Chapter 2

Thermodynamic analysis of dry autothermal reforming of Glycerol
Abstract

Dry autothermal reforming of glycerol uses a combination of dry (CO$_2$) reforming and partial oxidation reactions to produce syngas rich product stream. The objective of the chapter is to evaluate the thermodynamic feasibility of dry autothermal reforming of glycerol by identifying the thermodynamic domain of the DATR process operation, study the variation of product distribution pattern and describe the optimum conditions to maximize yield of the desired product and minimize the undesired product formation. Glycerol is used as fuel in this study. The thermodynamic equilibrium data for dry autothermal reforming of glycerol was generated for temperature range 600–1000 K, 1 bar pressure, OCGR [feed O$_2$/C (C of glycerol only) ratio] 0.1 to 0.5 and CGR [feed CO$_2$/glycerol ratio] 1 to 5 and analyzed. Higher OCGR and higher CGR yielded a syngas ratio, with lower carbon and methane formation, while lower CGR and lower OCGR yielded good hydrogen and total hydrogen, with low water and CO$_2$ in the product gas. The best thermoneutral condition for DATR of glycerol operation was seen at a temperature of 926.31 K at 1 bar pressure, OCGR=0.3 and CGR=1 that gave 2.67 mol of hydrogen, 4.8 mol of total hydrogen with negligible methane and carbon formation.
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2.1 Glycerol as fuel

Glycerol is a byproduct of biodiesel production process. Biofuels like ethanol and biodiesel are gaining significance due to the consistent decline in fossil fuels like oil and natural gas reserves worldwide. Glycerol will be extensively available as byproduct after the commercialization of biodiesel production processes. This has prompted researchers to find ways for utilization of glycerol to valuable products. Researchers working in the field of hydrogen and syngas production have now started focusing on the use of glycerol for hydrogen and syngas production by various techniques.

Some of the important glycerol utilization techniques reported in literature are as follows:

2.1.1 Catalytic & Experimental studies

Dauenhauer et al. (2006) have studied the autothermal reforming of glycerol and its solutions in water over platinum and rhodium based catalysts supported on alumina foams at a contact time of ~10 ms. Simonetti et al. (2007) have studied the rate of glycerol conversion to syngas mixtures under kinetically controlled reaction conditions over carbon-supported platinum and platinum-rhenium catalysts. Zhang et al. (2007) have studied the hydrogen production from steam reforming reactions of ethanol and glycerol using ceria-supported Ir, Co and Ni catalysts. Valliyappan et al. (2008a) have studied the pyrolysis of glycerol for H\textsubscript{2} and syngas production in various flow rates of N\textsubscript{2} (30-70 ml/min), temperatures (650-800 °C) and types and sizes of packing material in a tubular reactor at atmospheric pressure. Slinn et al. (2008) have reported that steam reforming of impure glycerol was a viable alternative for use of glycerol. Lehnert et al. (2008) have studied the catalytic conversion of glycerol to hydrogen by aqueous-phase reforming (APR) on several platinum based catalysts. Byrd et al. (2008) have studied the hydrogen production by supercritical water reforming of glycerol over a Ru/Al\textsubscript{2}O\textsubscript{3} catalyst with low
methane and carbon monoxide formation. Wen et al. (2008) have studied the activities and stabilities of Pt, Ni, Co, and Cu catalysts and the effect of support on activity and stability for H\textsubscript{2} production by aqueous-phase reforming of glycerol using a fixed-bed flow reactor. Luo et al. (2008) have studied the effect of metal loadings and operating conditions for hydrogen production from glycerol solution by aqueous phase reforming process over Pt supported catalysts. Cui et al. (2009) have studied the steam reforming of glycerol (1, 2, 3 - propantriol) with non-substituted and partially Ce substituted La\textsubscript{(1-x)}Ce\textsubscript{x}NiO\textsubscript{3} mixed oxides and compared the activities with Pt metal catalysts and thermodynamic equilibrium. Fernandez et al. (2009) have investigated the pyrolysis of glycerol over carbonaceous catalysts to produce synthesis gas in a fixed-bed reactor. Iriondo et al. (2009) have studied the performance of monometallic (Ni and Pt) and bimetallic (Pt-Ni) catalysts and also the effect of lanthana-modified alumina support in the glycerol steam reforming process. Luciene et al. (2009) have studied the catalytic activity of Ni/CeO\textsubscript{2}-Al\textsubscript{2}O\textsubscript{3} catalysts modified with noble metals (Pt, Ir, Pd and Ru) for steam reforming of glycerol. Kunkes et al. (2009) have reported a gas phase catalytic process for glycerol reforming based on the use of two catalyst beds that can be tuned to yield hydrogen and CO\textsubscript{2} or synthesis gas at 573 K and 1 atm pressure. Buffoni et al. (2009) have studied the effect of nickel catalysts supported on commercial alpha-Al\textsubscript{2}O\textsubscript{3} and alpha-Al\textsubscript{2}O\textsubscript{3} modified by addition of ZrO\textsubscript{2} and CeO\textsubscript{2} to obtain hydrogen by steam reforming of glycerol. Xu et al. (2009) have studied the catalytic gasification of glycerol with supercritical water in a continuous tubular-flow reactor operated at 380-500 °C and 25 MPa pressure with or without Na\textsubscript{2}CO\textsubscript{3} catalyst. Dou et al. (2009) have experimentally studied the catalytic steam reforming of glycerol in a continuous flow fixed-bed reactor at atmospheric pressure within a temperature range of 400-700 °C using a commercial Ni-based catalyst and a dolomite sorbent for in-situ CO\textsubscript{2} removal. Swami et al. (2006) have successfully studied steam and autothermal reforming of glucose, glycerol and industrial waste water using Ni/Pd/Cu catalyst at atm pressure within 500–800 °C temperature range. Soares et al. (2006) have reported the catalytic conversion of glycerol to syngas at lower
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temperatures. Valliyappan et al. (2008b) have studied catalytic steam gasification in presence of commercial Ni/Al₂O₃ catalyst and reported 15 mol % increased hydrogen yield in steam gasification process than pyrolysis process. Huber et al. (2003) have studied aqueous-phase reforming of glycerol over a tin-promoted Raney-nickel catalyst for hydrogen production. Douette et al. (2007) have experimentally investigated glycerol reforming and formulated a model defining the effect of oxygen to carbon ratio, steam to carbon ratio, and temperature on the process to improve hydrogen yield. Adhikari et al. have experimentally studied glycerin steam reforming using nickel catalysts with MgO, CeO₂ and TiO₂ supports (2008) and also by using Ni/Al₂O₃ and Rh/CeO₂/Al₂O₃ based catalysts (2007a). Hirai et al. (2005) have studied hydrogen production by steam reforming of glycerin on ruthenium catalyst. Iriondo et al. (2008) have used different catalyst functionalities to carry out aqueous-phase and vapor phase steam reforming of glycerol and found that the addition of Ce, La and Zr to Ni/Al₂O₃ improved the initial glycerol conversions in aqueous phase reforming of glycerol while the same catalysts improved hydrogen selectivity in steam reforming of glycerol. Kunkes et al. (2008) have experimentally studied aqueous solutions of glycerol over carbon-supported Pt and Pt-Re catalysts at 483 - 523 K and found that the turnover frequencies for production of H₂, CO, CO₂, and light alkanes (primarily methane) increase with addition of Re to Pt/C as it modifies the interaction of CO with surface sites.

2.1.2 Thermodynamic studies

Adhikari et al. (2007b) have performed thermodynamic equilibrium analysis of glycerol steam reforming process and described that temperature >900 K, atmospheric pressure and a molar ratio of water/glycerin at 9:1 are the best operating conditions for hydrogen production with minimizing methane and carbon formation. X. Wang et al. (2009) have performed a thermodynamic analysis of glycerol dry reforming by the Gibbs free energy minimization method as a function of CO₂ to glycerol ratio, temperature, and pressure. Luo
et al. (2007) have studied the thermodynamic analysis of autothermal reforming (a combination of water aqueous reforming and oxidation), aqueous hydrogen peroxide reforming and water aqueous reforming process and found that water aqueous reforming of glycerol gave the highest hydrogen yield in the absence of methanation. H. Wang et al. (2009) have performed thermodynamic analysis of glycerol autothermal reforming using Gibbs free energy minimization over a temperature range (700–1000 K), steam to glycerol ratio (1–12) and oxygen to glycerol ratio (0.0–3.0) and reported product yields at thermoneutral conditions. X. Wang et al. (2008) have studied the thermodynamic analysis of glycerin steam reforming as a function of water/glycerin molar ratios (1:1–12:1) within temperature range (550–1200 K) and pressure range (1–50 atm) and reported optimum conditions for hydrogen production, syngas production with minimum carbon formation. Chen et al. (2009) have performed thermodynamic analysis of adsorption-enhanced steam reforming of glycerol and shown that the maximum number of moles of hydrogen produced per mole of glycerol can be increased due to the CO$_2$ adsorption.

### 2.1.3 Other studies

Marshall and Haverkamp (2008) have reported a 66 % reduction in electrical energy consumption using electrochemical reforming of glycerol solution in a proton exchange membrane (PEM) electrolysis cell compared to water electrolysis in the same cell. Xuan et al. (2009) have discussed the research challenges and future development of biomass fuel processor along with a review of the biomass-derived fuel processing technologies from various perspectives including the feedstock, reforming mechanisms, catalysts and processor configurations. Selembo et al. (2009) have studied the use of glycerol for hydrogen gas production was examined via electrohydrogenesis using microbial electrolysis cells (MECs) which gave hydrogen yield of 3.9 mol-H$_2$/mol using glycerol and was observed to be higher than that possible by fermentation. Zhu et al. (2009) have reported plasma reforming of glycerol at
low temperature & atm pressure without external heating. Ito et al. (2005) have studied the hydrogen and ethanol production using Enterobacter aerogenes HU-101 from glycerol-containing wastes discharged from biodiesel manufacturing process. Some review articles (S. Adhikari, 2009; Vaidya and Rodrigues, 2009) for hydrogen production using glycerol are also published.

2.2 Thermodynamic analysis

A thermodynamic analysis of glycerol steam reforming (Adhikari, 2007; X. Wang, 2008), glycerol autothermal reforming (H. Wang, 2009) and glycerol dry reforming (X. Wang, 2009) have already been reported. On the similar lines, a thermodynamic study of pure glycerol dry autothermal reforming process was undertaken to evaluate the feasibility of the process. The role of CO₂ in DR has already been discussed in detail by X. Wang et al. (2009) and the same is applicable to this system, oxygen reacts with glycerol to produce energy that is in-situ transferred to dry reforming process. Dry autothermal reforming (DATR) is a better process than dry reforming (DR) for many reasons. DR requires external energy and more carbon is formed in the reactor while DATR does not require external energy and minimum carbon is formed at optimized conditions. The species such as glycerol (g) [1, 2, 3 Propanetriol], glycerol (l), O₂ (g), N₂ (g), CO₂ (g), H₂ (g), CO (g), H₂O (g), CH₄ (g), H₂O (l) and C(s) are considered in this study. The input species are glycerol, oxygen, nitrogen and CO₂ (all in gaseous phase) at particular temperature-pressure conditions reacting to give the products. Any other product – byproduct formation is not considered in this study.

The dry autothermal reforming of glycerol process operation is based on four main thermodynamic parameters like temperature, pressure, OCGR [feed O₂/C (C of glycerol only) ratio] and CGR [feed CO₂ to glycerol ratio]. The process engineer has to choose the best reactor operating conditions. A detailed study of product distribution trends of glycerol DATR process with
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respect to change in temperature, OCGR and CGR is essential. This chapter intends to study these things to locate the thermodynamic domain for reactor operation. The material and energy balance calculations were performed using the inbuilt databases in HSC Chemistry software package. The reaction products are assumed to be in thermodynamic equilibrium at the exit of the reactor. 1 mole of glycerol (gaseous phase) was taken in each case, so the product moles obtained were for 1 mole glycerol input. The operating temperature range for this exercise was 600 to 1000 K, with CGR 1, 3 & 5 and OCGR zero, 0.1, 0.3 and 0.5. Complete (100 %) conversion of glycerol and positive product yields with accurate material balances was observed in all the considered cases, indicating the feasibility of the DATR process. The case of zero OCGR represents the dry reforming of glycerol and these results have already been reported (X. Wang, 2009). The accuracy of the data presented is within reasonable error limit.

2.3 Results and Discussion:

2.3.1. Hydrogen yield

Hydrogen is always a desired product of reforming processes for its end use in fuel cells or syngas manufacture. Steam reforming of natural gas is a popular process for hydrogen production. With availability of cheaper fuel options like glycerol, the hydrogen production processes might shift to use the available feedstock. Table 2.1 shows the hydrogen yield in DATR of glycerol process at various pressures. It was found that the hydrogen yield decreased at higher pressures, making low pressure (1 bar) operation a favorable process parameter. The further thermodynamic studies for DATR of glycerol were done at 1 bar process pressure only. Figure 2.1 shows the effect of oxygen addition on hydrogen production by glycerol dry autothermal reforming at various conditions of process temperature, CGR and OCGR at 1 bar pressure.
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<table>
<thead>
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<tr>
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<td>950</td>
<td>2.26</td>
<td>2.11</td>
<td>1.87</td>
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</tbody>
</table>

Table 2.1: Hydrogen yield in DATR of Glycerol at different pressures

It is observed that hydrogen production steadily increases with temperature till 850 K and later starts saturating and also declines in later stages. The increase in CGR decreases the hydrogen output. However, hydrogen production trend is same for dry reforming and DATR. The moles of hydrogen produced at 950 K for increase in CGR from 1 to 5, decrease from 2.8 to 2.56 (DR) and decrease from 2.88 to 2.26 (for CGR = 1), 2.69 to 1.92 (for CGR = 3) and 2.43 to 1.67 (for CGR = 5) for OGOR increase from 0.1 to 0.5 in DATR. Taking the extreme conditions, the maximum hydrogen yield at 950 K is 2.88 moles for OGOR = 0.1 and CGR = 1 and the minimum hydrogen yield of 1.67 moles is noted for the other extreme condition of OGOR = 0.5 and CGR = 5 in
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DATR process. Hence it can be observed that higher OCGR and higher CGR actually decrease the hydrogen yield in this process.

![Figure 2.1: Hydrogen yield in DR and DATR of Glycerol](image)

2.3.2 CO yield

Carbon monoxide is an undesired product and poison for applications that require pure hydrogen. However it is very much desired for syngas feeding applications. CO can be converted to hydrogen using a series of WGS reactors, while the very low CO levels can be preferentially oxidized to CO$_2$ or converted to methane using a methanation catalyst. Figure 2.2 shows the moles of CO produced in the DR and DATR of glycerol process as a function of temperature, CGR and OCGR at 1 bar pressure. It is observed that the CO yield increases with increase in process temperature in all cases. With increase in OCGR at constant CGR, the CO yield decreases. Similarly, at constant OCGR, the CO yield increases with increase in CGR. The moles of CO produced at 950 K for increase in CGR from 1 to 5, increase from 2.09 to
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4.18 (DR), decrease from 2.46 to 1.7 (for CGR = 1), 3.39 to 2.07 (for CGR = 3) and 3.83 to 2.32 (for CGR = 5) for OCGR increase from 0.1 to 0.5 in DATR. The maximum CO yield at 950 K was found to be ~3.83 moles for OCGR = 0.1 and CGR = 5 and the minimum CO yield of 1.7 was observed at OCGR = 0.5 and CGR = 1 for DATR process.

![Figure 2.2: CO yield in DR and DATR of Glycerol](image)

2.3.3 Variation of Syngas ratio (H₂/CO) of product gas

Syngas is the basic building block for petrochemicals. Dry reforming gives more CO than steam reforming processes. Hence syngas can be preferably manufactured by glycerol DATR process. Moreover the syngas ratio in the range of 1–3 (desirable for use in petrochemical manufacture) is easily obtained in this process. Figure 2.3 shows the variation of syngas ratio as a function of temperature, CGR and OCGR for DR-DATR of glycerol. The syngas ratio of the product gas shows a regular decline with increase in DR-DATR process temperature. Increase in OCGR at constant CGR and increase
in CGR at constant OCGR also show a decrease in product syngas ratio in the same trend. The product syngas ratio obtained at 950 K for increase in CGR from 1 to 5, decreases from 1.34 to 0.61 (DR) and increases from 1.17 to 1.33 (CGR = 1), 0.79 to 0.93 (CGR = 3) and 0.63 to 0.72 (CGR = 5) for OCGR increase from 0.1 to 0.5 in DATR. The maximum syngas ratio at 950 K is 1.33 obtained at OCGR = 0.5 and CGR = 1 while the minimum syngas ratio of 0.63 is seen at OCGR = 0.1 and CGR = 5 for DATR process. The syngas ratio around 1 (0.63–1.33) is obtained at 950 K for CGR variation from 1–5, making this process favorable for syngas manufacture.

2.3.4 Total hydrogen (H₂+CO) potential

Total hydrogen potential of a process is the sum of moles of hydrogen and carbon monoxide obtainable in the process. This terminology is useful in identifying and ranking fuels for hydrogen production processes. It is assumed
that almost all the CO can be converted to hydrogen by coupling a series of WGS reactors to the DATR reactor. Figure 2.4 show the variation of total hydrogen moles obtained at different temperatures, OCGR and CGR.

![Figure 2.4: Moles of total hydrogen produced in DR and DATR of Glycerol](image)

It is observed that the total hydrogen obtainable increases with increase in OCGR till 850-950 K and later saturates. Increase in CGR at constant OCGR, increases the total hydrogen production although that increase is not significant. The moles of total hydrogen produced at 950 K for increase in CGR from 1 to 5, increase from 4.89 to 6.74 (DR) and decrease from 5.34 to 3.96 (for CGR = 1), 6.08 to 3.99 (for CGR = 3) and 6.26 to 3.99 (for CGR = 5) for OCGR increase from 0.1 to 0.5 in DATR. The maximum total hydrogen obtainable at 950 K is 6.26 at CGR = 5 and OCGR = 0.1, while the minimum is 3.96 at CGR = 1 and OCGR = 0.5.
2.3.5 Methane formation

Methane formation is undesirable due to the loss of hydrogen and carbon moles. Figure 2.5 shows the moles of methane produced at different temperatures, OCGR and CGR. Methane formation seems negligible and decreases with temperature in all the considered cases. The methane formation is lowest at high OCGR and high CGR. The moles of CH\textsubscript{4} produced at 950 K for increase in CGR from 1 to 5, decrease from 0.20 to 0.06 (DR) and decrease from 0.17 to 0.01 (for CGR = 1), 0.08 to 0.00 (for CGR = 3) and 0.04 to 0.00 (for CGR = 5) for OCGR increase from 0.1 to 0.5 in DATR. The maximum CH\textsubscript{4} moles formed at 950 K in DATR is 0.17 at CGR = 1 and OCGR = 0.1, while the minimum is 0.00 at CGR = 3 & 5 and OCGR = 0.5.

![Figure 2.5: Moles of methane produced in DR and DATR of Glycerol](image)

2.3.6 CO\textsubscript{2} obtained in product gas

One of the important aims of dry autothermal reforming is utilization of CO\textsubscript{2} to produce value added products like syngas and hydrogen without the use of
external energy. But the CO₂ production results obtained from thermodynamic study indicate that the regions for positive CO₂ utilization are very narrow. However, even if CO₂ is evolved from the process, the net CO₂ evolved (i.e. the product CO₂ – feed CO₂ moles) from the DATR process is very less. This makes the process more attractive. Figure 2.6 shows the CO₂ obtained in DR-DATR process at different temperatures, OCGR and CGR.

![Figure 2.6: Moles of CO₂ obtained in DR and DATR of Glycerol](image)

The CO₂ obtained in the product gas slightly increases till ~750 K and later decreases at higher temperatures. The CO₂ production increases with increase in CGR and also with increase in OCGR. The moles of CO₂ produced at 950 K for increase in CGR from 1 to 5, increase from 1.05 to 3.75 (DR) and increase from 1.18 to 2.29 (for CGR = 1), 2.53 to 3.93 (for CGR = 3) and 4.14 to 5.68 (for CGR = 5) for OCGR increase from 0.1 to 0.5 in DATR. The maximum CO₂ moles emitted at 950 K in DATR is 5.68 at CGR = 5 and OCGR = 0.5, while the minimum is 1.18 at CGR = 1 and OCGR = 0.1.
2.3.7 Water formation

Water formation is sometimes desired to increase humidity of the product gas as the humidified gas has better thermal transport properties. However, water formation takes place at the expense of hydrogen in the system. Figure 2.7 shows the moles of water formed at different temperature, CGR and OCGR in the DR-DATR of glycerol process.

The water formation decreases with increase in temperature till 850-950 K and then increases in majority of the cases. Higher CGR and higher OCGR seems to promote more water formation in the process. The moles of water produced at 950 K for increase in CGR from 1 to 5, increase from 0.8 to 1.31 (DR) and increase from 0.78 to 1.72 (for CGR = 1), 1.15 to 2.08 (for CGR = 3) and 1.50 to 2.33 (for CGR = 5) for OCGR increase from 0.1 to 0.5 in DATR. The maximum H$_2$O moles formed at 950 K in DATR is 2.33 at CGR = 5 and OCGR = 0.5, while the minimum is 0.78 at CGR = 1 and OCGR = 0.1.
2.3.8 Carbon formation

Carbon is also an undesired component of reforming processes as it deactivates the catalyst and increases pressure drop in reactors. Dry reforming process has always had this as major problem. DATR uses in-situ partial oxidation to reduce this problem. The carbon formation at different temperatures, OCGR and CGR is shown in figure 2.8. As seen from the figure, the carbon formation is more in DR than DATR and it increases with increase in CGR, but decreases with increase in OCGR and increase in temperature. At 950 K the carbon formation decreases from 0.66 to 0.00 as CGR increases from 1–5 in DR of glycerol. Similarly at 950 K, the maximum carbon formation of 0.19 moles is observed only in the case of CGR = 1 and OCGR = 0.1, and it decreases to zero for higher OCGR and higher CGR.

Figure 2.8: Moles of carbon produced in DR and DATR of Glycerol
2.3.9 Process Enthalpy and Thermoneutral points

Reaction enthalpy is always a crucial parameter in reforming processes. Thermoneutral operation of DATR of glycerol requires no external energy for cooling or heating, which makes it valuable from energy consumption point of view. Figure 2.9 shows the variation of enthalpy of DATR of glycerol process with change in OCGR and CGR along the thermoneutral line (zero enthalpy line).

![Figure 2.9: Process enthalpy for DATR of Glycerol](image)

The intersection of reaction enthalpy curves with temperature axis shows the thermoneutral temperatures. It is observed that the process exothermicity increases with increase in OCGR at constant CGR. Table 2.2 shows the product gas yields at thermoneutral conditions. It is observed that the reaction endothermicity increases with increase in CGR from 1 to 5, at constant OCGR, and also show a decrease in thermoneutral temperatures. Similarly, the thermoneutral temperatures show an increase with the increase in OCGR.
at constant CGR which indicate an increase in exothermicity of the reaction. Lower OCGR and higher CGR gave lower thermoneutral point (temperatures) and vice versa. The thermoneutral temperatures range from 771.48 K (OCGR = 0.1, CGR = 5) to 1346.85 K (OCGR = 0.5, CGR = 1).

<table>
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<th>CGR</th>
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<th>CO (g)</th>
<th>Total hydrogen ($\text{H}_2 + \text{CO}$)</th>
<th>Syngas ratio ($\text{H}_2/\text{CO}$)</th>
<th>$\text{CO}_2$ (g)</th>
<th>$\text{CH}_4$ (g)</th>
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</tr>
<tr>
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<td>5.42</td>
<td>0.000</td>
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Table 2.2: Product gas composition in DATR of Glycerol at thermoneutral temperatures (K) & 1 bar pressure
2.4 Conclusions

A thermodynamic analysis of glycerol dry autothermal reforming process has been done to map the effect of OCGR and CGR on product distribution pattern at 1 bar pressure and 600–1000 K temperature range. The study shows the thermodynamic feasibility of the process in the parameter range considered. This process seems favorable for syngas production as it gives a syngas ratio in the desirable range (~1). Hydrogen production can also be achieved. The results show good CO\(_2\) utilization potential. Experimentation will be helpful for comparing the theoretical results obtained here. Higher OCGR and higher CGR are good for syngas production (ratio ~1), lower carbon and methane formation, while lower CGR and lower OCGR give good hydrogen and total hydrogen yields, low water and CO\(_2\) production. The process temperature around 850 K is good for minimizing methane, water and carbon formation. Thermoneutral temperature of 926.31 K at 1 bar pressure, OCGR = 0.3 and CGR = 1 gave 2.67 moles of hydrogen, 4.8 moles of total hydrogen with negligible methane and carbon formation, and was identified as the best thermoneutral condition for DATR operation.

2.5 References


CHAPTER 2: Thermodynamic analysis of dry autothermal reforming of Glycerol


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