the production rate e.g. the composition of the gas can affect the outlet stream reason being a feed gas with high sulphur, mercury and water content needs to be removed before compression can take place and this reduces the volume of the gas that is charged into the main cryogenic heat exchanger where the actual liquefaction takes place.

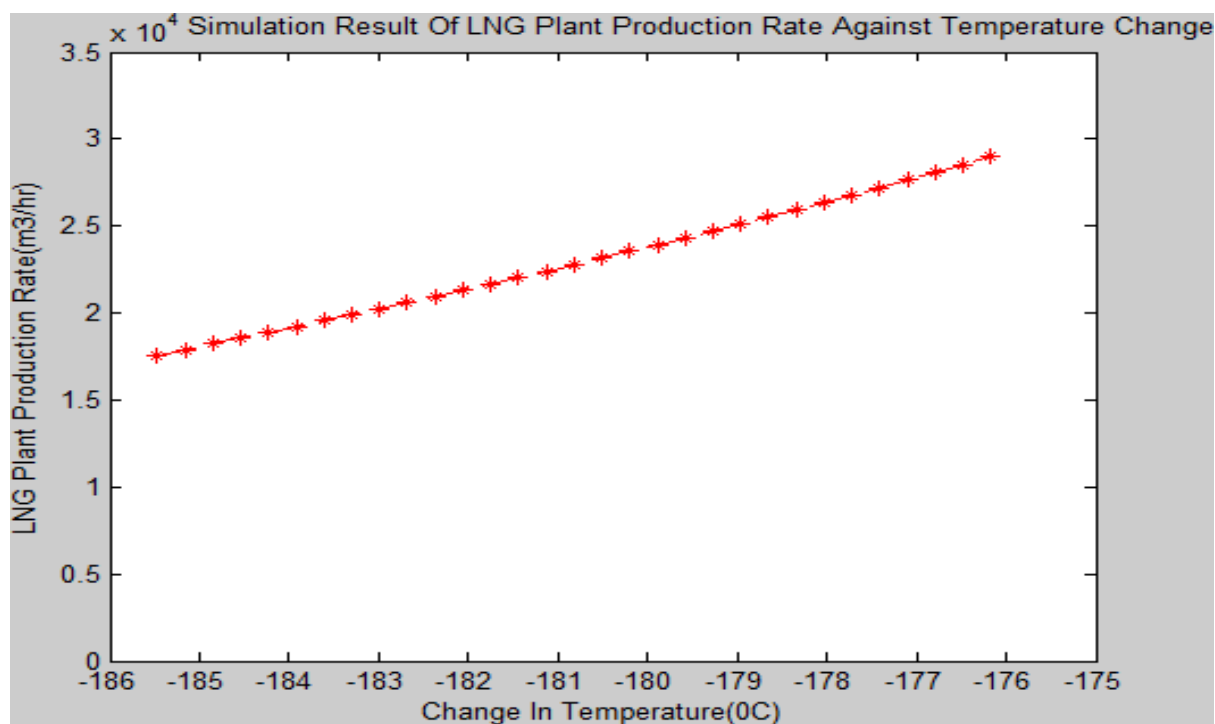


Figure 3 Plot of LNG productions against change in Temperature

Figure 3 shows plot of LNG production rate against change in temperature. As ΔT increases there is a corresponding increment in LNG production rate. This also results in increase of energy and thus reduces the coefficient of performance. In conclusion, as $\Delta T \propto$ LNG losses due to boil of gas increases.

CONCLUSION

A theoretical functional thermodynamics equation capable of simulating Nigerian LNG operation for the LNG compression temperature, production rate of LNG plant has been developed. The model prediction was validated with plant data from Nigerian liquefied natural gas plant bonny, Nigeria. The final compression temperature was estimated at -158.4°C with a deviation of 0.52. This deviation was due to the assumption that the feed gas compression is constant. A decrease in LNG outlet temperature decreases the LNG production rate. This suggests that cooling the LNG beyond its design temperature of -161°C is not advantageous as these results in LNG losses due to increased boil off gas production rates in the LNG storage tanks and during loading operations. It was also established that there was reduction in the volume of the LNG production when compared to feed NG charged into the plant and this is the bane of the liquefaction process.

NOMENCLATURE

LNG = liquefied natural gas.

MCHE = Main cryogenic heat exchanger

T_2 = Final temperature of plant operation

T_1 = Initial temperature of plant operation

C_p = Specific heat capacity at constant pressure, kJ/kgk

C_v = Specific heat capacity at constant volume, kJ/kgK

n = Number of moles

R = Universal gas constant, kJ/kgK

V_2 = Final volume of gas after compression, m^3

V_1 = Initial volume of gas, m^3

dw = Work done over an incremental distance

du = Change in internal energy

REFERENCES

- American Gas Association, New York, 1963; and A.G.A. Gas Measurement Committee Report 3 46 (1969).
- BP Statistical Review of World Energy June 2006, Bp Plc (2006) [Access 11th October, 2011] www.bpstatic.com/gas/review
- Chadwick, T. F. (1974). Physical chemistry part 3: George Allen and Unwin, London 40-43.
- Carvalho C, et al (2006); small-scale LNG plant technology. *Oil and gas Journal* 2, 1.
- Don W. Green, Robert H. Perry (2007); Perry's chemical engineering hand book 8th Ed: McGraw-Hill USA, 2-178
- INL, (2006); Natural gas technologies, small-scale methane liquefaction system, [Access 15th June 2010] www.hamworthy.com/production/products.asp?strareno=27
- Nigeria LNG Operating manual UNIT-1400 Liquefaction, (2000)
- Ravavarapu, V. Oakley, J., H. & White, C., C. (1996). Thermodynamic Analysis of a Baseload LNG Plant; Proceeding of the Chemeca 96: Excellence in Chemical Engineering: 24th Australian and New Zealand Chemical Engineering Conference and Exhibition: 143-148.
- Tarik A, (1999); Engineering Thermodynamics 4th Ed. 30: Tarik Alshemmeri and Ventus Publishing APS.
- Wordu, A. A, & Peterside, B. (2013); Estimation of BOG generation from refrigerated vessel of LNG plant. *International Journal of engineering and technology*, 3(1), 44-49.
- Wordu A. A (2013); Functional thermodynamic model equations for Simulation of Compression-liquefaction Process of Natural Gas Plant. *Transnational Journal of Science and Technology*, 3(3), 51-70.
- Younglove, B.A, & Ely J. (2006); Thermophysical Properties of Fluid. 11. Methane, Ethane, Propane, Isobutane, and Normal Butane Lecture note University of Saopalo Brazil. Dept.of Chemical Engineering.
- Yunnus, A. C & Micheal, A.B (2006); Thermodynamics; An Engineering Approach, 5th Edition, McGraw-Hill, 358- 361.