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A Novel Process Design for Waste Respirator Processing

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Abstract

The ongoing COVID-19 pandemic increases the consumption of respirators. In this work, we propose a novel and effective waste respirator processing system that aims to protect public health and mitigate climate change. Respirator sterilization and pre-processing technologies are incorporated simultaneously to resist viral infection and facilitate unit processes for manufacturing and separating products, so the greenhouse gas (GHG) emission can be reduced via carbon reallocation from CO₂ to downstream products. High-fidelity process simulations are performed to extract detailed life cycle inventories used for evaluating environmental performance. Results reveal the economic viability in terms of the payback time (seven years) and the internal rate of return (21.5%). The proposed waste respirator processing system reduces GHG emissions by 59.08% compared to incineration, which reflects the potential of climate change mitigation.

Keywords: waste respirator processing, COVID-19, process design and integration.

1. Introduction

The U.S. has been trapped in the COVID-19 pandemic with no shutdown in sight. During the COVID-19 pandemic, people consume massive respirators to stem coronavirus infection, which substantially triggers the usage and disposal of respirators across the U.S (Bartoszko et al., 2020). Notably, the virus will transmit among the public if massive discarded respirators are mismanaged. In this regard, we apply the incineration process to treat these waste respirators in typical medical waste disposal sites (Nzediegwu and Chang, 2020). However, a large amount of greenhouse gases (GHGs) are emitted when incinerating respirators, which give rise to serious climate change (Klemeš et al., 2020). Even worse, the mixed-plastic component within discarded respirators can be decomposed into toxic chemicals (Bora et al., 2020), which are then digested by organics and accumulated in the food-web (Heward, 2018). In these regards, we currently call for a novel and effective waste respirator processing system to reduce the risk of viral infection and GHG emissions when fighting for the COVID-19 pandemic.

To fill in this current knowledge gap, we develop and propose a waste respirator processing system, which incorporates respirator sterilization and pre-processing technology to protect the public health and for manufacturing and separating products, so the greenhouse gas (GHG) emission can be reduced via carbon reallocation from CO₂ to downstream products. We consider seven sections in the processing system, namely respirator pre-processing, pyrolysis, light hydrocarbon separation, CO₂ separation, hydrogenation, hydrogen production, and onsite combustion. A commercially available sterilization process, which can shred, sterilize, and dehydrate the waste N95 respirators, is included in this system to disinfect respirators and triggers the thermal-cracking process

in the pyrolysis section (Nutsch and Spire, 2004) similar to plastics processing (Zhao and You, 2021). We apply a detailed life cycle assessment (LCA) approach to systematically quantify the GHG emissions from cradle-to-gate so that the potential in mitigating climate change can be evaluated. Specifically, high-fidelity process simulations of the waste respirator processing system integrated with the data from Ecoinvent V3.6 are used for extracting the detailed life cycle inventory. Techno-economic analysis (TEA) is also conducted to evaluate the economic viability by calculating the capital and operating expenses. We demonstrate the economic feasibility of establishing respirator processing systems and their potential for climate change mitigation through evaluating a proposed respirator processing system, which aims to treat 582 million waste N95 respirators that are corresponding to the HHS's recommended annual production amount in eight northeastern states in the U.S. (NY Times, 2020), namely New York, New Jersey, Pennsylvania, Massachusetts, New Hampshire, Vermont, Rhode Island, and Connecticut.

2. Process Description for the Waste Respirator Processing System

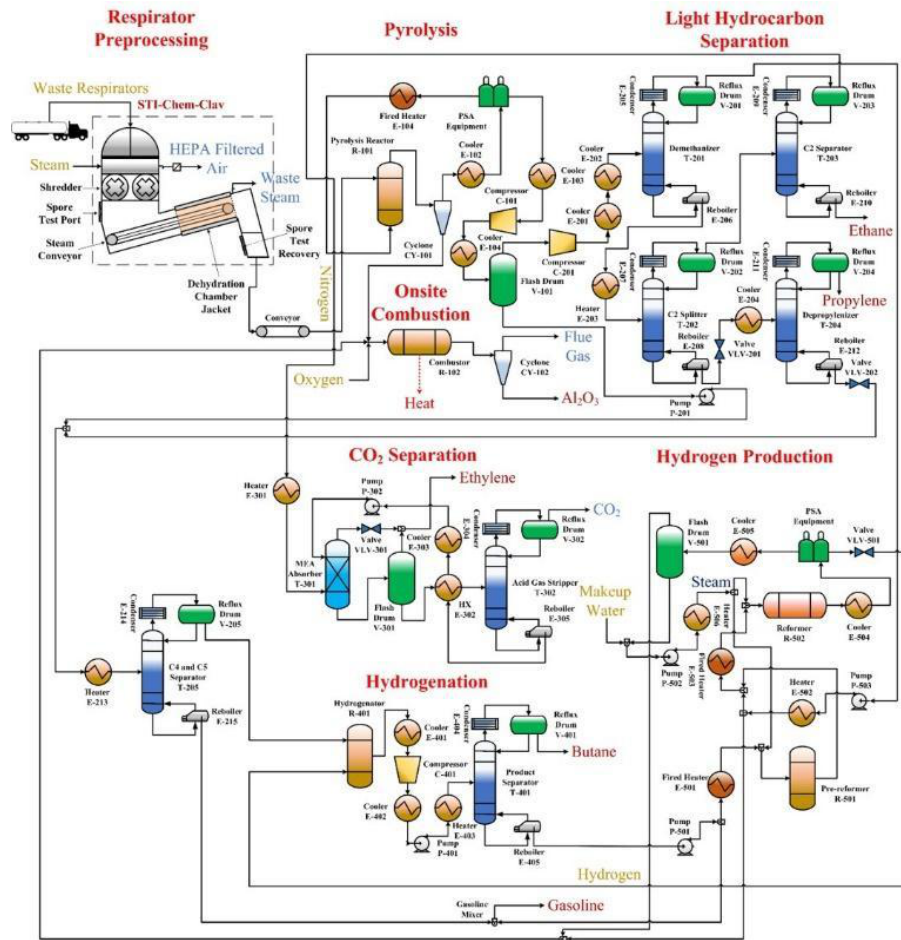


Figure 1. Process flowsheet of the proposed waste respirator processing system.

In this work, we develop and propose a novel and effective waste respirator processing system. As shown in Figure 1, the processing system integrates seven sections, namely respirator preprocessing, pyrolysis, light hydrocarbon separation, CO₂ separation, hydrogenation, hydrogen production, and onsite combustion. Detailed description of the whole processing system is shown as follows.

The whole process starts with the respirator preprocessing section, where the transported waste respirator can be shredded, sterilized, and dehydrated by steam (147.7°C, 44.61 bar) simultaneously. Notably, this section can effectively deactivate the coronavirus under the sterilization condition (95–120°C) (Nutsch and Spire, 2004). With the usage of nitrogen gas as the inert fluidized gas, the disinfected respirator particles are then thermally cracked into various inorganic and hydrocarbon chemicals in a fluidized bed pyrolyzer. The nitrogen gas is split by a pressure-swing adsorption (PSA) unit and circulated in this section. The volatile stream is then split into streams with light and heavy components in a flash tank, while the stream with char is sent to the onsite combustion section to generate high-temperature heating energy. In the light hydrocarbon separation section, the stream with light components is split into methane, ethane, ethylene, and propylene products. Notably, the methane stream is directly sent to hydrogen production or onsite combustion sections (Yang et al., 2018), while the stream with ethylene is fed into the CO₂ separation section to separate CO₂ from ethylene products. In the C₄ and C₅ Separator (He et al., 2015), the overhead liquid with C₄ components is sent to the hydrogenation section to produce butane product, while the raffinate is fed into a gasoline mixer or used for producing hydrogen (Gong et al., 2017).

Specifically, we apply NiMo catalyst (Swanson et al., 2010) in the hydrogenator to convert C₄ components into butane in the hydrogenation section. To satisfy the usage of hydrogen in this section, a hydrogen production section is implemented within the waste respirator processing system. Notably, the partial raffinate stream from the hydrogenation section is mixed with steam and produces lighter components in the pre-reformer to trigger the steam-methane reforming reaction in the downstream reformer. In the reformer, the steam is mixed with streams of methane and CO from the light hydrocarbon separation section and the mixture is converted into hydrogen following the kinetic of steam-methane reforming reaction (He et al., 2016). The hydrogen stream is separated from the PSA unit and sent to the hydrogenation section, while the steam is regenerated via pressurizing and heating the mixture of the makeup water stream and pre-cooled water stream from the flash tank. The remaining gaseous stream from the flash tank is mixed with oxygen, char, and gaseous chemical components, such as methane, and sent to the combustor to be ignited under 1000°C. The high-temperature heating energy is released from the combustor, while the solid stream (mainly Al₂O₃) is sold.

3. LCA and TEA Methodology

3.1. LCA Methodology

In this work, we apply the LCA methodology to systematically evaluate the potential of climate change mitigation via quantifying the GHG emissions from the waste respirator processing system, so the goal of this LCA is defined. Five life cycle stages, namely waste respirator transportation, waste respirator processing, offsite heating utilities production, offsite electricity production, and offsite production for inlet material, are confined by the system boundary from cradle-to-gate, as shown in Figure 2. We choose the functional unit as one thousand respirators treated within the waste HDPE processing system.

We compile the detailed life cycle inventories (LCIs) based on the mass and energy balances throughout these five life-cycle stages, of which data are extracted with the help of combining high-fidelity Aspen-Plus-based process simulations and Ecoinvent V3.6 Database. In the process simulation, we assume the chemical composition of pyrolysis products as the weighted average of chemical composition for pyrolyzing each single plastic compound (Westerhout et al., 1998).

We apply the global warming potential over the course of 100 years (GWP_{100}) to quantify the greenhouse impacts relative to that of CO_2 and thus evaluate the potential of climate change mitigation. Specifically, the GWP_{100} of methane is 28 due to the same greenhouse impacts of emitting 1 kg of methane and those of 28 kg CO_2 over the course of 100 years (Hartmann et al., 2003). The GHG emissions of each life cycle stage are quantified in this work and the results are shown as GHG emissions breakdowns.

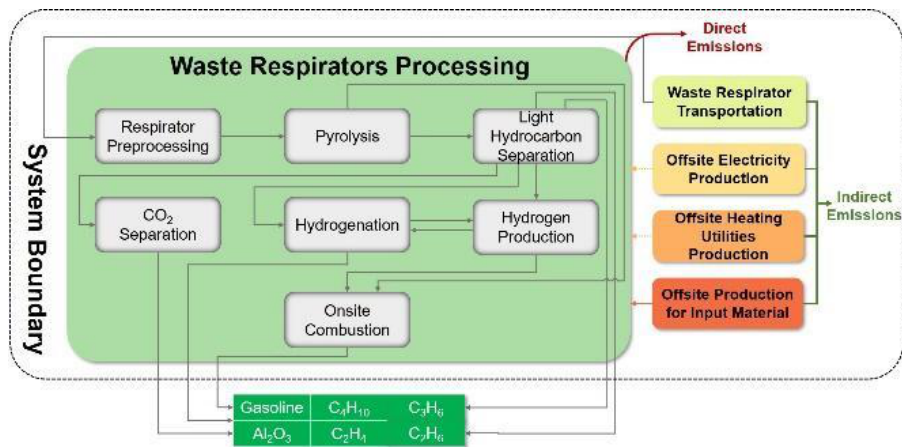


Figure 2. System boundary of a cradle-to-gate LCA for the waste respirator processing system.

3.2. TEA Methodology

We consider the capital expenditure (CAPEX) and operating expenditure (OPEX) to evaluate the economic viability of establishing the respirator processing system in terms of the net present value (NPV), payback year, and internal rate of return (IRR). CAPEX includes the direct capital, indirect capital, working capital of all equipment units, and the land cost used for setting up the processing system (Gong and You, 2018). OPEX includes the cost of transporting waste respirators, feedstock cost, utility cost, cost of operations and maintenance (O&M), property tax and insurance (PT&I), general expense, and income tax. The linear depreciation method is adopted to calculate the depreciation cost. Notably, the net present value (NPV) is calculated via subtracting the CAPEX from the summation of annualized cash flow in each operating year. The direct capital costs are extracted from Aspen-Plus Capital Cost Estimator.

4. Results and Discussion

4.1. TEA Results of the Waste Respirator Processing System

We present the breakdowns of CAPEX and OPEX of establishing the waste respirator processing system (near Citiwaste Medical Waste Disposal) in Figure 3. Notably, the total capital investment (\$16.31 million) is the major contributor to the total expenses, which

is further broken down into four categories, namely the total installation cost, total indirect capital, land cost, and working capital. The income tax is another major contributor (\$14.14 million), so that the high profitability of the waste respirator processing system is demonstrated. Specifically, the high indirect capital (\$5.82 million) is owing to the high costs for the procurement and installation of various equipment units and reactors (\$9.71 million). Owing to various distillation units and the refrigeration cycle to maintain cryogenic conditions when separating methane, the installed cost of the light hydrocarbon separation section (\$3.21 million) mainly contributes to the total installation cost, as shown in Figure 3. The installed costs for other sections are also shown in Figure 3.

The feasibility of establishing the waste respirator processing system can be illustrated in terms of the payback time of seven years, and an IRR of 21.5%. This high economic performance is mainly contributed by the various products converted from waste respirators, as well as the heat integration that minimizes the utility usage.

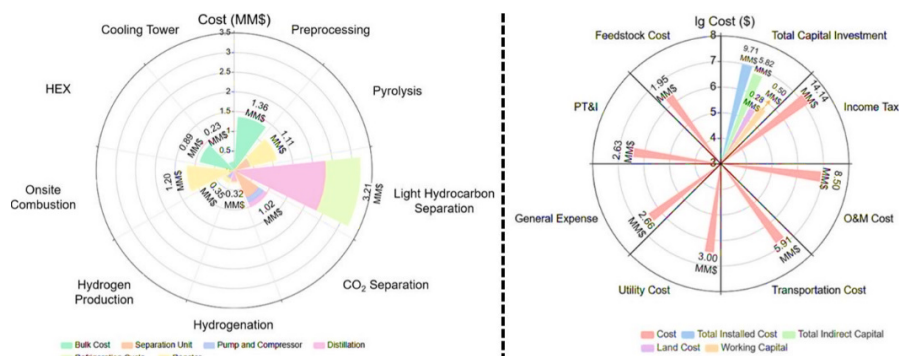


Figure 3. CAPEX, OPEX, and installed cost breakdowns.

4.2. LCA Results of the Waste Respirator Processing System

The direct emissions from the offsite combustion section and indirect emissions share 56% and 44% of total emissions, respectively. The indirect emissions can be further broken down and the major contributor to the indirect emissions is from the offsite production for inlet material (56% of indirect emissions). Moreover, GHG emissions from the offsite production of steam contribute most emissions (91.11%) among the offsite production for inlet materials, which due to the massive usage of steam in the sterilization system. Specifically, the unit GHG emissions of the respirator processing system is 12.93 kg CO₂-eq/thousand respirators, which reduces by 59.08% compared to the incineration-based system (31.60 kg CO₂-eq per thousand respirators). Hence, it is viable to establish a respirator processing system with high economic profitability and the potential to mitigate climate change.

5. Conclusion

In this work, we developed and proposed a novel and effective waste respirator processing system to protect public health and mitigate climate change. The waste respirator processing system included seven sections to convert waste respirators into various products. TEA results deciphered the economic viability for setting up the waste respirator processing system in terms of the payback time of seven years with an IRR of

21.5%. LCA results illustrated the potential of climate change mitigation by showing a reduction of GHG emissions by 59.08% compared to the incineration-based system.

References

- J. J. Bartoszko, M. Farooqi, W. Alhazzani, M. Loeb, 2020, Medical masks vs N95 respirators for preventing COVID-19 in healthcare workers. *Influenza and other respiratory viruses*, 14, 365.
- R. R. Bora, R. Wang, F. You, 2020, Waste Polypropylene Plastic Recycling toward Climate Change Mitigation and Circular Economy: Energy, Environmental, and Technoeconomic Perspectives. *ACS Sustainable Chemistry & Engineering*, 8, 16350-16363.
- J. Gong, F. You, 2015, Sustainable design and synthesis of energy systems. *Current Opinion in Chemical Engineering*, 10, 77-86.
- J. Gong, M. Yang, F. You, 2017, A systematic simulation-based process intensification method for shale gas processing and NGLs recovery process systems under uncertain feedstock compositions. *Computers & Chemical Engineering*, 105, 259-275.
- J. Gong and F. You, 2018, A new superstructure optimization paradigm for process synthesis with product distribution optimization: Application to an integrated shale gas processing and chemical manufacturing process. *AIChE Journal*, 64(1), 123-143.
- A. Nutsch and M. Spire, 2004. Carcass disposal: a comprehensive review. National Agricultural Biosecurity Center, Kansas State University, Manhattan, KS.
- D. Hartmann, A. Tank, and M. Rusticucci, 2013. IPCC fifth assessment report, climate change 2013: The physical science basis. *Ipcc Ar5*, 5, 31-39.
- J. J. Klemeš, Y. Fan, R. R. Tan, P. Jiang, 2020. Minimising the present and future plastic waste related to COVID-19. *Renewable and Sustainable Energy Reviews*, 127, 109883.
- M. Haward, 2018. Plastic pollution of the world's seas and oceans as a contemporary challenge in ocean governance. *Nature Communications*, 9, 667.
- C. He, F. You, 2014, Shale Gas Processing Integrated with Ethylene Production: Novel Process Designs, Exergy Analysis, and Techno-Economic Analysis. *Industrial & Engineering Chemistry Research*, 53, 11442-11459.
- C. He, F. You, 2016, Deciphering the true life cycle environmental impacts and costs of the megascale shale gas-to-olefins projects in the United States. *Energy & Environmental Science*, 9, 820-840.
- NYS Government, Apr. 2020. Continuing Temporary Suspension and Modification of Laws Relating to the Disaster Emergency.
- C. Nzediegwu, S. X. Chang, 2020. Improper solid waste management increases potential for COVID-19 spread in developing countries. *Resour Conserv Recycl*, 161, 104947-104947.
- NYT, Mar. 2020. Some Hospitals Are Close to Running Out of Crucial Masks for Coronavirus. <https://www.nytimes.com/2020/03/09/health/coronavirus-n95-face-masks.html>
- R. M. Swanson, A. Platon, J. A. Satrio, R. C. Brown, and D. D. Hsu, 2010. Techno-Economic Analysis of Biofuels Production Based on Gasification. National Renewable Energy Lab, Golden, CO (United States).
- R. W. J. Westerhout, M. P. Van Koningsbruggen, A. G. Van Der Ham, J. A. M. Kuipers, and W. P. M. Van Swaaij, 1998. Techno-economic evaluation of high temperature pyrolysis processes for mixed plastic waste. *Chemical Engineering Research and Design*, 76(3), 427-439.
- M. Yang, X. Tian, F. You, 2018, Manufacturing Ethylene from Wet Shale Gas and Biomass: Comparative Technoeconomic Analysis and Environmental Life Cycle Assessment. *Industrial & Engineering Chemistry Research*, 57, 5980-5998.
- M. Yang, F. You, 2018, Modular methanol manufacturing from shale gas: Techno-economic and environmental analyses of conventional large-scale production versus small-scale distributed, modular processing. *AIChE Journal*, 64, 495-510.
- X. Zhao, F. You, 2021, Waste high-density polyethylene recycling process systems for mitigating plastic pollution through a sustainable design and synthesis paradigm. *AIChE Journal*, 67, e17127.