Research Article

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Simulation-based Design of Plate-fin Heat Exchangers for Cryogenic CO_2 Removal from Biogas

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ABSTRACT

Carbon Capture, Utilization, and Storage (CCUS) is essential for mitigating carbon dioxide (CO_2) emissions from major emission sources, with CO_2 removal being a fundamental step. In biomethane upgrading, the effective removal of CO_2 from biogas is essential to meet pipeline-quality requirements and improve its energy content. Among the available removal techniques, cryogenic CO_2 removal has gained considerable interest because of its ability to selectively and efficiently separate CO_2 at low temperatures. Plate-fin Heat Exchangers (PFHEs), recognized for their high heat-transfer efficiency and compact configuration, are particularly suitable for cryogenic applications. This study presents the design of a PFHE for cryogenic CO_2 removal during biomethane upgrading using Aspen EDR software. This study investigates the effect of CO_2 concentration on heat-exchanger design and heat-transfer rate.

Keywords: Cryogenic CO_2; Biogas; Plate-fin heat exchangers; Aspen EDR software.

1. INTRODUCTION

Plate-fin heat exchangers (PFHEs) are widely employed in cryogenic applications because of their exceptional thermal efficiency, compact design, and versatility under many working circumstances (Yang *et al.* 2016). An important feature that differentiates PFHEs from other heat exchangers is their remarkably high surface-area-to-volume ratio, generally surpassing 1800 m^2/m^3 (Gupta *et al.* 2017). This feature facilitates efficient heat exchange by optimising the contact area between fluid streams in a limited space. As a result, PFHEs can attain efficacy levels above 95%, rendering them exceptionally appropriate for thermal control in low-temperature, high-performance systems (Reay *et al.* 2013).

The enhanced heat transmission efficiency of PFHEs is primarily due to the use of extended surfaces, referred to as fins, strategically positioned between the heat transfer plates. These fins are crucial in enhancing the effective heat transfer area, thereby promoting more efficient energy exchange between various fluid streams. Fins utilised in PFHEs are often categorised into four distinct types: (a) Plain fins, (b) Louvred fins, (c) Offset strip fins, and (d) Wavy fins (Saggu *et al.* 2020).

The offset strip fin arrangement is particularly useful in improving thermal performance. This design generates periodic disruptions in the flow channel, so inducing turbulence and interfering with the establishment of the thermal boundary layer. Consequently, there is a significant rise in fluid velocity, temperature differentials, and localised heat transfer coefficients. These effects not only improve heat transfer but also lead to an elevated pressure drop, which can be advantageous in specific design contexts (Yang *et al.* 2016). Additionally, the "f" boundary layer disturbance is essential for the enhancement of convective heat transfer by reducing thermal resistance (Joshi *et al.* 1987).

A primary benefit of PFHEs is their capacity to concurrently manage several fluid streams inside a singular, cohesive unit. This capacity makes them especially beneficial in intricate thermal systems where spatial optimisation and thermal integration are essential. Besides multi-stream management, PFHEs provide: (a) The capability for intermediate stream ingress and egress, facilitating adaptable process topologies, and (b) An advantageous weight-to-performance ratio, crucial for weight-sensitive applications like aircraft systems (Das *et al.* 2012).

Due to their functional and design benefits, PFHEs are utilised in a diverse range of sectors. Their applications encompass, but are not confined to, the aerospace sector, automotive thermal management systems, air removal units, natural gas and hydrogen liquefaction processes, regenerative cryocoolers, helium liquefaction and purification systems, and high-temperature superconducting (HTS) technologies

(Chang *et al.* 2015). The versatility, efficiency, and compactness of PFHEs render them essential in both traditional and innovative cryogenic engineering applications.

Plate-fin heat exchangers have recently attracted increasing attention in cryogenic CO_2 capture systems, establishing themselves as a crucial element in the development of efficient low-temperature removal methods (Tan *et al.* 2017b). CO_2 capture is a vital component of the Carbon Capture, Utilisation, and Storage (CCUS) strategy, aimed at mitigating greenhouse gas emissions from significant stationary sources, including natural gas and coal-fired power plants, cement production facilities, and iron and steel manufacturing plants (Magli *et al.* 2022).

The incorporation of PFHEs into cryogenic CO_2 collecting systems has many advantages, *viz*., small design, superior heat transfer efficiency, and multi-stream functionality.

Tan *et al.* (2019) proposed a detailed design framework for multi-stream PFHEs, emphasizing the impact of thermo-physical properties. Their findings revealed that thermal conductivity significantly influences exchanger sizing uncertainty, more than viscosity. Wang *et al.* (2001) introduced a novel design methodology that incorporates both pressure drop and thermal load requirements, validated through an industrial application case study. Prasad *et al.* (1987) developed a differential approach for sizing PFHEs with gaseous streams, observing a marked pressure drop near the warm end of the heat exchanger.

Peng *et al.* (2009) employed artificial neural networks (ANNs) to optimize PFHE performance, creating accurate predictive models for the Colburn factor, fanning friction factor, and pressure drop achieving errors of just 1.5% and 1%, respectively. Yousefi *et al.* (2011) employed Particle Swarm Optimization (PSO) to minimize the total annual cost of a crossflow PFHE, demonstrating faster convergence than traditional genetic algorithms. In addition to design methods, several studies have focused on empirical modeling and correlation development. Joshi *et al.* (1987) developed predictive models for the heat transfer coefficient and fanning friction factor of offset strip-fin surfaces, effective for both laminar and turbulent regimes, with prediction errors within 20%. Song *et al.* (2017) proposed new empirical correlations for the Colburn and friction factors, showing 13% and 8% deviations, respectively, when compared to the widely used Manglik and Bergles correlation.

Tan *et al.* (2017a) evaluated various models for estimating viscosity and thermal conductivity of CO_2 mixtures with non-condensable gases. They found that the Kestin-Ro-Wakeham model produced an absolute average deviation of 1.3%, compared to 3.5% from the Ely and Hanley model. Castillo *et al.* (2019) presented a surface-design-based method for multi-stream PFHEs, reducing the number of heat exchanger sections from three to two, as verified against existing literature. Experimental and simulation-based investigations further validate and refine these design approaches.

Goyal *et al.* (2014) performed an experimental study on a three-layer PFHE using nitrogen and helium gases, confirming good agreement with a finite-volume-based 2D numerical model in predicting exit and endplate temperatures. Prasad *et al.* (1991) introduced a method for evaluating multi-stream PFHE performance based on stacking patterns, demonstrating that symmetric stacking enhances performance in two-stream configurations and that distributed stream passages yield improved heat transfer efficiency. Cho *et al.* (2017) applied a genetic algorithm to optimize thermal stacking arrangements for reduced thermal stress, achieving a 30% improvement over baseline designs.

The heat exchanger plays a crucial role in the efficiency of the cryogenic CO_2 capture process. A detailed study is essential, as the process involves heat exchange between extremely low-temperature streams. This study focuses on the design and analysis of a plate fin heat exchanger specifically for cryogenic CO_2 capture applications.

The primary objective of this study is to design and analyze a PFHE for cryogenic CO_2 removal in biomethane upgrading applications. The study aims to evaluate the impact of varying CO_2/CH_4 concentrations on PFHE performance using Aspen EDR software. Key focus areas include assessing changes in heat load, geometry, pressure drop, and thermal effectiveness.

2. PFHE DESIGN METHODOLOGY

Aspen Exchanger Design & Rating (Aspen EDR) software is used to perform detailed thermal and mechanical design simulations. Aspen EDR combines rigorous thermal modeling with validated heat transfer and pressure drop correlations, allowing for accurate performance prediction of compact heat exchangers such as PFHEs.

In this study, a two-stream PFHE is employed to analyze the effect of varying CO_2 concentrations in biogas on the performance and design of the heat exchanger. While multistream heat exchangers are typically used in cryogenic carbon capture systems to fully utilize multiple hot and cold streams, a two-stream configuration is chosen here to isolate and clearly understand the influence of CO_2 content in the feed gas.

The variation in CO_2 concentration is essential, as raw biogas composition differs significantly

depending on the source. Therefore, the CO_2 content in the feed gas is varied from 0% to 50% by volume to reflect real-world conditions.

In this setup, raw biogas, primarily composed of CO_2 and H_2, is treated as the hot fluid, while nitrogen gas is used as the cold fluid. The inlet temperature of the biogas is set at 30°Cwith an inlet pressure of 50 bar, and the outlet temperature is fixed at –123°C. This outlet temperature is maintained constant across all cases to specifically assess how CO_2 concentration affects the heat exchanger design and the cooling duty required from the nitrogen stream.

The estimated pressure drop on the hot fluid side is 0.6 bar, while the cold side experiences a pressure drop of 0.12 bar. The cold stream (nitrogen) is maintained at a pressure of 2 bar throughout the analysis.

3. RESULTS AND DISCUSSIONS

Table 1 presents the detailed specifications of the fins incorporated in the design of the PFHE. These specifications are critical, as the fin geometry including parameters such as fin frequency, length, and thickness directly influences the overall heat transfer performance, pressure drop, and compactness of the heat exchanger. The selection of appropriate fin characteristics ensures efficient thermal exchange between the hot and cold streams while maintaining mechanical integrity and minimizing flow resistance within the cryogenic operating conditions.

Table 1. Specifications of fins used in the heat exchanger

		Fin 1	Fin 2	Fin 3	Fin 4
Fin code/bank number		1	2	3	4
Fin used in exchanger		Yes	Yes	Yes	Yes
Fin type		Serrated (offset)	Perforated	Plain	Perforated
Fin height	mm	6.4	6.4	6.4	6.4
Fin thickness	mm	0.41	0.41	0.61	0.61
Fin frequency	#/m	787	787	472	472
Fin porosity (fraction)	-		0.05		0.05
Fin serration length	mm	3			
Subchannel aspect ratio	-	6.93	6.93	3.84	3.84
Blockage fraction	-	0.36	0.36	0.36	0.36
Hydraulic diameter	mm	1.51	1.51	2.39	2.39
Flow area per unit width	mm	4.08	4.08	4.12	4.12
Primary perimeter per unit width	-	1.36	1.36	1.42	1.42
Secondary perimeter per unit width	-	9.43	8.96	5.47	5.19

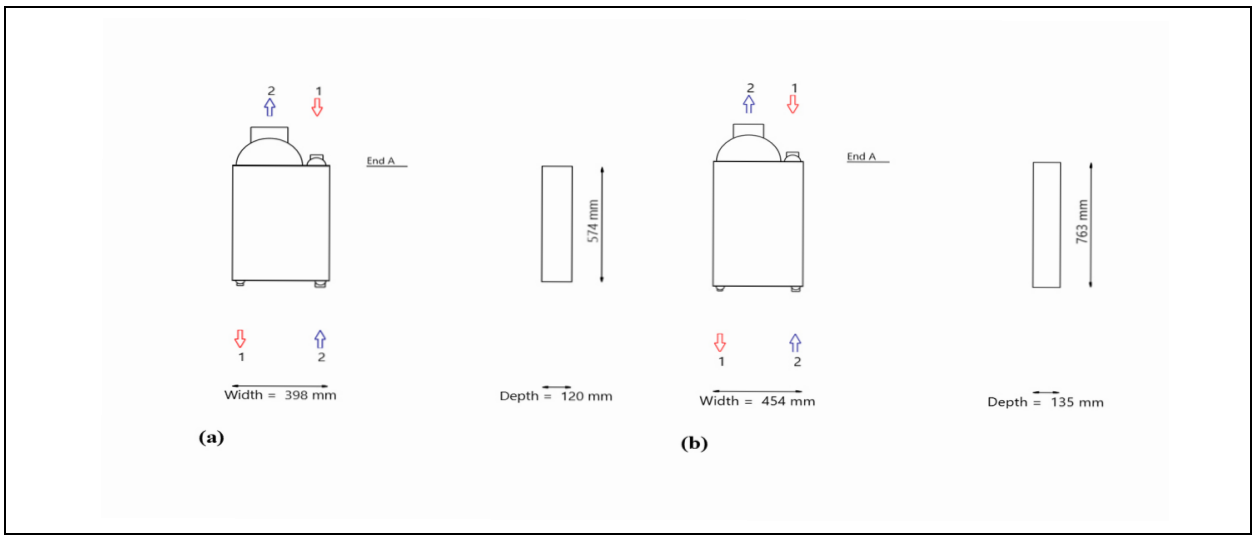


Fig. 1: (a) Design specifications of the heat exchanger for a gas mixture containing 50% CH_4 concentration and (b) Design specifications of the heat exchanger for pure CH_4 (100% concentration)

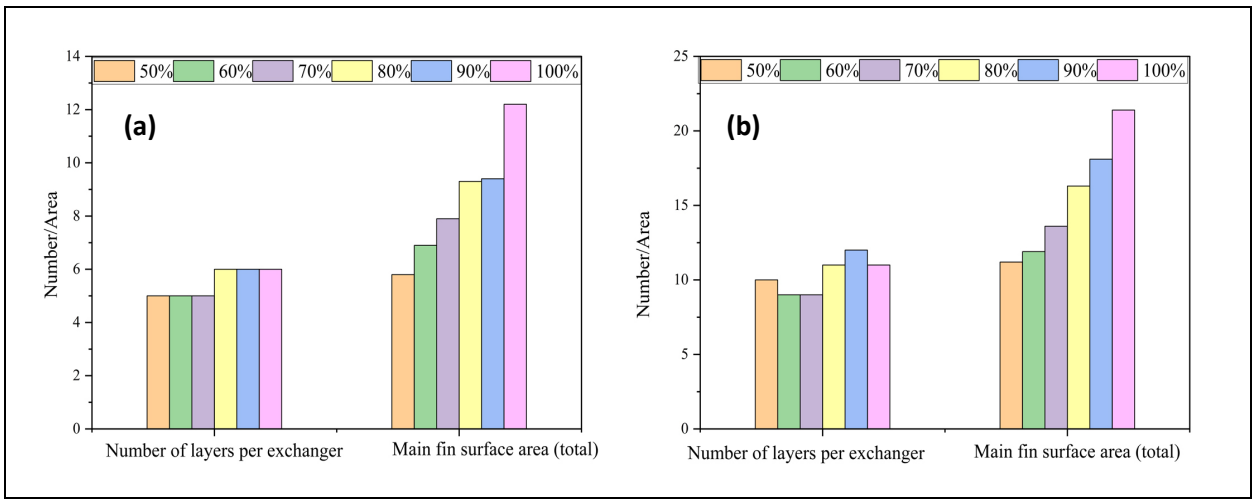


Fig. 2: (a) Relationship between the number of layers and heat transfer area on the hot side of the PFHE with concentration of CH_4 and (b) relationship between the number of layers and heat transfer area on the cold side of the PFHE with concentration of CH_4

Fig. 1 compares the heat exchanger designs for two methane concentrations, 50% and 100%. Changes in gas composition affect geometry of heat exchanger.

Fig. 2 illustrates the impact of methane concentration on the design characteristics of the PFHE, specifically focusing on the number of layers and corresponding heat transfer area.

Fig. 2(a) shows the relationship between the number of layers and the heat transfer area on the hot side of the PFHE as the CH_4 concentration varies. As CH_4 concentration increases (implying a decrease in CO_2 content), the thermophysical properties of the gas mixture change, leading to variations in heat capacity and heat transfer coefficients.

Fig. 2(b) presents a similar trend for the cold side of the PFHE. Higher CH_4 concentrations require a larger surface area on the cold side to ensure sufficient heat removal and temperature drop in the hot stream.

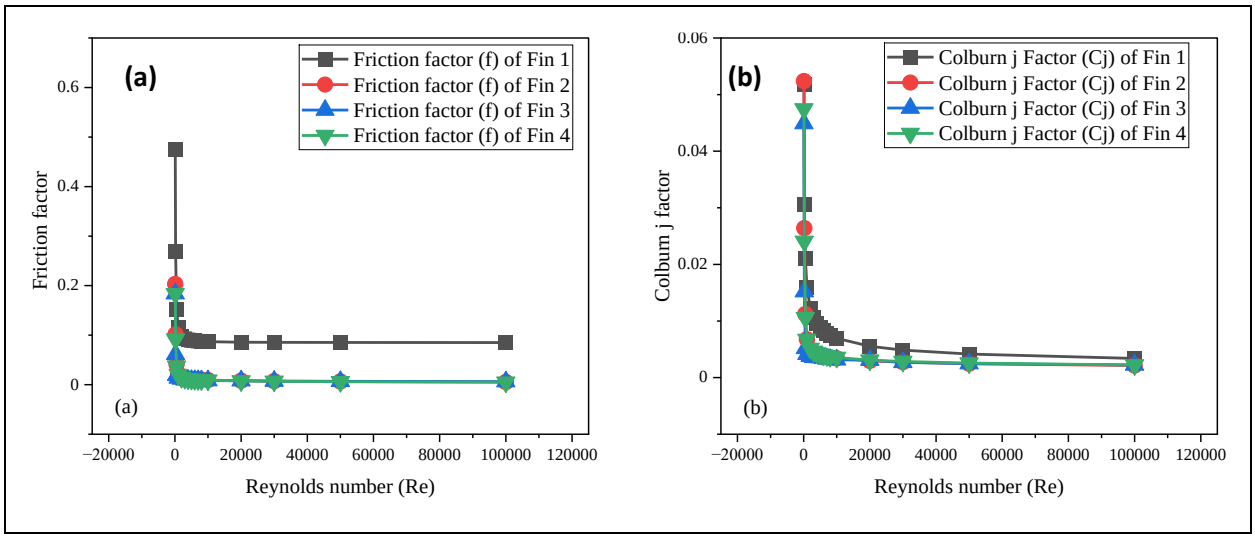


Fig. 3: (a) Variation of friction factor and Reynolds number and (b) variation of Colburn j-factor and Reynolds number

Fig. 3 illustrates the variation of key dimensionless parameters friction factor and Colburn j-factor with respect to the Reynolds number, which is a measure of flow regime (laminar, transitional, or turbulent) within the PFHE. Fig. 3(a) shows the variation of the friction factor with Reynolds number. As observed, the friction factor decreases with increasing Reynolds number. This trend is typical in compact heat exchangers, particularly in laminar and transitional flow regimes. At lower Reynolds numbers, viscous forces dominate, leading to higher resistance to flow and thus higher friction factor. As the flow rate increases, inertial forces

become more significant, reducing the relative contribution of viscous effects, and hence, the friction factor declines. This behavior is crucial for estimating pressure drop and optimizing the design for energy efficiency.

Fig. 3(b) presents the variation of the Colburn j-factor with Reynolds number. The j-factor also decreases with increasing Reynolds number, which is consistent with established correlations for compact heat exchangers. The Colburn j-factor represents the convective heat transfer capability normalized to fluid velocity and properties. At lower Reynolds numbers, enhanced mixing due to laminar flow and fin effects results in relatively higher j-factor values. As the Reynolds number increases, although absolute heat transfer may rise, the normalized efficiency (j-factor) tends to decline due to diminishing relative enhancement.

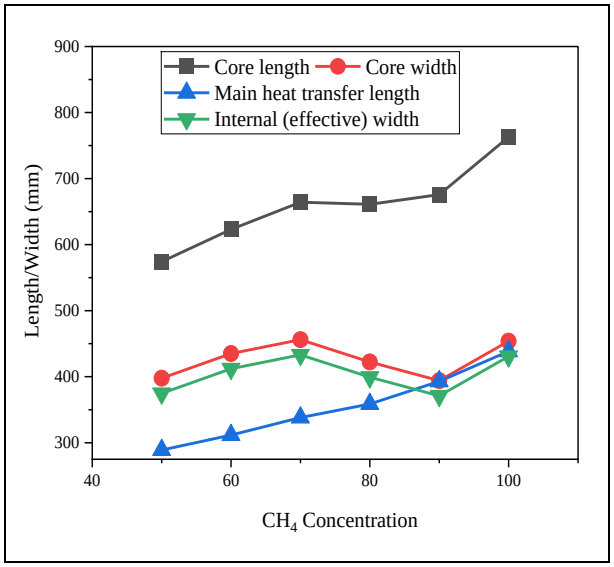


Fig. 4: Variations of dimensions of PFHE with CH_4 concentration

Fig. 4 illustrates the key dimensions of the PFHE, including core length, core width, main heat transfer length, and internal effective width. These geometric parameters are critical to the overall thermal and hydraulic performance of the heat exchanger.

As the methane concentration increases, all these dimensions show a corresponding increase. This trend is primarily due to the change in the thermophysical properties of the biogas mixture. With higher CH_4 content, the gas mixture has lower density and specific heat compared to CO_2-rich compositions. Consequently, a larger heat transfer surface area is required to achieve the same cooling duty and outlet temperature in the hot stream.

The core length and main heat transfer length increase to provide sufficient residence time and heat transfer surface area for effective cooling of the hot stream.

The core width and internal effective width expand to accommodate more flow passages or layers, enabling better heat distribution and lower pressure drop across the heat exchanger.

This dimensional scaling ensures that the PFHE can maintain high thermal effectiveness despite variations in feed gas composition. The increase in geometric size is a necessary design adjustment to handle the reduced heat transfer capability of CH_4-rich biogas, ensuring consistent performance in the cryogenic CO_2 removal process.

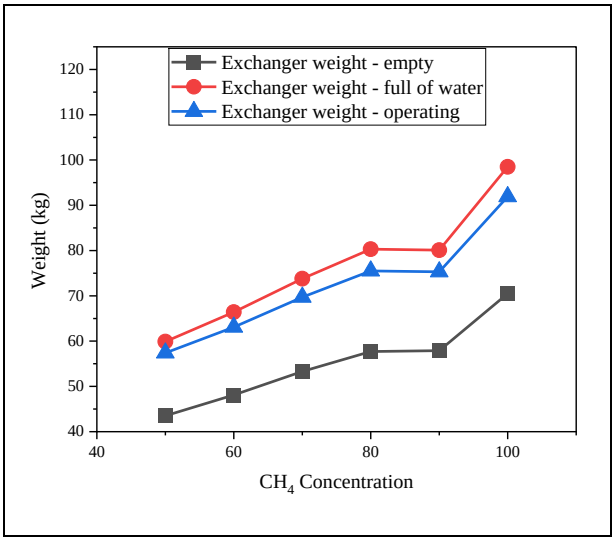


Fig. 5: Variations of weight of PFHE with CH_4 concentration

Fig. 5 illustrates the variation in the weight of the PFHE with respect to increasing methane concentration in the feed biogas stream. The figure clearly demonstrates that the weight of the PFHE increases progressively as the CH_4 concentration rises.

This trend is primarily attributed to the impact of CH_4 concentration on the thermal properties of the gas mixture and the resulting changes in heat exchanger design requirements. As the CH_4 concentration increases (i.e., CO_2 concentration decreases), the specific heat capacity and thermal conductivity of the biogas decrease, which reduces the ability of the gas to transfer heat efficiently.

To make up for the diminished heat transfer capacity, the PFHE must be reengineered with enlarged dimensions, encompassing an extended core length, width, and an augmented number of layers to enhance the heat transfer surface area. The increase in geometric dimensions directly leads to a rise in the overall material volume utilised for the heat exchanger, thus augmenting its entire weight.

Furthermore, the supplementary fins and flow channels required to sustain optimal thermal efficiency in CH_4-rich environments substantially augment the structural mass. This correlation underscores a vital design consideration: elevated CH_4 concentrations necessitate more durable and heavier heat exchangers to get equivalent cooling performance.

Comprehending this relationship is crucial for assessing the mechanical, structural, and economic ramifications of employing cryogenic PFHEs in biomethane upgrading applications, where feed composition can significantly fluctuate based on the source.

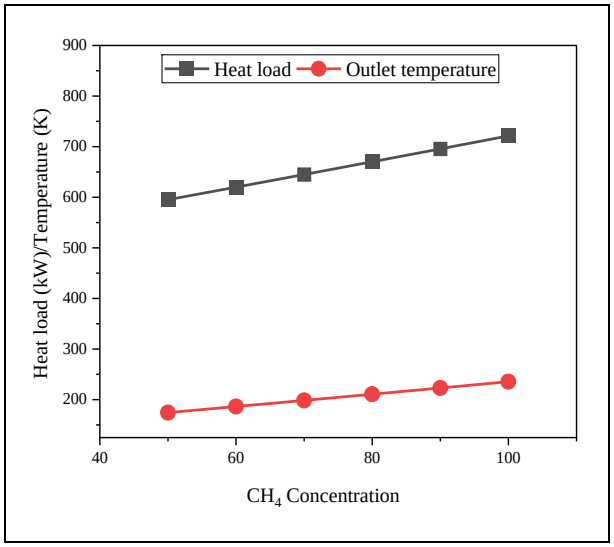


Fig. 6: Variation of heat load of PFHE and outlet temperature of cold fluid with CH_4 concentration

Fig. 6 illustrates the fluctuation of the heat load of the PFHE and the outlet temperature of the cold fluid in relation to the rising concentration of methane in the feed biogas mixture. The figure distinctly illustrates that both the thermal burden and the exit temperature of the cold stream escalate with increasing CH_4 concentration.

This behavior can be explained by examining the thermodynamic and heat transfer characteristics of the gas mixture. As CH_4 concentration increases and CO_2 concentration decreases, the overall specific heat capacity and thermal conductivity of the biogas are reduced. Consequently, to achieve the same cooling target (e.g., –123°C at the hot side outlet), the PFHE must handle a greater thermal duty, as more heat needs to be extracted to compensate for the reduced natural heat absorption capacity of the CH_4-rich mixture. This results in an increased heat load on the heat exchanger.

Simultaneously, the cold fluid (nitrogen) absorbs more heat from the hot stream, leading to a rise in its outlet temperature. Since the cold stream is designed to remove a larger amount of heat at higher CH_4 concentrations, its temperature increases more significantly as it exits the heat exchanger. This also indicates a more intensive heat exchange process within the PFHE to meet the performance requirements.

This trend highlights the importance of accurately predicting heat loads and outlet conditions for variable biogas compositions, ensuring that the PFHE design remains effective and reliable under different feed scenarios.

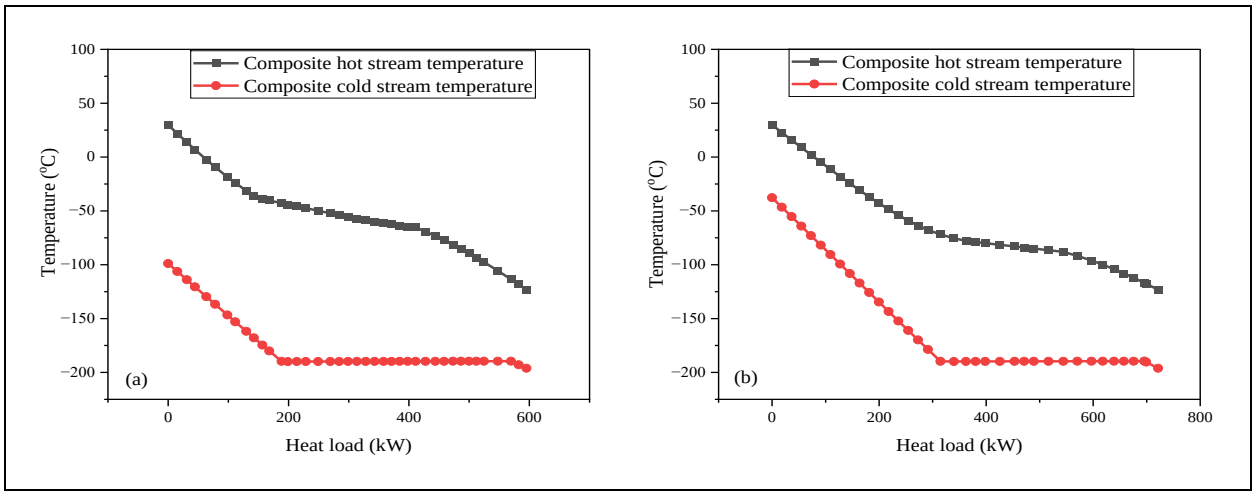


Fig. 7: Composite temperature heat (enthalpy) profile for two different methane concentrations: 50% CH_4 and 100% CH_4

Fig. 7 presents the composite temperature–enthalpy (heat) profile for two methane concentrations, 50% CH_4 and 100% CH_4. The curves illustrate the heat exchange between the hot and cold streams. A higher CH_4 concentration results in a larger temperature difference and shift in the heat capacity curve, indicating changes in thermal load and exchanger effectiveness due to the altered thermophysical properties of the gas mixture.

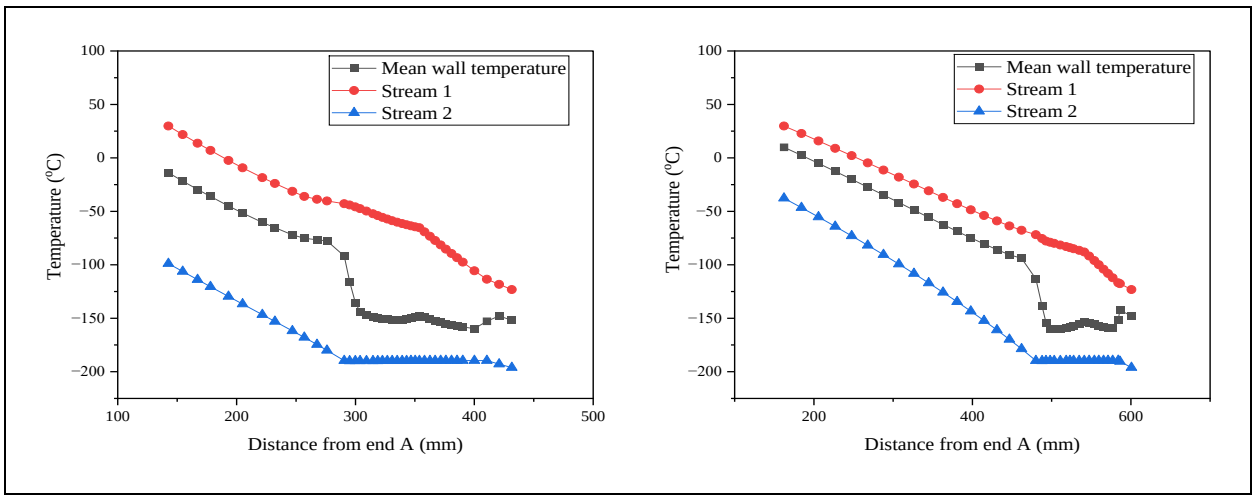


Fig. 8: Variation of hot stream, cold stream, and mean wall temperatures along the length of the heat exchanger (distance from end A) for two different methane concentrations: 50% CH_4 and 100% CH_4

Fig. 8 shows the temperature profiles of the hot stream, cold stream, and mean wall along the heat exchanger length from end A for the two methane concentrations. In both cases, the hot and cold streams flow in a counter-current configuration. As the distance from end A increases, the temperature of both streams decreases due to heat exchange. This trend is observed for both CH_4 concentrations, with higher CH_4 content slightly affecting the cooling rate due to its lower thermal properties. Table 2. Shows the comparison of work carried out by Alyaseen *et al*. (2023) with current Aspen EDR simulation.

Table 2. Comparison of work carried out by Alyaseen *et al.* (2023)

Stream	Air	Waste Nitrogen	Gaseous Oxygen	Low Pressure Nitrogen	High Pressure Nitrogen
Mass flow rate (kg/hr)	17258.6	10958.3	3432.8	1798.6	1001.1
Pressure (kPa)	678.3	121.6	135.2	128.4	544.5
Inlet temperature (K)	198.48	308.15	308.15	308.15	308.15
Outlet temperature	311.15	193.15	193.15	193.15	193.15
Heat transfer (kW) (Alyaseen *et al.* 2023)	553.82	360.82	100.11	59.23	33.66
Heat transfer (kW) (Current Result)	557.3	365.34	99.04	59.65	33.26

The simulation inputs are presented in Table 2. The experimental heat transfer results reported by Alyaseen *et al*. (2023) are compared with those obtained from the current simulation study. The comparison indicates that the discrepancy between the experimental and simulated results is minimal and within an acceptable margin of error.

4. CONCLUSION

This study examines the design and performance attributes of a PFHE employed for cryogenic CO_2 removal in biomethane upgrading, emphasising different amounts of methane. Key characteristics, including heat load, pressure drop, heat transfer area, and temperature profiles, were analysed for various gas compositions using Aspen EDR software. The results indicate that an increase in CH_4 concentration leads to a decline in thermal performance, attributed to reduced heat capacity and conductivity, necessitating greater dimensions and surface area of heat exchangers to sustain cooling efficiency. As a result, the weight and expense of the PFHE likewise escalate. Temperature profiles validate effective counter-flow functioning, whereas enthalpy-temperature profiles illustrate variations in thermal duty. The research highlights the necessity of accounting for biogas composition in PFHE design to guarantee maximum thermal performance and system efficiency. Aspen EDR demonstrated its utility as a sophisticated tool for comprehensive modelling, facilitating the creation of energy-efficient solutions for carbon capture in biomethane upgrading systems.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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