

Design of wastewater treatment plant for the removal of phenol using CHEMCAD® process simulator

R W Gaikwad^{1#*}, Hemant Sadafale^{2#}, Vikas S Hakke^{3#}, Shirish H Sonawane^{3#} & A R Warade^{2#}

¹Chemical Engineering Department, Jawaharlal Nehru Engineering College, Aurangabad 431001 (MS), India

²Chemical Engineering Department, Pravara Rural Engineering College, Loni 413736 (MS), India

³Chemical Engineering Department, National Institute of Technology Warangal 506004 (TS), India

*E-mail:rwgaikwad1@gmail.com

Received 10 July 2023; accepted 09 July 2024

Wastewater containing phenol is produced in lots of the steel industry's coking provisions. A usual concentration for phenol in the coke ovens effluent water is 600–3900 mg/L. Before this water can be discharged to the environment, the phenol concentration has to be reduced to 1 mg/L. Extraction using supercritical CO₂, is one of the method for removal of phenol from wastewater. This method has to be economically competitive with the alternatives. These replacement consist of biological processes, moist air oxidation (supercritical water oxidation), and incineration. Process simulation has been widely utilized in recent times to plan, assess or improve processes, systems and particular operations of the chemical manufacturing and its allied branches. Presently, CHEMCAD® is a highly operated process simulators since the large number of chemical and petrochemical processes that can be simulated. The simulation of the wastewater treatment plant for the removal of phenol using process simulator is accomplished by utilizing the process simulator CHEMCAD® version 5.1.0. It is observed that the proposed simulation plant actually reduced the effluent characteristics down to the CPCB of India's limitations.

Keywords: CHEMCAD, Design, Phenol removal, Simulation, Wastewater treatment plant

Introduction

The industrial sector's need for water has grown significantly over the past few decades, leading to the exploitation of water resources to meet demand¹. The iron and steel industry are the foundation of economic development and progress in developing nations like China and India.

Steel industry is one of the major industry which carries phenol in the wastewater streams. In India, there are seven integrated iron and steel factories, five of which are owned by the Steel Authority of India Limited (SAIL), one of which is in the private sector, and one of which is the Visakhapatnam Steel Project in Visakhapatnam. India contributes 14.05 million tones of the 715.4 million tons of steel produced annually. For every ton of steel produced, several process stages must be completed, requiring 25 to 60 cubic meters of water and 4 to 5 tons of raw materials. In contrast to India's 25 to 60 cubic meters, other nations' water usage ranges from 3 to 6 cubic meters^{2,3}. Plant wise water use is shown in Table 1.

The wastewater produced by the coke oven by product (COBP) plant is thought to be the most polluted stream in an integrated iron and steel industry⁴. The typical pollutants found in coking wastewater include phenol, SCN⁻, CN⁻, oil and grease, ammoniacal nitrogen, and COD^{5,6}. When discharged off to public sewers, rivers, or surface water, the occurrence of phenolic chemicals, even at small quantities, has a negative impact on environmental as well as living beings. The European Union (EU) and the United States Environmental Protection Agency (USEPA) have designated phenolic compounds as pollutants of primary concern. Due to the fact that these

Table 1 — Water used (cumulative) for each ton of steel produced

Name of Steel Plant	Consumption of water per ton of steel produced (m ³)
Rourkela (SAIL)	68
Bhilai (SAIL)	32
Bokaro (SAIL)	57
Durgapur (SAIL)	47
IISCO, Burnpur (SAIL)	42
TISCO Jamshedpur	25
Vizag Steel (Rastriya Plant Ispat Nigam)	28

[#]These authors contributed equally

Table 2 — Wastewater discharge standards at an integrated iron and steel Plant (Source: Central Pollution Control Board; cpcb.nic.in)

Sl. No.	Coke oven byproduct plant parameter (mg/L)	Concentration (mg/L) except pH (Not to exceeded)
1	pH	6-8.5
2	Suspended solids	100
3	Phenol	1
4	Cyanide	0.2
5	BOD, 3 day 27°C	30
6	COD	250
7	Ammonia Nitrogen	50
8	Oil & grease	10

compounds are known to be hazardous and to have negative short and long term impacts on both humans and animals, this enlistment is necessary⁷. When released untreated, this wastewater contains toxic compounds like phenol, cyanide, and ammonia that are damaging to the receiving water bodies. As shown in Table 2, the pollution control authorities have announced discharge norms specifically for COBP wastewater in recognition of the detrimental effects on the receiving environment.

The industry has reacted in recent years by upgrading or constructing new wastewater treatment plants in response to rising demand from pollution control agencies. This COBP effluent is treated at existing facilities by cyanide, ammonia, and phenol biochemical oxidation. These effluent treatment plants are also referred to as BOD plants, which stand for bio-chemical oxidation and dephenolization. In addition to treatment, it is important to reduce wastewater discharge and pollutant concentration at the source. Adsorption, chemical oxidation, biological treatment, precipitation, distillation, solvent extraction, ion exchange, membrane processes, reverse osmosis, and electrochemical procedures are the most frequently used techniques for removing phenol from aqueous solutions⁸⁻¹¹. However, there are some drawbacks to these techniques, including their high cost, poor efficiency, and production of hazardous byproducts. At minor concentration of phenol, all the above cited method will not be appropriate to take care of the waste water; in addition these turn into expensive methods for its industrial scale-up operation¹². The conventional treatment methods adopted for removal of phenol depend upon the maintenance of the toxic limit of phenol concentration and adequate acclimatization of the biomass. The trickling filter and the activated sludge

process are generally in use for the treatment of phenolic waste water. In activated sludge process the requirement of air for aeration increase with phenol concentration. The phenol loading removal is effective only up to a certain level. The discharged effluent standard being 1 mg/L, the conventional methods are not efficient to bring down the phenol concentration to such a low level in the treated effluent⁸. To overcome this problem, there is an urgent need of design of the wastewater treatment plant for the removal of phenol using supercritical extraction using CO₂. Recently CHEMCAD® simulator has been used to model and simulate extensive variety of processes, for instance: the simulation of an olive pits fed rotary kiln pyrolysis plant installed in Southern Italy¹³; the conceptual design of an acetaldehyde manufacturing plant¹⁴; the simulation of the biodiesel production process by transesterification of vegetable oils¹⁵, the simulation of a gasification plant equipped with a fluidized bed gasifier¹⁶; the use of stochastic optimization algorithms for the systematic process retrofit of complex chemical processes¹⁷; the simulation of the formaldehyde production process via Formox technology, and comparison between the obtained and the acquired results using Super Pro Designer process simulator¹⁸; and the conceptual design of a small-scale plant to obtain several components from turpentine oil¹⁹.

In this investigation, the theoretical design of the wastewater treatment plant for the removal of phenol using CHEMCAD® process simulator is carried out²⁰. This study aims to understand the mass composition of the different streams involved in the wastewater treatment process, so it is possible to determine the main design parameters of process equipment; to calculate the flow rate of the different auxiliary consumed. The outcomes attained in this simulation analysis will assist to illustrate the wastewater treatment plant for phenol removal using supercritical extraction with CO₂ from the technical point of view; and can be used to gain the essential methods to intensify the pollutant removal, get better economics and to aid in drop in the contamination; as well as to form the necessary details for forthcoming optimization investigations.

Experimental Section

Process simulation for design of process for phenol removal

The phenol removal process using supercritical extraction with CO₂ was selected for simulation since

Table 3 — Equipment description

Description	Equipment ID	Description	Equipment ID
Pump	1	Distillation Column	7
Extractor	2	Component Separator	4, 18
Valve	3,15,16,20	Compressor	23
Heat Exchanger	5, 6, 9, 14, 17, 19, 24	Mixer	21, 22, 25

satisfactorily the most important thermodynamic variables of all the chemicals used according to the different existing phases. Using this model and the SRK model (Soave-Redlich-Kwong) allows determining the values of the equilibrium constant K and other important thermodynamic parameters. Additionally, it is taken into account some useful recommendations provided by the simulator itself.

PSRK is an estimation method for the calculation of phase equilibria of mixtures of chemical components. The original goal for the development of this method was to enable the estimation of properties of mixtures containing supercritical components. This class of substances cannot be predicted with established models, for example UNIFAC. As stated previously, the PSRK model is based on a combination of the Soave-Redlich-Kwong equation of state with a mixing rule whose parameters are determined by the UNIFAC method. The equation of state of Soave is defined as follows:

$$P = \frac{RT}{v_m - b} - \frac{a}{v_m(v_m - b)}$$

where P , T and nm are the system pressure, temperature and molar volume, respectively; a and b are parameters of PSRK EoS.

$$a_i = \frac{0.42748R^2T_{c,i}^2f(T)}{P_{c,i}}, \quad b_i = \frac{0.08664RT_{c,i}}{P_{c,i}}$$

$$f(T) = 1 + C_1(1 - T_r^{0.5})^2$$

$$C_1 = 0.48 + 1.574\omega - 0.17\omega^2, \quad T_r = \frac{T}{T_c}$$

where $P_{c,i}$ and $T_{c,i}$ stand for the critical pressure and critical temperature of pure component i , respectively; u is the acentric factor. The PSRK mixing rule is written as

$$a = b \left[\frac{g_0^E}{A_1} + \sum y_i \frac{a_i}{b_i} + \frac{RT}{A_1} \sum y_i \ln \frac{b}{b_i} \right]$$

$$b = \sum y_i b_i$$

$$g_0^E = RT \sum y_i \ln \gamma_i$$

$$\frac{a}{bRT} = \frac{1}{A_1} \sum y_i \ln \gamma_i + \frac{1}{A_1} \sum y_i \ln \frac{b}{b_i} + \frac{1}{A_1} \sum y_i \frac{a_i}{b_i RT}$$

where g_0^E is excess Gibbs energy; the recommended value of A_1 is -0.64663 in the PSRK model; the activity coefficient of component i , γ_i is calculated using the UNIFAC model.

Phase envelope

Phase diagram or phase envelope is a relation between temperature and pressure that shows the condition of equilibria between the different phases of chemical compounds, mixture of compounds, and solutions. Phase diagram is an important issue in chemical thermodynamics and solution reservoir. It is very useful for process simulation, reactor design, and petroleum engineering studies. It is constructed from the bubble line, dew line, and critical point. Bubble line and dew line are composed of bubble points and dew points, respectively. Bubble point is the first point at which the gas is formed when a liquid is heated. Meanwhile, dew point is the first point where the liquid is formed when the gas is cooled. Critical point is the point where all of the properties of gases and liquids are equal, such as temperature, pressure, amount of substance, and others. Critical point is very useful in processing and dissolution of certain chemicals. Michelsen²¹ described the calculation of the phase envelope. However, to determine the phase of the obtained liquid stream, CHEMCAD was used to generate the phase envelope of the liquid stream. The PSRK model refers to the thermodynamics package that was used in the creation of the critical point, and the dew and bubble lines of the liquid phase envelope. The operating condition of the plant was located on the phase envelope diagram as well.

Results and Discussion

The results obtained regarding composition of the intermediate and exit streams, equipment design variables, phase envelopes, the temperature and mole fractions profiles of Phenol/ Carbon Dioxide and sizing of distillation column is carried out, are shown in the following sections. Table 4 and Table 5 show the results obtained for the equipment by CHEMCAD process simulator.

Tables 4 — Results obtained for the equipment by CHEMCAD process simulator

Equipment No.	7	Equipment No.	2
Name	Distillation column	Name	Extractor
No. of stages	10	No. of stages	10
1 st Feed stage	5	1 st feed stage	1
Top pressure, (bar)	75.00	2 nd feed stage	9
Sub cooled temp.(°C)	40.00	Pressure Top(bar)	65.00
Equipment No.	1	Equipment No.	23
Name	Pump	Name	Compressor
Pressure increase, bar	3.00	Pressure out bar	35.00
Efficiency	0.95	Efficiency	0.95
Calculated power (kcal/h)	815.1743	Cp/Cv	1.7548
Calculated pressure out(bar)	4.00	Ideal Cp/Cv	1.1876
Head (m)	30.7127	Calculated pressure out (bar)	65.00
Vol. flow rate (m ³ /h)	10.7930	Type of compressor	1
Equipment No.	21	22	25
Name		Mixer	
Output pressure bar	35.00	35.00	1.00

Table 5 — Results for the heat exchangers, valves, and component separators by CHEMCAD® simulator

Equipment No.	5	6	9	14	17	19	24
Name				Heat exchanger			
Pressure drop				40.00			
Temp out (°C)	45.00	35.00	35.00	60.00	55.00	40.00	45.00
Calculated heat duty	536661	-3259.4	-52429.1	-123823	452464	-149359	240597
Str 1 pressure out (bar)	65.00	35.00	4.00	75.00	50.00	50.00	35.00
Equipment No.	3	15	16	20			
Name			Valve				
Pressure out (bar)	65.00	1.00	50.00	1.00			
Equipment No.	21	22	25				
Name		Mixer					
Output pressure (bar)	35.00	35.00	1.00				
Equipment No.	4	18					
Name	Component Separator						
Component 1	0.9890	0.990					

The results of the simulation are shown numerically in WinWord window as shown Table 6. The results show mass flow rates in each stream together with an overall input/output balance. The important stream summary for phenol wastewater treatment with supercritical CO₂ is given in the Table 7.

Phase envelope

The phase envelope of the gas stream was generated by using the simulation software packages, as shown in Fig. 2. The phase envelope assists in determining the optimum operating

conditions since it shows the pressure and corresponding temperature at which a single phase or two phases may exist, hence, providing data that allow for efficient design. Bubble point which forms bubble line in Fig. 2 and Fig. 3 is a point separating the liquid phase and the two phases region, namely the liquid phase and the gaseous phase. Dew point which forms dew line in Fig. 2 & 3 is a point separating the gaseous phase and the two phases region, namely the liquid phase and the gaseous phase. State of pressure and temperature at which all properties of the gas and liquid phases are

equal at a certain point is known as critical point. These figures illustrate that the operating condition lies very close to the dew line of the phase envelope. Thus, any movement along a straight line to the left or

right (by changing the temperature) results in a change of the phase; i.e. it results in a change in the rate of the gas production. The pressure and temperature correlation is shown in Fig. 2 & 3.

Table 6 — Simulation results for Phenol wastewater treatment with supercritical CO₂ (CHEMCAD simulator generated)

Stream No.	1	2	3	4
Stream Name				WASTE WATER
Temp C	14.0843	40.0750	35.0000	40.0000
Pres bar	65.0000	4.0000	35.0000	1.0000
Enth kcal/h	-6.9022E+007	-3.8126E+007	-7.1250E+005	-3.8127E+007
Vapor mole fraction	0.00000	0.00000	0.99959	0.00000
Total kmol/h	730.2475	563.8000	7.5593	563.8000
Flowrates in kmol/h				
Carbon Dioxide	719.2156	0.0000	7.5485	0.0000
Phenol	7.8017	7.8000	0.0018	7.8000
Water	3.2302	556.0000	0.0090	556.0000
Stream No.	5	6	7	8
Stream Name				
Temp C	26.3600	45.0000	45.0000	97.1157
Pres bar	65.0000	35.0000	65.0000	75.0000
Enth kcal/h	-6.9022E+007	-7.0554E+007	-1.2488E+006	-7.0924E+005
Vapor mole fraction	0.58376	1.0000	0.00000	1.0000
Total kmol/h	730.2475	749.0403	18.9433	7.5593
Flowrates in kmol/h				
Carbon Dioxide	719.2156	749.0295	7.9113	7.5485
Phenol	7.8017	0.0018	7.8017	0.0018
Water	3.2302	0.0090	3.2302	0.0090
Stream No.	11	15	16	17
Stream Name				
Temp C	45.0000	313.8549	60.0000	61.1467
Pres bar	65.0000	75.0000	75.0000	1.0000
Enth kcal/h	-6.8485E+007	-3.9391E+005	-5.1043E+005	-5.1043E+005
Vapor mole fraction	0.96974	0.00000	0.00000	0.013792
Total kmol/h	730.2475	11.3840	11.3730	11.3730
Flowrates in kmol/h				
Carbon Dioxide	719.2156	0.3628	0.2305	0.2305
Phenol	7.8017	7.8000	7.7976	7.7976
Water	3.2302	3.2212	3.3449	3.3449
Stream No.	18	19	20	21
Stream Name				
Temp C	18.3350	12.7184	10.9791	55.0000
Pres bar	35.0000	65.0000	50.0000	50.0000
Enth kcal/h	-7.0795E+007	-4.0841E+007	-4.0841E+007	-4.0388E+007
Vapor mole fraction	1.0000	0.00000	0.029461	0.038327
Total kmol/h	749.0403	583.2604	583.2604	583.2604
Flowrates in kmol/h				
Carbon Dioxide	749.0295	30.4816	30.4816	30.4816
Phenol	0.0018	0.0001	0.0001	0.0001
Water	0.0090	552.7787	552.7787	552.7787

(contd.)

Table 6 — Simulation results for phenol wastewater treatment with supercritical CO₂ (CHEMCAD simulator generated) (*contd.*)

Stream No.	22	23	24	25
Stream Name				
Temp C	55.0000	40.0000	39.9649	55.0000
Pres bar	50.0000	50.0000	1.0000	50.0000
Enth kcal/h	-3.7518E+007	-3.7659E+007	-3.7659E+007	-2.8433E+006
Vapor mole fraction	0.00000	0.00000	0.00020509	1.0000
Total kmol/h	553.0836	552.9540	552.9540	30.1768
Flowrates in kmol/h				
Carbon Dioxide	0.3048	0.3127	0.3127	30.1768
Phenol	0.0001	0.0000	0.0000	0.0000
Water	552.7787	552.6413	552.6413	0.0000
Stream No.	27	28	29	31
Stream Name				CO2
Temp C	40.9195	45.0000	18.3352	35.0000
Pres bar	35.0000	65.0000	35.0000	1.0000
Enth kcal/h	-3.5558E+006	-6.7239E+007	-7.0795E+007	-6.5778E+005
Vapor mole fraction	1.00000	1.00000	1.00000	1.00000
Total kmol/h	37.7361	711.3042	749.0403	7.0000
Flowrates in kmol/h				
Carbon Dioxide	37.7253	711.3042	749.0295	7.0000
Phenol	0.0018	0.0000	0.0018	0.0000
Water	0.0090	0.0000	0.0090	0.0000
Stream No.	32	35		
Stream Name				
Temp C	10.7802	35.0000		
Pres bar	1.0000	4.0000		
Enth kcal/h	-7.1212E+007	-3.8178E+007		
Vapor mole fraction	1.00000	0.00000		
Total kmol/h	756.0403	563.8000		
Flowrates in kmol/h				
Carbon Dioxide	756.0295	0.0000		
Phenol	0.0018	7.8000		
Water	0.0090	556.0000		

Table 7 — Important stream summary for phenol wastewater treatment with supercritical CO₂

Stream No.	4	31	17	24
Stream Name	Wastewater	CO ₂	Phenol	Treated water
Temp. (°C)	40	35	61.14671	39.9649
Pressure (bar)	1	1	1	1
Vapour fraction	0	1	0.01379197	0.0002050926
Enthalpy (kcal/h)	-3.81266e+007	-657782	-510430	-3.765927e+007
Total flow (Kmol/h)	563.8	7	11.373	552.964
Carbon Dioxide (Kmol/h)	0	7	0.2305051	0.3127099
Phenol (Kmol/h)	7.8	0	7.797562	4.735389e-005
Water (m ³ /h)	556	0	3.344937	552.6413

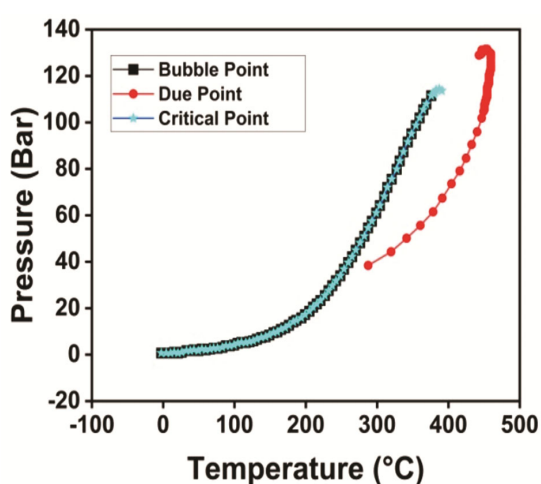


Fig. 2 — Phase envelop for phenol removal stream No.17

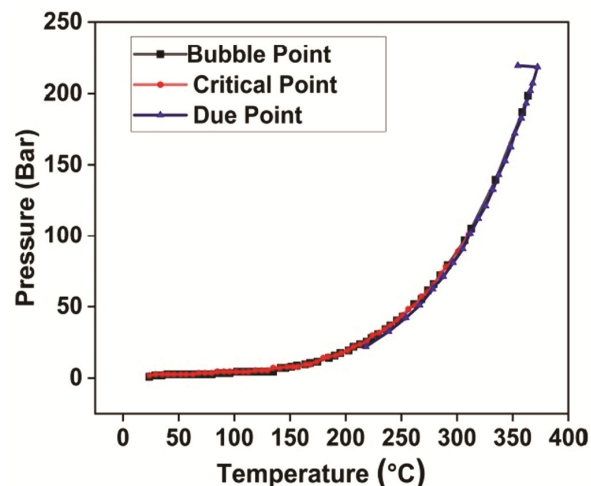


Fig. 3 — Phase envelop for treated water stream No.24

The process simulation of the system is shown in Figure. The temperature and mole fractions profiles have directly drawn using plot function in CHEMCAD, which is illustrated in Fig. 4.

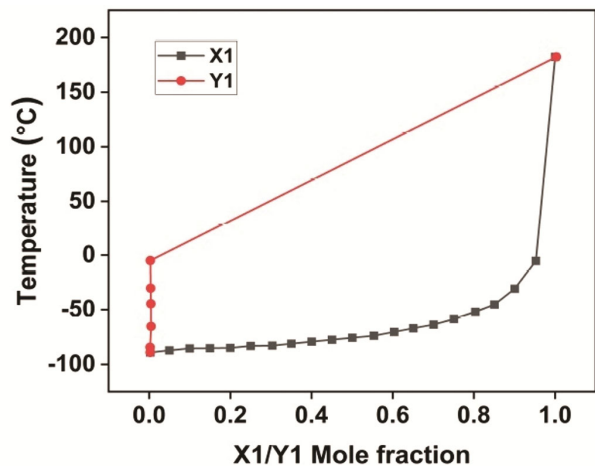


Fig. 4 — Temperature and mole fractions profiles Phenol/ Carbon dioxide at 1.01 Bar By PSRK for Distillation Column 7

Sizing of distillation column

The results of the simulation are shown numerically in WinWord window as shown in Table 8. Vapour load is defined as the vapour from the tray below. Liquid load is defined as the liquid on the tray. The results show the sizing of distillation column internals such tower internal diameter, tray spacing, tray area, down comer dimensions etc. CHEMCAD has successfully converged the design of the wastewater treatment plant for the removal of phenol from steel Industry wastewater. The material and energy complexities were reduced to a greater extent. Different component of mixed waste stream were separated more or less to pure form. It can be visualized from flow summaries of streams. Sizing of distillation column was done which gives the internal details for fabrication. Around 7.8 Kmol/h of phenol concentration was processed in through stream no. 4 and almost zero concentration of phenol comes out through stream no. 24 which means there is no phenol available in treated water. 7.7976 Kmol/h of phenol concentration is recovered through stream no. 17.

Table 8 — Simulation results for sizing of distillation column for phenol wastewater treatment with supercritical CO₂

Tray Loadings	Vapor		Liquid
	792.677 kg/h		460.137
	1.170 m ³ /h		0.586
Density	677.783 kg/m ³		784.668
Tower internal diameter, m	.....		0.305
Tray spacing, cm	.....		60.960
No. of tray liquid passes	.....		1
Downcomer dimension, Side	Width cm	Length cm	Area m ²
	4.445	21.515	0.007
Avg. weir length, cm	.....		21.515
Weir height, cm	.....		5.080
Flow path length, cm	.....		21.590
Flow path width, cm	.....		27.693
Tray area, m ²	.....		0.073
Tray active area, m ²	.....		0.060
% flood	.....		38.070
No. of caps	.....		3
Fractional entrainment	.....		0.000
Aeration factor	.....		0.946
Tray press loss, cm	.....		3.039
Tray press loss, bar	.....		0.002
Downcomer clearance, cm	.....		7.620
Downcomer backup, cm	.....		8.717
Downcomer residence time, sec	.....		3.526
Liquid holdup, m ³	.....		0.002
Liquid holdup, kg	.....		1.274
Design pressure, bar	.....		75.000
Joint efficiency	.....		0.850
Allowable stress, bar	.....		944.582
Corrosion allowance, cm	.....		0.079
Column thickness, cm	.....		1.588
Bottom thickness, cm	.....		1.588

Conclusion

The current investigations are found effective for the Design of the wastewater treatment plant for the removal of phenol using CHEMCAD® process simulator. The simulated plant was able to reduce the effluent streams to below the regulatory threshold established by the Central Pollution Control Board. The study's findings support the possibility that CHEMCAD® could serve as a tool for environmental engineers and engineering students to use while designing, running, and controlling processes that must adhere to environmental limitations. The results showed that the CHEMCAD® may be used in the wastewater treatment application with excellent agreement. Overall, this study highlights the ability of using commercial simulation software packages, such as CHEMCAD®, to simulate industrial processes. Furthermore, it shows that the PSRK model thermodynamics package gives the best fit in the simulation of design of wastewater treatment plant, since the obtained results were comparable to the measured values from real industrial data. Thus, it confirms the validity of the model, which is required before completing any further study (e.g., sensitivity study or optimization).

References

- Alotaibi B A, Baig M B, Najim M MM, Shah A A & Alamri Y A, Water scarcity management to ensure food scarcity through sustainable water resources management in Saudi Arabia, *Sustainability*, 15 (2023) 10648.
- Annual Report; Min of Steel, *www.steel.gov.in* (2009-10).
- Battacharjee S, Sponge Iron Industry: Current scenario, Secretary, *Steel world*, (2007) 29.
- Mondal M, Mukherjee R, Sinha A, Sarkar S & De S, Removal of cyanide from steel plant effluent using coke breeze, a waste product of steel industry, *J Water Process Eng*, 28 (2019) 135.
- Das P, Mondal G C, Singh S, Singh A K, Prasad B & Singh K K, Effluent treatment technologies in the iron and steel industry-A state of the art review, *Water Environ Res*, 90 (2018) 395.
- Pillai I M S & Gupta A K, Anodic oxidation of coke oven wastewater: Multiparameter optimization for simultaneous removal of cyanide, COD and phenol, *J Environ Manag*, 176 (2016) 45.
- Mahugo-Santana C, Sosa-Ferrera Z, Torres-Padrón M E & Santana-Rodríguez J J, Analytical methodologies for the determination of nitroimidazole residues in biological and environmental liquid samples: A review, *Anal Chim Acta*, 665 (2010) 113.
- Rodriguesa L A, Silvab M L C P D, Alva- rez-Mendesc M O, Coutinhoc A D R & Thima G P, Phenol removal from aqueous solution by activated carbon produced from avocado kernel seeds, *Chem Eng J*, 174 (2011) 49.
- Senturka H B, Ozdesa D, Gundogdua A, Durana C & Soylakb M, Removal of phenol from aqueous solutions by adsorption on to organo modified tirebolubentonite: Equilibrium, kinetic and thermodynamic study, *J Hazard Mater*, 172 (2009) 353.
- Aravindhnan R, Rao J R & Nair B U, Application of a chemically modified green macro alga as a biosorbent for phenol removal, *J Environ Manag*, 90 (2009) 1877.
- Abdelwahaba O, Aminb N K & El-Ashtoukhy E S Z, Electrochemical removal of phenol from oil refinery wastewater, *J Hazard Mater*, 163 (2009) 711.
- Meikap B C & Roy G K, Removal of phenolic compounds from industrial wastewaters by semi fluidized bed bioreactor, *J Inst Public Health Eng*, 3 (1997) 54.
- Benanti E, Freda C, Loreface V, Braccio G & Sharma V, Simulation of olive pits pyrolysis in a rotary kiln plant, *Therm Sci*, 15 (2011) 145.
- Eliasson J, *Design of a plant for manufacturing of acetaldehyde*. Sweden: Department of Chemical Engineering, Lund University (2010).
- Chilev C & Simeonov E, Simulation of biodiesel production by transesterification of vegetable oils, *J Chem Technol Metall*, 49 (2014) 479.
- Moneti M, Delfanti L, Marucci A & Bedini R, Simulations of a plant with a fluidized bed gasifier WGS and PSA, *Contemp Eng Sci*, 8 (2015) 1461.
- Otte D, Lorenz H M & Repke J U, A toolbox using the stochastic optimization algorithm MIPT and CHEMCAD for the systematic process retrofit of complex chemical processes, *Comput Chem Eng*, 84 (2016) 371.
- Johansen T, Johnsen A & Christiansen I, *A Comparison of Training Simulators for the Formox Process*. Norway: Norwegian University of Science, Faculty of Natural Sciences and Technology. Department of Chemical Engineering and Technology, (2013).
- Sarwar, *Plant Design for the Separation of Various Components from Turpentine Oil*. (Master of Science Thesis), Göteborg, Sweden: Chalmers University of Technology (2012).
- Chemstations, *Chem CAD Professional® (Version 5.2.0)*. Houston, Texas: Chemstations Inc. www.chemstations.com, (2002).
- Michelsen M L, Calculation of phase envelopes and critical points for multicomponent mixtures, *Fluid Phase Equilib*, 4 (1980) 1.