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Biogas upgrading using ionic liquid [Bmim][PF_6] followed by thermal-plasma-assisted renewable hydrogen and solid carbon production

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Abstract

The use of hydrogen as clean energy has attracted significant attention because conventional industrial hydrogen production processes show negative environmental impact, require intensive energy, and/or are dependent on natural gas. The main objective of this study is to develop an innovative and environment-friendly hydrogen production process utilizing biogas as an alternative to natural gas. Ionic liquid [Bmim][PF_6] shows high potential for the replacement of aqueous amine solutions for CO_2 absorption and are employed for biogas upgrading, while thermal plasma (TP), which is beneficial for converting electrical energy to chemical energy, is employed for the simultaneous production of clean “turquoise” hydrogen and solid carbon. In addition, an intercooler is used to improve CO_2 removal in the absorber. Heat and power integration is employed to enhance the performance of the upgrading process and thermal-plasma-assisted hydrogen production. The results show that the proposed configuration using an intercooler can afford higher hydrogen purity, which is increased from 99.8% to 99.9%. Solid carbon production from biomethane also increases compared to that in the proposed base case. The savings in both the heater used to preheat the TP reactor and the third flash drum are 100%, while the saving in power consumption in the compression section is 73.3%. Furthermore, sensitivity is investigated to determine the effect of biomethane composition on the performance of the proposed configuration.

Keywords: Biogas upgrading; ionic liquid; [Bmim][PF6]; heat integration; turquoise hydrogen; thermal plasma

1. Introduction

The current processes utilizing nonrenewable sources, such as natural gas as well as oil reforming and coal gasification, account for 96% of hydrogen production [1]. Several new technologies for renewable hydrogen production, such as electrolysis of water (green hydrogen), biomass thermochemical conversion, biological methods, and solar photochemical conversion methods, are under development [2]. Recently, a process in which methane (CH_4) can be thermally or thermo-catalytically decomposed into carbon and hydrogen (turquoise hydrogen) without CO_2 production has attracted considerable attention of the researchers worldwide [3]. By solely considering hydrogen production, direct methane decarbonization is eight times less costly than water electrolysis [4]. Furthermore, this process can produce solid carbon that can be used in many applications [5].

Thermal plasma (TP) offers several benefits for the conversion of electrical to chemical energy, providing a flexible, controllable, and tunable heating source without direct CO_2 emission [4]. Furthermore, it is suitable for endothermic processes and in cases where high temperatures are required. Extensive efforts have been directed toward applying TP for the production of hydrogen and high value-added solid carbon from polymers [6] and methane [4], [7]. Monolith Materials, founded in 2012, has built a plant near Hallam that converts natural gas into clean hydrogen and solid carbon [8].

Biogas is a mixture of methane (55–70 wt%), CO_2, and trace elements such as H_2O, H_2S, NH_3, and siloxanes [9]. Biogas can be produced by the anaerobic digestion of wet biomass, such as the organic fraction of municipal solid waste, energy crops, agricultural residues (mainly manure and straw), sewage sludge, and other organic waste [10]. When CO_2 is removed during the upgrading process, methane concentration increases, and the resulting biomethane can be utilized as an alternative to natural gas [11], which can reduce the dependence on natural gas and positively affect the environment by affording a renewable source of energy and reducing greenhouse gas emissions.

Among the commercially available upgrading technologies, CO_2 absorption by aqueous amine solutions is the most mature gas separation technology. However, because of amine degradation, high equipment maintenance cost, high energy requirement in the regeneration step, and environmental hazards, a better solvent system should be explored. Ionic liquids (ILs) have been recently investigated as effective solvents that show high potential for the replacement of aqueous amine solutions because of their favorable properties, such as low vapor pressure, high boiling point, high CO_2 solubility and selectivity, easy regeneration, and high tunability [12]. However, ILs have several drawbacks, such as high viscosity after CO_2 absorption, which increases the energy required for solvent pumping, and high cost [13].

Therefore, the development of an efficiently integrated hydrogen production process from biogas is required. To the best of our knowledge, this is the first report describing the development of an efficiently integrated hydrogen production process from biogas comprising IL-assisted biogas upgrading and hydrogen production using TP. An intercooler is used to improve CO_2 removal in the absorber. Moreover, heat and power integration is employed to enhance the performance of the upgrading process and thermal-plasma-assisted hydrogen production. An effective configuration based on the improvements in the compression section, absorber, flash drum, and plasma reactor is proposed. Finally, sensitivity is investigated to determine the effect of biomethane composition on product performance.

2. Base case

Even though methane can be used as a feed for producing clean hydrogen and solid carbon using TP [14], biomethane, which is a substitute for fossil natural gas and is obtained from biomass or biowaste, is more attractive because of net-zero emissions. The facility for biogas production and upgrading comprises three stages: anaerobic digestion stage in which the organic fraction of the treated waste is decomposed producing biogas, initial biogas conditioning stage in which H_2S and ammonia are removed, and the purification step that involves CO_2 removal to achieve sufficient purity [15]. In this study, a process including IL-assisted biomethane upgrading and hydrogen production using TP was developed. All simulations in the biomethane upgrading unit were performed using the Aspen Plus V10.0 software by employing the Peng-Robinson (PR) equation of state [16]. For hydrogen production using TP, the UNIQUAC properties package was employed [17].

2.1. Biomethane upgrading using IL

Biogas obtained from the anaerobic digestion unit primarily consists of CH_4 and CO_2, whose relative contents mainly depend on the nature of the substrate and reactor pH [10]. Before its usage in the TP reactor for hydrogen production, biogas should be treated for CO_2 removal by the upgrading unit (Figure 1).

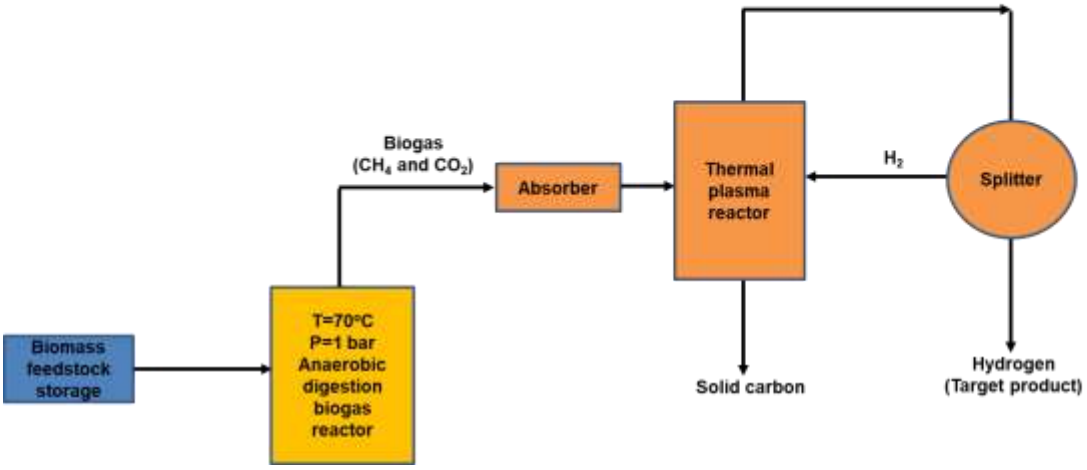

Figure 1. Schematic of the process for the co-production of hydrogen and solid carbon.

Among the commercially available upgrading technologies, CO_2 absorption by aqueous amine solutions is the most mature and popular technique. However, as mentioned previously, owing to amine degradation, high equipment maintenance cost, high energy requirement in the regeneration step, and environmental hazards, a better solvent system is required. In the past few years, ILs have been utilized as gas absorbents owing to their advantages over the traditional solvents, which include thermal stability, non-volatility, designability, and tunability [16]. Considerable efforts have been directed toward investigating the absorbent properties of the ILs for gases such as CO_2, H_2S, N_2, and H_2 [18][19]. In particular, ILs have been widely applied to C1–C4 absorption and reported as effective acidic gas absorbents [20]. However, the selection of a suitable IL for a specific process is important, considering that the solubility of a gas is different in different ILs. In other words, the selection of an appropriate IL can determine the technical and economic feasibility of the gas removal process.

Several studies have shown that 1-butyl-3-methylimidazolium hexafluorophosphate [Bmim][PF_6] can be used as an alternative absorbent to the aqueous amine solutions for CO_2 removal [21]. This IL has been demonstrated to be a suitable solvent for CO_2/CH_4 separation with the highest absorption selectivity among the imidazolium-based ILs. Additionally, it has a viscosity of 0.246 Pa·s at 298.15 K and low-to-moderate toxicity (e.g., the $\log EC_{50}$ value against leukemia rat cell line is 3.10). Notably, the solubilities of CO_2 and CH_4 in [Bmim][PF_6] have been experimentally determined in a wide range of temperature and pressure values, allowing a reliable regression of the thermodynamic model parameters for modeling the phase behaviors of this system in the absorber. For instance, Haider et al. [16] successfully fitted the parameters for [Bmim][PF_6] and CO_2/CH_4 for a set of equation of state models, where the PR method selected in this work showed the lowest standard deviations of 0.0330 and 0.0079 for calculating the solubilities of CH_4 and CO_2, respectively, in this IL. Thus, in this work, [Bmim][PF_6] was selected as a solvent for CO_2 removal to upgrade biomethane.

Biogas was first compressed to 40 bar before its entry into the absorber. Figure 2 shows that the biogas produced by anaerobic digestion comes into contact with the IL in the absorber. The process was designed to recover 96% biomethane with purity of 99.5 wt%. The number of stages (N) was varied to optimize the absorber. Figure 3 shows the effect of the number of absorber stages on the IL to feed (IL/F) ratio. The IL/F value decreases rapidly upon an increase in N from 2 to 8, and increases slightly when it is increased from 8 to 12. Upon a further increase in N, the IL/F value remains stable. Therefore, a value of 12 for the number of stages was employed in the design of the absorber. Figure 4 shows the composition profile of CO_2 in the absorber, which indicates that almost all CO_2 is absorbed in the bottom half of the scrubber.

A series of flash drums was used to recover [Bmim][PF6], which were operated at 9.8, 0.8, and 0.1 bar [16]. Notably, to completely strip the gas and recover [Bmim][PF6], a load of 3,150 kW was applied in the third flash drum. The bottom stream of the third flash drum was pumped to increase the pressure before it was recycled to the absorber.

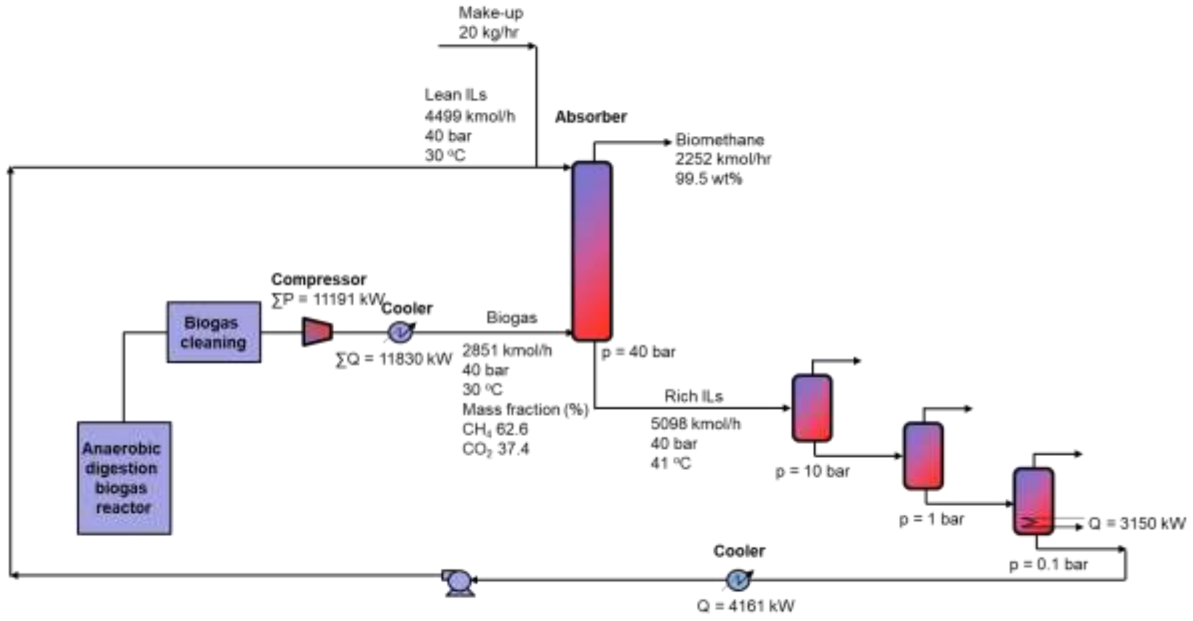

Figure 2. Simplified flow sheet illustrating the ionic liquid (IL)-assisted biogas upgrading unit.

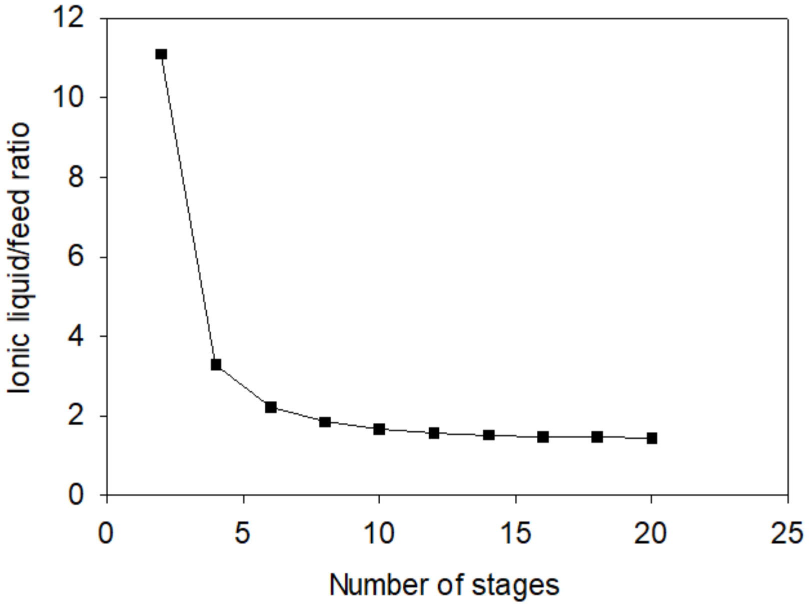

Figure 3. Effect of the number of absorber stages on ionic liquid to feed ratio (IL/F).

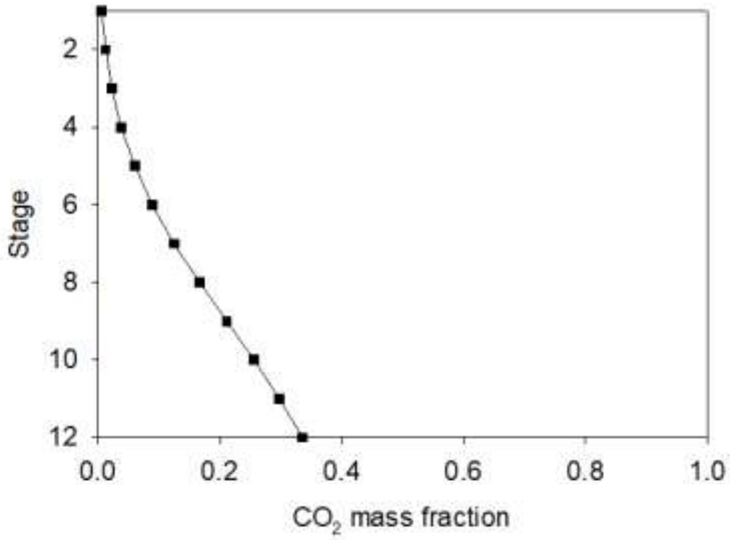

Figure 4. Composition profile of CO_2 in the absorber.

2.2. Hydrogen production using TP

Upgraded biomethane was then heated to 600 °C before being fed into the TP reactor with two reaction zones; this splitting into two serial reaction zones increased the chemical yield of the TP reactor [4]. First, the produced biogas entered zone 2 to produce hydrogen and solid carbon. Then, the outlet from the TP reactor was fed into a separator to separate solid carbon and hydrogen. A fraction of hydrogen was recycled to zone 1 to produce hydrogen radicals before entering zone 2. Figure 5 shows a simplified flow sheet illustrating the hydrogen production unit using TP.

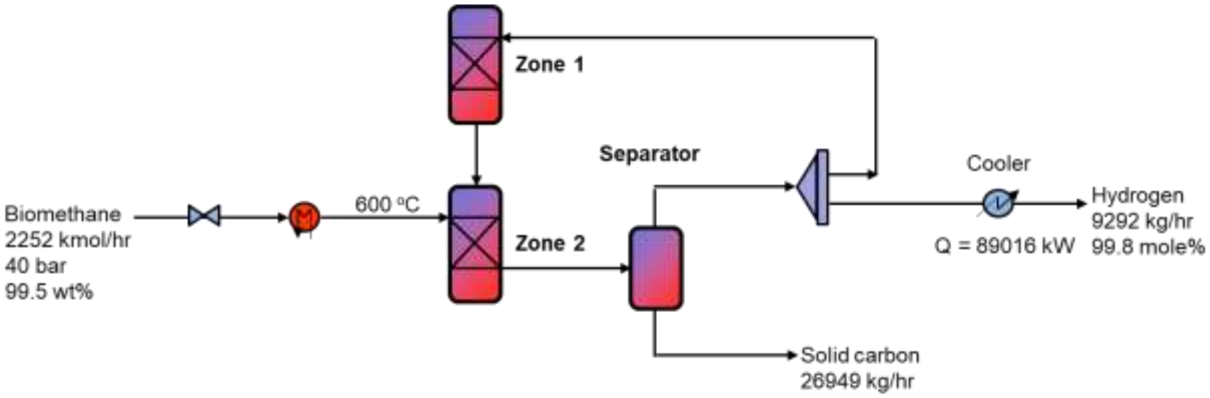

Figure 5. Simplified flow sheet illustrating the thermal plasma (TP) reactor for hydrogen production.

3. Process improvement

3.1. Absorber improvement

A useful method for enhancing CO_2 removal involves the application of an intercooler to the absorber columns [22]. Absorption is an exothermic process that leads to an overall temperature increase of the solvent. This phenomenon can cause decreases in the driving force of absorption as well as absorption capacity of the solvent system. The absorption efficiency may be improved by withdrawing a fraction of solvent in the absorber and cooling the solvent prior to its return to the absorber [23].

The important design parameters for intercooler design are the location and cooling duty. As the temperature of the 11th tray was the highest, the intercooler was installed in that section (Figure 6a), and intercooler duty was then used for optimization (Figure 6b). Figure 6b shows that CO_2 removal increases when the intercooler duty is increased from 0 to 1200 kW. However, above 1200 kW, the temperature of the absorber is <30 °C, which is a constraint to use the cooling water. Thus, an intercooler duty of 1000 kW was employed in the intercooler design. As shown in Figure 6a, the temperature profile is shifted to the left, i.e., the temperature in the column decreases in comparison to that in the base case. As a result, 96.1% biomethane with a purity of 99.7 wt% can be recovered.

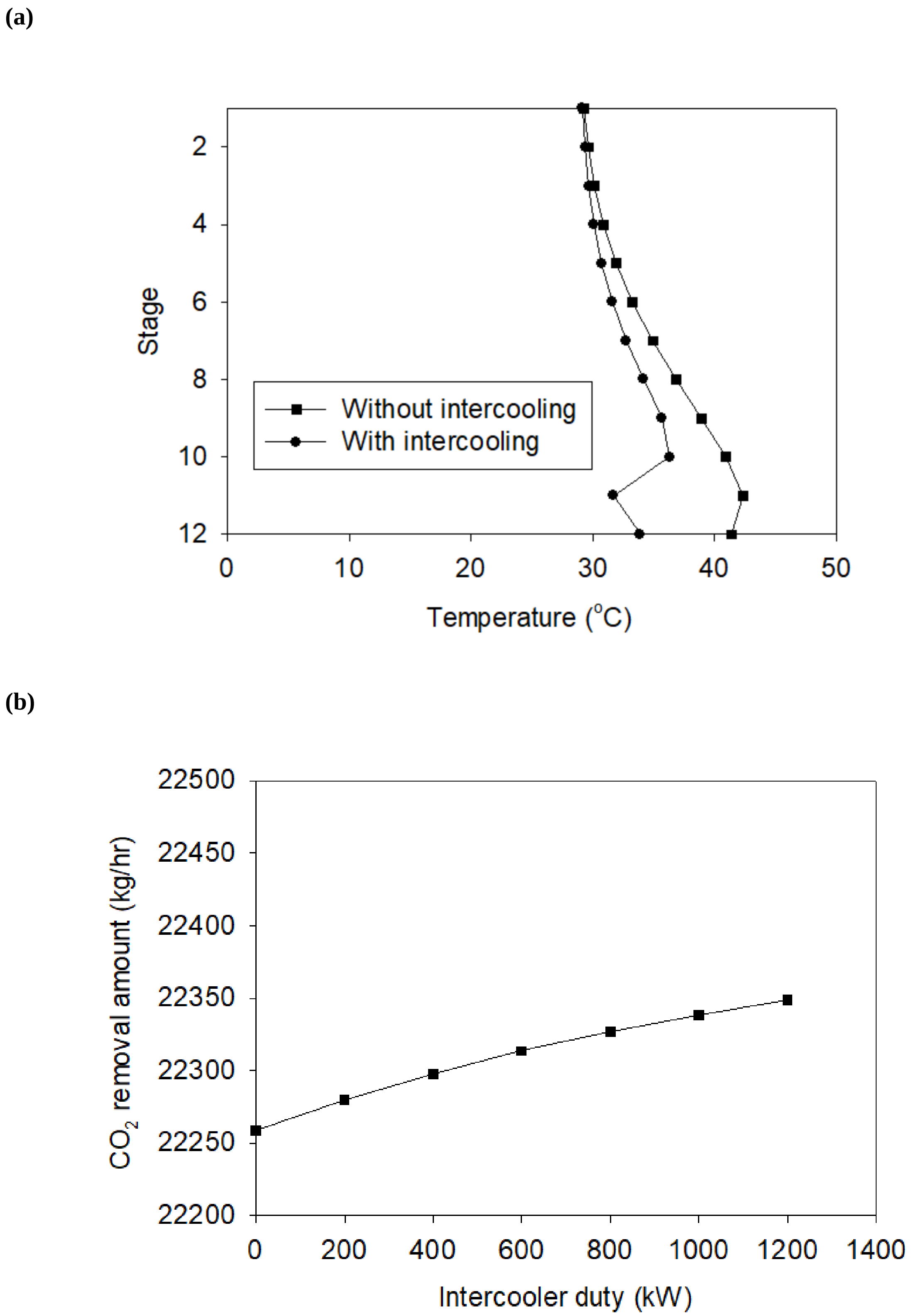

Figure 6. (a) Temperature profile; (b) effect of intercooler duty on CO_2 removal.

3.2. Improvement in TP reactor

Since there is no effect of the temperature of zone 1 on the total efficiency [17], only the temperature of zone 2 was varied in this study. Figure 7 shows that biomethane conversion increases rapidly when the temperature of zone 2 is increased from 700 °C to 1200 °C, while it increases slightly with an increase in temperature from 1200 °C to 1500 °C. Thereafter, the conversion remains stable upon a further increase in the temperature of zone 2. Thus, 1500 °C was selected to design the TP reactor in the proposed configuration.

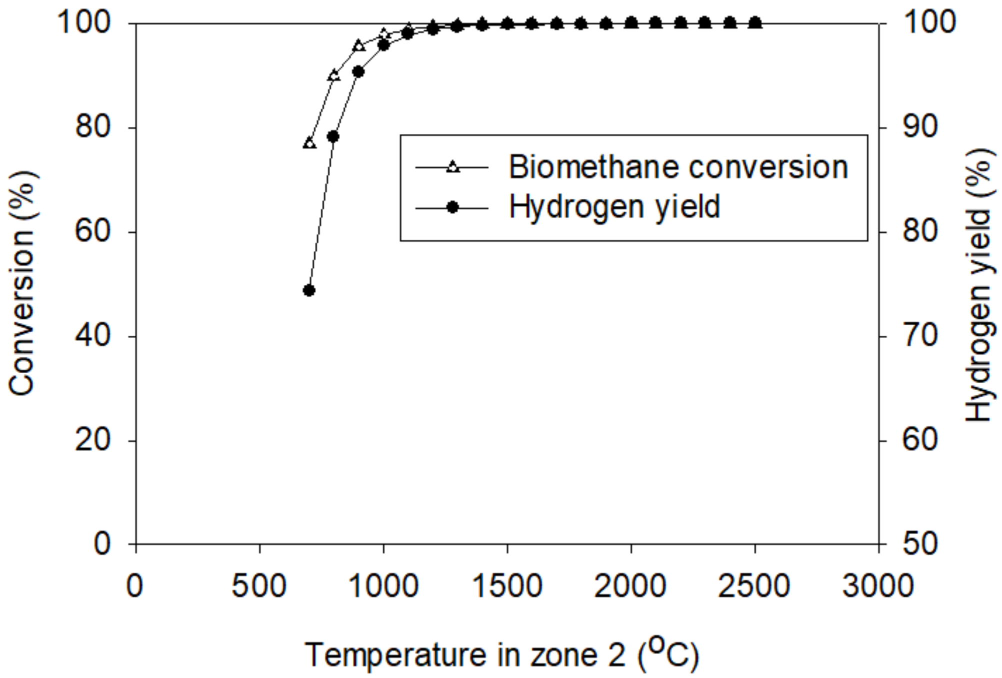

Figure 7. Effect of the temperature of TP in zone 2.

3.3. Heat and power integration

3.3.1. Feed preheating

Since the outlet from the TP reactor has a high temperature, the heat from this stream can potentially be used to preheat the TP reactor feed and supply heat to the third flash drum for IL regeneration. In particular, the outlet stream of zone 2 is used to preheat the biogas feed to 600 °C before being fed into a separator to separate solid carbon and hydrogen. This can lead to a reduction of the thermal load of the reactor. Note that, to prevent methane cracking in the pipes, the upper threshold for the preheating temperature of methane is 700 °C. Heat integration can result in a saving of 100% in terms of the heat required to preheat the feed stream of the TP reactor.

3.3.2. Flash drum improvement

Since extra heat is available in the hydrogen product stream, it can be utilized for the third flash drum. Thus, a heat exchanger was used for heat integration between the hot stream (hydrogen product) and cold stream (liquid in the third flash drum). Notably, the minimum temperature in this study was 10 °C. The results show that it is possible to save 3150 kW power in the third flash drum, which corresponds to 100% saving in terms of flash drum duty.

3.3.3. Turbine

Since the top stream of the absorber has a high pressure, a turbine can potentially be used to drive the electricity generators. The force of the purified biomethane on the blades rotates the rotor shaft of a generator. In turn, the generator converts the mechanical (kinetic) energy of the rotor into electrical energy. As a result, turbine use can generate a power of 2461 kW, i.e., it can save 22.0% of the total compression power to increase the inlet biogas of the absorber.

3.3.4. Electricity generation

It is also possible to utilize heat from the condenser in the compression unit and the remaining heat from the outlet of the TP reactor to generate electricity. In particular, the hydrogen product stream can be used as a heat source to generate steam, which can then be used to drive the turbine to produce a power of 5397 kW (Figure 8). The same approach can be applied to utilize the heat from the cooler in the compression unit, which can generate a power of 350 kW. This generated electricity can be used to drive the compressors in the compression section.

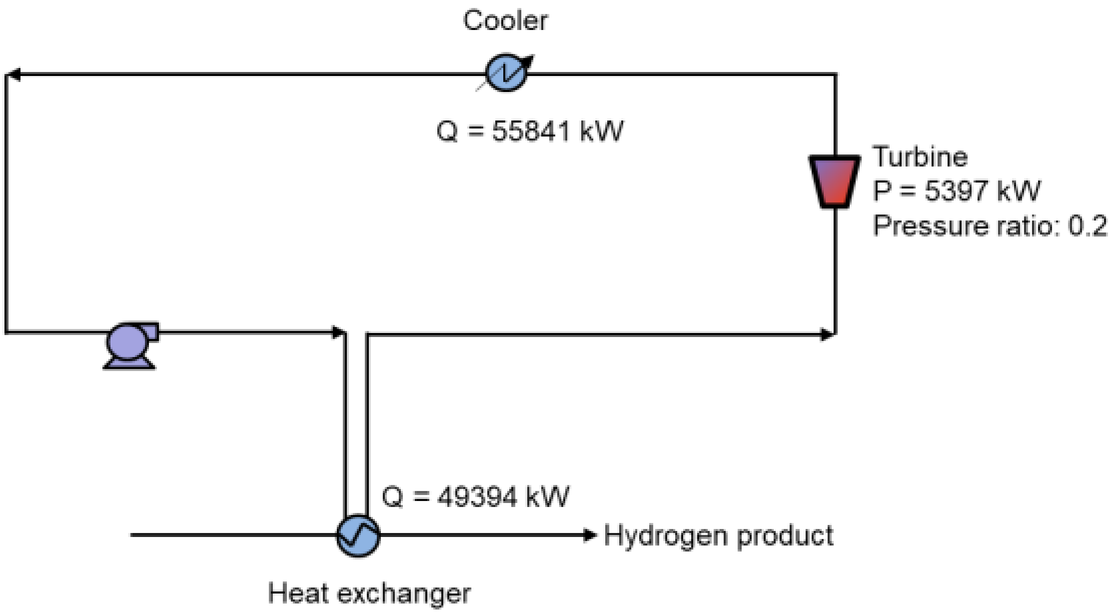

Figure 8. Simplified flow sheet of the electricity generation system.

4. Proposed configuration

Figure 9 shows the proposed integrated IL-assisted absorber for biogas upgrading as well as thermal-plasma-assisted reactor producing hydrogen and solid carbon. In this configuration, an intercooler is used to improve the absorber performance, and zone 2 of the TP reactor is operated at 1500 °C. This configuration can afford a higher hydrogen purity, which is increased from 99.8% to 99.9%, as biomethane purity is increased with the use of an intercooler. Furthermore, the solid carbon product, which is also produced from biomethane, increases in comparison to that in the proposed base case.

Total electric energy that can be generated from the turbine by utilizing the high pressure of the scrubber top stream as well as electricity generated utilizing the heat from the condenser in the compression unit and remaining heat from the outlet of the TP reactor is 8208 kW, affording a 73.3% saving in power consumption in the compression section. Notably, the savings in the heater to preheat the TP reactor and third flash drum are 100% in both cases.

Since the methane composition in biogas depends on the type of feedstock, technology used, and operating conditions, the effect of methane composition on product performance was determined. As shown in Figure 10, the hydrogen amount increases with increasing methane content, because hydrogen is the direct product obtained from methane. This can afford high hydrogen purity, which is an important parameter for designing. For different applications of hydrogen, the hydrogen purity from the production section should be different.

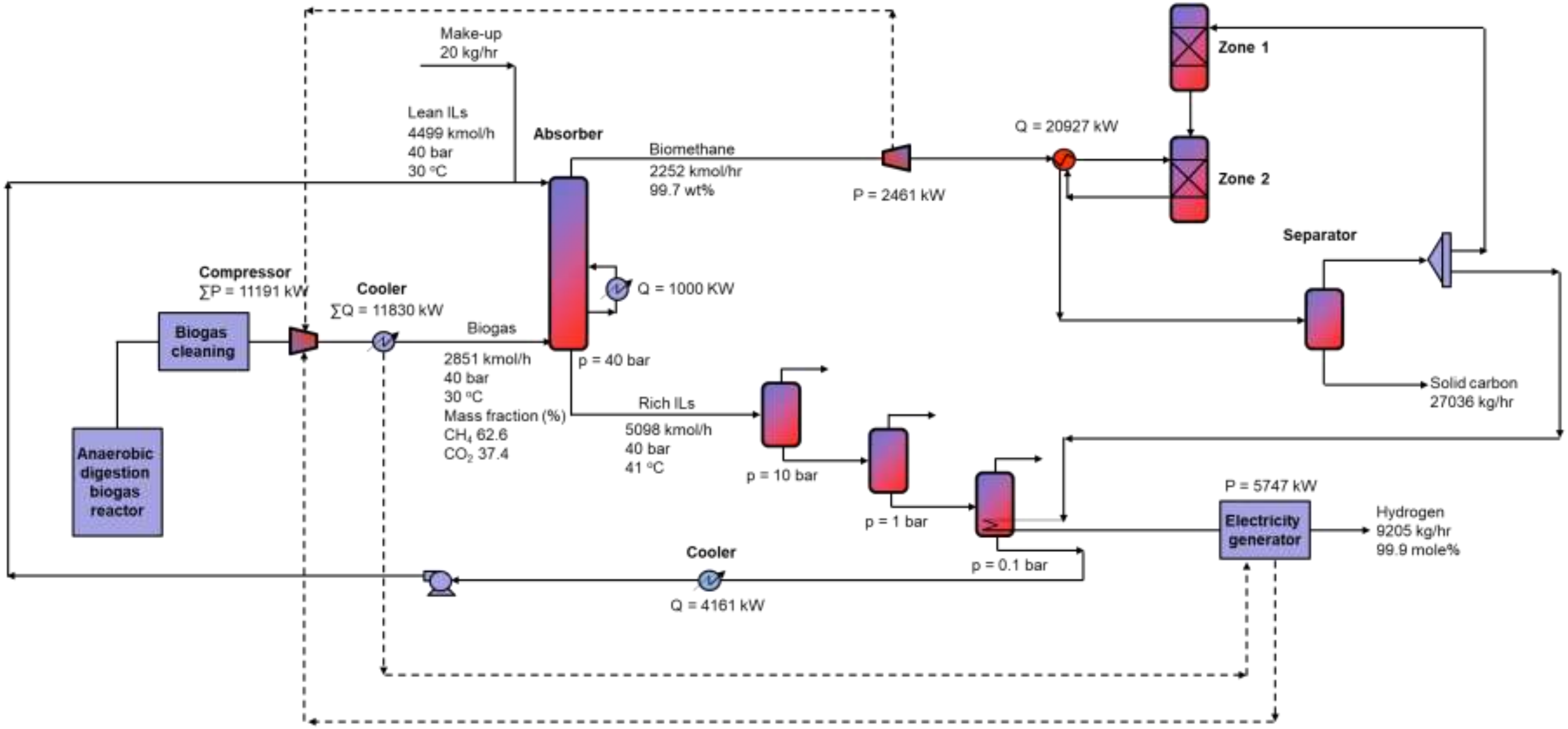

Figure 9. Simplified flow sheet illustrating the proposed process.

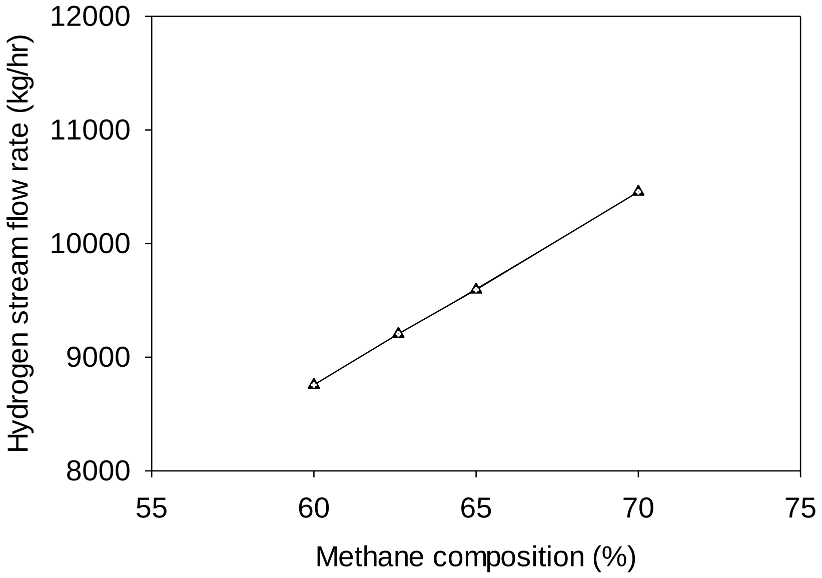

Figure 10. Effect of methane composition on product performance.

5. Conclusions

The method described in this work is an attractive solution for both clean hydrogen and solid carbon production, affording 96% biomethane recovery with a purity of 99.5% using [Bmim][PF6]. An intercooler is effectively employed to improve CO_2 removal; in particular, the process employing [Bmim][PF6] with an intercooler can afford 99.7% pure biomethane. In the proposed configuration, [Bmim][PF6] is used as a solvent, and the combined use of an intercooler with heat and power integration results in enhanced performance. Moreover, the proposed configuration affords a higher hydrogen purity with an increase from 99.8% to 99.9%. Furthermore, the yield of the solid carbon product, which is also produced from biomethane, increases in comparison to that in the proposed base case. The heater savings to preheat the TP reactor and third flash drum are 100% in both cases, while the power consumption saving in the compression section is 73.3%. Moreover, hydrogen productivity increases with an increase in the methane composition in biogas. Considering the significant potential of the proposed integration process, additional efforts should be directed toward the application of large-scale IL screening as well as the conversion of CO_2 and hydrogen produced in this process to more valuable components such as methanol in the future.

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References

[1] A. Arregi, M. Amutio, G. Lopez, J. Bilbao, and M. Olazar, “Evaluation of thermochemical routes for hydrogen production from biomass: A review,” *Energy Convers. Manag.*, vol. 165, pp. 696–719, 2018.

[2] T. K. Patra, S. Mukherjee, and P. N. Sheth, “Process simulation of hydrogen rich gas production from producer gas using HTS catalysis,” *Energy*, vol. 173, pp. 1130–1140, 2019, doi: 10.1016/j.energy.2019.02.136.

[3] H. F. Abbas and W. M. A. Wan Daud, “Hydrogen production by methane decomposition: A review,” *Int. J. Hydrogen Energy*, vol. 35, no. 3, pp. 1160–1190, 2010, doi: 10.1016/j.ijhydene.2009.11.036.

[4] M. Gautier, V. Rohani, and L. Fulcheri, “Direct decarbonization of methane by thermal plasma for the production of hydrogen and high value-added carbon black,” *Int. J. Hydrogen Energy*, vol. 42, no. 47, pp. 28140–28156, 2017, doi: 10.1016/j.ijhydene.2017.09.021.

[5] M. J. Afroughi, F. Falahati, L. W. Kostiuk, and J. S. Olfert, “Properties of carbon black produced by the thermal decomposition of methane in the products of premixed flames,” *J. Aerosol Sci.*, vol. 131, no. January, pp. 13–27, 2019, doi: 10.1016/j.jaerosci.2019.02.002.

[6] S. Mohsenian, M. S. Esmaili, J. Fathi, and B. Shokri, “Hydrogen and carbon black nano-spheres production via thermal plasma pyrolysis of polymers,” *Int. J. Hydrogen Energy*, vol. 41, no. 38, pp. 16656–16663, 2016, doi: 10.1016/j.ijhydene.2016.05.150.

[7] A. Mašláni *et al.*, “Pyrolysis of methane via thermal steam plasma for the production of hydrogen and carbon black,” *Int. J. Hydrogen Energy*, vol. 46, no. 2, pp. 1605–1614, 2021, doi: 10.1016/j.ijhydene.2020.10.105.

[8] M. Olberding, “Japanese company invests in Monolith’s hydrogen plant near Hallam,” 2020. https://journalstar.com/business/local/japanese-company-invests-in-monoliths-hydrogen-plant-near-hallam/article_ef29032a-4469-5e33-a7ef-b4b03049e2e1.html.

[9] F. Ardolino, G. F. Cardamone, F. Parrillo, and U. Arena, “Biogas-to-biomethane upgrading: A comparative review and assessment in a life cycle perspective,” *Renew. Sustain. Energy Rev.*,

vol. 139, no. xxxx, p. 110588, 2021, doi: 10.1016/j.rser.2020.110588.

[10] I. Angelidaki *et al.*, “Biogas upgrading and utilization: Current status and perspectives,” *Biotechnol. Adv.*, vol. 36, no. 2, pp. 452–466, 2018, doi: 10.1016/j.biotechadv.2018.01.011.

[11] K. Starr, X. Gabarrell, G. Villalba, L. Talens, and L. Lombardi, “Life cycle assessment of biogas upgrading technologies,” *Waste Manag.*, vol. 32, no. 5, pp. 991–999, 2012, doi: 10.1016/j.wasman.2011.12.016.

[12] H. Zhai and E. S. Rubin, “Systems analysis of physical absorption of co_2 in ionic liquids for pre-combustion carbon capture,” *Environ. Sci. Technol.*, vol. 52, no. 8, pp. 4996–5004, 2018, doi: 10.1021/acs.est.8b00411.

[13] E. S. Rubin, H. Mantripragada, A. Marks, P. Versteeg, and J. Kitchin, “The outlook for improved carbon capture technology,” *Prog. Energy Combust. Sci.*, vol. 38, no. 5, pp. 630–671, 2012, doi: 10.1016/j.pecs.2012.03.003.

[14] L. Fulcheri and Y. Schwob, “From methane to hydrogen, carbon black and water,” *Int. J. Hydrogen Energy*, vol. 20, no. 3, pp. 197–202, 1995, doi: 10.1016/0360-3199(94)E0022-Q.

[15] E. Martín-Hernández, L. S. Guerras, and M. Martín, “Optimal technology selection for the biogas upgrading to biomethane,” *J. Clean. Prod.*, vol. 267, 2020, doi: 10.1016/j.jclepro.2020.122032.

[16] J. Haider, M. A. Qyyum, B. Kazmi, M. Zahoor, and M. Lee, “Simulation study of biomethane liquefaction followed by biogas upgrading using an imidazolium-based cationic ionic liquid,” *J. Clean. Prod.*, vol. 231, pp. 953–962, 2019, doi: 10.1016/j.jclepro.2019.05.252.

[17] M. M. Sarafraz *et al.*, “Tri-fold process integration leveraging high- and low- temperature plasmas : From biomass to fertilizers with local energy and for local use,” no. January, pp. 1–21, 2021, doi: 10.1002/amp2.10081.

[18] J. M. M. V. Sousa, T. E. Sintra, A. G. M. Ferreira, P. J. Carvalho, and I. M. A. Fonseca, “Solubility of H_2S in ammonium-based ionic liquids,” *J. Chem. Thermodyn.*, vol. 154, 2021, doi: 10.1016/j.jct.2020.106336.

[19] M. Ramdin, S. P. Balaji, A. Torres-Knoop, D. Dubbeldam, T. W. De Loos, and T. J. H. Vlugt,

“Solubility of natural gas species in ionic liquids and commercial solvents: experiments and monte carlo simulations,” *J. Chem. Eng. Data*, vol. 60, no. 10, pp. 3039–3045, 2015, doi: 10.1021/acs.jced.5b00469.

[20] J. Wang, Z. Song, H. Cheng, L. Chen, L. Deng, and Z. Qi, “Multilevel screening of ionic liquid absorbents for simultaneous removal of CO_2 and H_2S from natural gas,” *Sep. Purif. Technol.*, vol. 248, no. April, p. 117053, 2020, doi: 10.1016/j.seppur.2020.117053.

[21] T. Ma *et al.*, “A process simulation study of CO_2 capture by ionic liquids,” *Int. J. Greenh. Gas Control*, vol. 58, pp. 223–231, 2017, doi: 10.1016/j.ijggc.2017.01.017.

[22] A. Cousins, L. T. Wardhaugh, and P. H. M. Feron, “A survey of process flow sheet modifications for energy efficient CO_2 capture from flue gases using chemical absorption,” *Int. J. Greenh. Gas Control*, vol. 5, no. 4, pp. 605–619, 2011, doi: 10.1016/j.ijggc.2011.01.002.

[23] K. A. H. Yann Le Moullec, Thibaut Neveux, Adam Al Azki, Actor Chikukwa, “Process modifications for solvent-based post-combustion CO_2 capture,” *Int. J. Greenh. Gas Control*, vol. 31, pp. 96–112, 2014.