energies

Reply

Reply to Variny et al. Comment on "Hamayun et al. Evaluation of Two-Column Air Separation Processes Based on Exergy Analysis. *Energies* 2020, *13*, 6361"

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1. Introduction

This is a reply to the paper by Variny et al. [1] who have commented on our recently published work, "Evaluation of Two-Column Air Separation Processes Based on Exergy Analysis" [2].

We greatly appreciate the careful review carried out by Variny et al. [1] and their valuable feedback, which could prove helpful in future studies of air separation units. The comments of Variny et al. [1] are summarized in the following:

- Model assumptions as formulated in Hamayun et al. [2] are incomplete. The pressure drop in heat exchangers assuming a constant value of 10 kPa, regardless of the position in the process scheme is unjustified, similarly to assuming zero pressure losses.
- Hamayun et al. [2] omitted pressure losses in adsorbers. The issue of pressure loss in adsorbers is of serious concern and can be subject to optimization. It contributes to energy consumption of the air separation unit and should thus be considered.
- Adsorbers are modeled as component splitters, which assumption is over-simplified. The effect of water steam adsorption heat should be considered as it may reach up to 3000 to 4000 kJ/kg of adsorbed steam for conventional zeolites used in compressed air drying by adsorption. The resulting temperature increase in air passing through adsorbent layer can thus exceed 10 or even 20 °C depending on the water steam content in the inlet air which, in turn, impacts the equipment downstream.
- The energy consumption evaluation is incomplete as it does not incorporate energy needed for adsorber regeneration. As mentioned above, significant amount of heat is released by steam adsorption on adsorbent and thus its regeneration is energy intense and contributes to the overall energy consumption of the air separation plant. Heat recuperation is often proposed to cut down the adsorbent regeneration cost which, however, adds another complexity to the plant.
- Moist air cooling in multi-stream heat exchanger directly to –100 °C and below after its intake from ambient environment as depicted in process scheme C7 is technically infeasible. It would lead to ice formation and air path blockage, possibly followed by heat exchanger damage.
- The importance of using a proper thermodynamic package should be addressed. Peng–Robinson equation is recommended for applications comprising nonpolar gases and vapors, which holds true for nitrogen and oxygen, or dry air but certainly not for water steam.

2. Our Replies

At the outset, we would like to re-emphasize the scope of our study by quoting from our published work [2]:

"This work focuses on the selection of suitable cryogenic air separation process by evaluating seven alternative designs of the two-column air separation process based on detailed exergy analysis. The feed conditions (500 tons/h, and 50% relative humidity of air), product purities (99 mole% for both nitrogen and oxygen), and operational conditions (pressures of both distillation columns) are kept same in all designs."

And also:

"The main objective of this work is to identify the most suitable two-column ASU configuration by evaluating these seven alternatives based on exergy analysis. To allow a fair comparison, the feed conditions, product purities, and operational conditions are kept same in all designs."

It should be clear that our study can be described as a constrained topological optimization of the number and order of equipment in the process, but not as a parametric optimization of the process conditions in individual pieces of equipment. This is fully qualified for an early-stage design exercise, where the prime objective should be to quickly develop a ranking of the process alternatives and to be able to reject as many alternatives as reliably possible, and as soon as sufficient information for such rejection becomes available. The cycle is then repeated with increased depth of analysis and the ranking of process alternatives is revised, but for fewer candidates. This is not to say that the "other" parameters are not important. On the contrary, they enter the design process as constraints, which are then gradually relaxed in the next design cycles. For each variable at each design cycle, we thus ask two questions: (1) Is the impact of this variable large enough to affect the ranking of process alternatives? And (2) Is the computational effort (depending upon the number of candidate solutions as well as the complexity of this variable's impact on the overall process) justified to remove the constraint? We argue that if the answer to these questions is negative, the variable in question can be treated as a constraint, at least at the current design stage.

2.1. Pressure Drop in Heat Exchangers

The assumption of no pressure drop or fixed pressure drop in heat exchangers is already reported in the literature for air separation processes [3–5]. If we used more rigorous equations for pressure drop calculations in heat exchangers, e.g., those proposed by Variny et al. [1], the pressure drop would indeed be different for different exchangers in different configurations. This would also give rise to apparent performance differences between different exchangers, their importance being proportional to their magnitudes. After this detailed exercise on all exchangers in all configurations, we could possibly find that the impact of this constraint is about the same order of magnitude as the impact of assuming constant heat transfer coefficient for all exchangers. Of course, it is possible to remove these constraints and instead develop rigorous designs for all exchangers in all configurations. The question is, will the resulting gain be substantial enough to alter the ranking of alternative configurations? The answer is no.

2.2. Pressure Drop and Energy Consumption in Adsorbers

The air separation process can be effectively split into two sections: (1) the compression section, and (2) the cryogenic section. The adsorbers would then be the last unit operations in the compression section before the air is sent to the cryogenic section. Because the pressures of the two cryogenic distillation columns are fixed, the compression and the cryogenic sections are fully independent of each other. If pressure drop in adsorbers is to be accounted for, an equivalent higher pressure must be developed in the compressors. In other words, the only impact of pressure drop consideration in adsorbers would be an increase in the discharge pressure and hence the mechanical work of compressors. Because the condition of air at both the inlet of the compression section (i.e., 50% relative humidity) and the exit of the compression section (i.e., no moisture and carbon dioxide) is kept the same in all configurations, the effective load on adsorbers is essentially same. This means that the adsorbers are similarly sized in all configurations, produce similar pressure drop, and require similar energy for their regeneration. In short, this consideration would change the absolute values of total energy consumption in different configurations, as correctly pointed out by Variny et al. [1], but would not alter their relative order.

Secondly, to the best of our knowledge, a rigorous adsorber model is not directly available in Aspen Plus® and the proposed exercise will need an integration of Aspen Plus® with Aspen Adsorption® or Aspen Custom Modeler®. As already explained, such undertaking is justified only at an advanced design stage and is outside the scope of our work.

2.3. Formation of Ice and Air Path Blockage

We are thankful to Variny et al. [1] for highlighting this issue. In configurations C1–C6 as reported in our published work [2], adsorbers precede multi-stream heat exchangers, and it is safe to assume that the air entering the cryogenic section has negligible moisture content. However, in configuration C7 as reported in our published work [2], a multi-stream heat exchanger precedes adsorbers, thus exposing it to incoming air with high relative humidity. When cooled to cryogenic temperatures, this could indeed result in ice formation and cause damage to the equipment. This can be resolved by moving the adsorbers before the multi-stream heat exchanger as shown in Figure 1. Steady-state simulation results (Table 1) show that the effect of this rearrangement remains confined to the compression section and the first multi-stream heat exchanger. The total exergy destruction in the revised configuration C7r (Figure 1) is 35.95 MW, compared to the previously reported 36.04 MW, and does not affect the relative rank of this configuration.

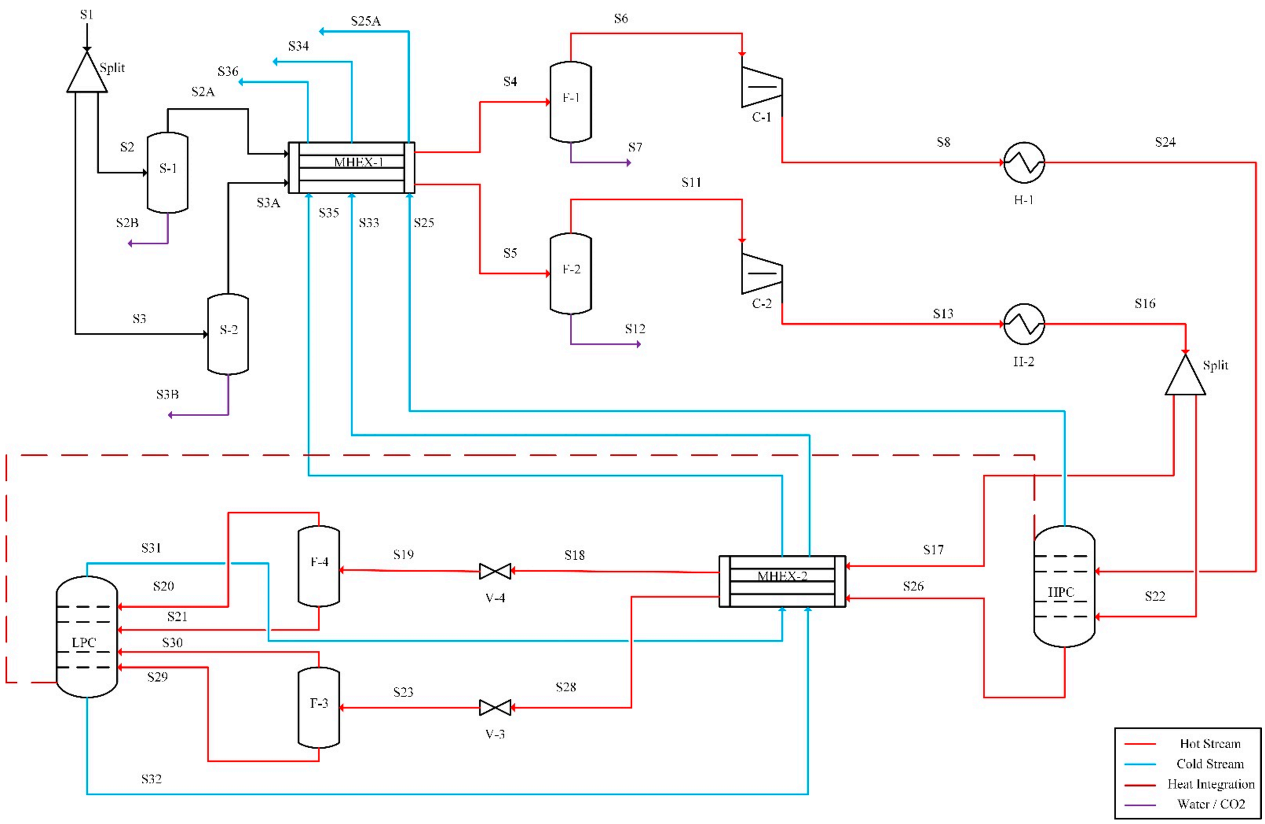

Figure 1. Process flow diagram of the revised ASU configuration C7r.

Table 1. Steady-state simulation results for the revised ASU configuration C7r.

Stream	Temp °C	Pressure Bar	Flow Tons/h	Composition N_2	O_2	Ar	H_2O	CO_2
S1	25.0	1.0	500.0	0.77	0.21	0.01	0.02	0.00
S2	25.0	1.0	350.0	0.77	0.21	0.01	0.02	0.00
S2A	25.0	1.0	346.4	0.78	0.21	0.01	0.00	0.00
S2B	25.0	1.0	3.6	0.00	0.00	0.00	0.98	0.02
S3	25.0	1.0	150.0	0.77	0.21	0.01	0.02	0.00
S3A	25.0	1.0	148.5	0.78	0.21	0.01	0.00	0.00
S3B	25.0	1.0	1.5	0.00	0.00	0.00	0.98	0.02
S4	−160.0	1.0	346.4	0.78	0.21	0.01	0.00	0.00
S5	−99.6	1.0	148.5	0.78	0.21	0.01	0.00	0.00
S6	−160.0	1.0	346.4	0.78	0.21	0.01	0.00	0.00
S7	0.0	1.0	0.0	0.00	0.00	0.00	0.00	0.00
S8	−58.2	5.8	346.4	0.78	0.21	0.01	0.00	0.00
S11	−99.6	1.0	148.5	0.78	0.21	0.01	0.00	0.00
S12	0.0	1.0	0.0	0.00	0.00	0.00	0.00	0.00
S13	56.4	5.8	148.5	0.78	0.21	0.01	0.00	0.00
S16	−167.3	5.8	148.5	0.78	0.21	0.01	0.00	0.00
S17	−167.3	5.8	108.4	0.78	0.21	0.01	0.00	0.00
S18	−173.4	5.8	108.4	0.78	0.21	0.01	0.00	0.00
S19	−188.4	1.5	108.4	0.78	0.21	0.01	0.00	0.00
S20	−188.4	1.5	97.2	0.81	0.18	0.01	0.00	0.00
S21	−188.4	1.5	11.2	0.55	0.44	0.01	0.00	0.00
S22	−167.3	5.8	40.1	0.78	0.21	0.01	0.00	0.00
S23	−190.4	1.5	380.4	0.78	0.21	0.01	0.00	0.00
S24	−168.0	5.8	346.4	0.78	0.21	0.01	0.00	0.00
S25	−177.6	5.6	6.1	1.00	0.00	0.00	0.00	0.00
S25A	−8.8	5.5	6.1	1.00	0.00	0.00	0.00	0.00
S26	−175.0	5.8	380.4	0.78	0.21	0.01	0.00	0.00
S28	−180.0	5.7	380.4	0.78	0.21	0.01	0.00	0.00
S29	−190.4	1.5	340.4	0.76	0.23	0.01	0.00	0.00
S30	−190.4	1.5	40.0	0.92	0.08	0.00	0.00	0.00
S31	−192.2	1.2	413.1	0.90	0.09	0.01	0.00	0.00
S32	−179.6	1.5	75.8	0.00	0.99	0.01	0.00	0.00
S33	−178.0	1.4	75.8	0.00	0.99	0.01	0.00	0.00
S34	−8.8	1.3	75.8	0.00	0.99	0.01	0.00	0.00
S35	−174.5	1.1	413.1	0.90	0.09	0.01	0.00	0.00
S36	−8.8	1.0	413.1	0.90	0.09	0.01	0.00	0.00
PURGE	−191.7	1.5	0.00	0.90	0.09	0.01	0.00	0.00

2.4. Use of HYSYS-PR Property Package

The superiority of the HYSYS-PR property package over the standard Peng–Robinson property package is debatable. Using a subset of carefully selected properties, one can show that HYSYS-PR is a better property package for a given application and vice versa. Furthermore, we emphasize that (1) use of Peng–Robinson property package for modeling air separation processes has been widely reported in the literature [4,6–10], and (2) HYSYS-PR is a proprietary property package available only for AspenTech products, e.g., Aspen HYSYS® and Aspen Plus®, and it will be difficult to reproduce those results using other process simulation software.

3. Conclusions

In general, we agree that the comments by Variny et al. [1] are useful for advanced studies on air separation processes. However, the effects of these variables are mostly of secondary nature and considering the need to balance computational costs with the number of design alternatives being evaluated, especially during early-stage design studies, their rigorous treatment is not necessary.

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