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Comparison between Post- and Oxy-Combustion Systems in a Petroleum Refinery Unit Using Modeling and Optimization

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Abstract**—**A fluidized catalytic cracking unit (FCCU) is one of the effective units in many refineries. Modeling and optimization of FCCU were done by many researchers in past decades, but in this research, comparison between post- and oxy-combustion was studied in the regenerator-FCCU. Therefore, a simplified mathematical model was derived by doing mass/heat balances around both reactor and regenerator. A state space analysis was employed to show effects of the flow rates variables such as air, feed, spent catalyst, regenerated catalyst and flue gas on the output variables. The main aim of studying dynamic responses is to figure out the most influencing variables that affect both reactor/regenerator temperatures; also, finding the upper/lower limits of the influencing variables to ensure that temperatures of the reactors and regenerator work within normal operating conditions. Therefore, those values will be used as side constraints in the optimization technique to find appropriate operating regimes. The objective functions were modeled to be maximizing the energy in the reactor while minimizing the energy consumption in the regenerator. In conclusion, an oxy-combustion process can be used instead of a post-combustion one.

Keywords**—**FCCU modeling, optimization, oxy-combustion post-combustion.

I. Introduction

THE main objective of the FCCU is converting the heavy oil fractions to valuable products such as gasoline and liquid petroleum gas. Fig. 1 shows a simplified flow sheet of a typical FCCU. Fresh hydrocarbon feed (gasoil) and fresh catalyst (0.1% of the regenerated catalyst [1]) are preheated and then pumped to the riser bottom to be converted into small particles and meet the high-temperature regenerated catalyst coming from the regenerator since the residence time is typically five seconds in the reactor. The feed temperature must not exceed 400 °C to prevent coking of the heating coils; otherwise, preheating is often just a control feature. The heat from the regenerated catalyst vaporizes the feed and brings it to the desired reaction temperature. Then, the mixture of catalyst and hydrocarbons vapor is passed to the top of the reactor. The cracking reactions start when the feed contacts the hot regenerated catalyst in the riser and continues until the oil vapors are separated from the catalyst in the top of the reactor. The hydrocarbon vapors are passed to the multiprocessing fractionating column to yield valuable products. In the top of the reactor, steam is injected to remove hydrocarbons adsorbed on internal and external surfaces of catalyst. Because of cracking reactions, coke forming on the catalyst surfaces causes decreasing its activation; therefore, the spent catalyst leaving the reactor contains deposited coke. The spent catalyst enters the regenerator where coke reacts with air supplied by the air compressor at the ten seconds residence time.

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TABLE I
SYMBOLS' DEFINITION

Symbol	Unit	Definition
A	(-)	Coefficients Matrix of state variables
B	(-)	Coefficients matrix of influencing variables
C	(-)	Identity matrix
Cp_{air}	(kJ/kg.°C)	Specific heat of Air
Cp_{feed}	(kJ/kg.°C)	Specific heat of fresh feed
$Cp_{freshcat}$	(kJ/kg.°C)	Specific heat of fresh catalyst
$Cp_{fluegas}$	(kJ/kg.°C)	Specific heat of flue gases
Cp_{oxy}	(kJ/kg.°C)	Specific heat of mixture oxygen
$Cp_{product}$	(kJ/kg.°C)	Specific heat of product
Cp_{regcat}	(kJ/kg.°C)	Specific heat of regenerated catalyst
Cp_{spdcat}	(kJ/kg.°C)	Specific heat of spend catalyst
Cp_{steam}	(kJ/kg.°C)	Specific heat of steam
F_{air}	(kg /sec)	Air flow rate
F_{feed}	(kg /sec)	Feed flow rate
$F_{freshcat}$	(kg /sec)	Fresh catalyst flow rate
$F_{fluegas}$	(kg /sec)	Flue gases flow rate
F_{oxy}	(kg /sec)	Oxygen flow rate
$F_{product}$	(kg /sec)	Product flow rate
F_{regcat}	(kg /sec)	Regenerated catalyst flow rate
F_{spdcat}	(kg /sec)	Spend catalyst flow
M_{coke}	(kg)	Mass of coke
$M_{fluegas}$	(kg)	Mass of flue gases
$M_{product}$	(kg)	Mass of reactor product
M_{spdcat}	(kg)	Mass of spent catalyst
M_{regcat}	(kg)	Mass of regenerated catalyst
T_{air}	(°C)	Air temperature
T_{feed}	(°C)	Feed temperature
$T_{fluegas}$	(°C)	Flue gases temperature
$T_{freshcat}$	(°C)	Fresh catalyst temperature
T_{oxy}	(°C)	Oxygen temperature
$T_{product}$	(°C)	Product temperature
T_{rec}	(°C)	Reactor temperature
T_{ref}	(°C)	Reference temperature
T_{reg}	(°C)	Regenerator temperature
T_{spdcat}	(°C)	Spend catalyst temperature
T_{steam}	(°C)	Steam temperature
ΔH_{rxn}	(kJ/sec)	Heat of reaction
ΔH_{combxn}	(kJ/sec)	Heat of combustion

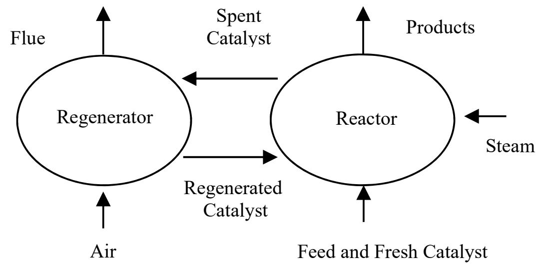

Fig. 1 A side by side FCCU

Variations of the air flow rate play a key role in controlling the regenerator temperature. After regeneration, the catalyst passes through the side valve and enters the bottom of the riser, thus forming a continuous catalyst circulation loop. The reaction is endothermic in the reactor while it is exothermic in the regenerator. Residence time in the reactor is in the 2-10 seconds range, while it is 10-15 minutes in the regenerator [1], [2]. Due to the reactions inside the FCCU, the CO_2 emitted from the regenerator typically represents 10 – 20 % of flue-gas in full post-combustion. Based on the design of the regenerator in the FCC process, two combustion schemes are possible: post- and oxy-combustion schemes. Nowadays, combustion reactions happen under two main schemes in the petroleum refining processes. Many differences are presented between these schemes such as concentration and amount of the carbon dioxide, type of products and operating cost. Post-combustion scheme happens in combustion of the fossil fuel such as natural gas or oil in existence of air which produces carbon dioxide, large amount of nitrogen, and water, while oxy-combustion scheme happens in combustion of the fossil fuel such as natural gas or oil in existence of pure oxygen which produces carbon dioxide and water. Diluted oxygen rather than air is used for combustion [3].

II. Reduced Order Model

Nowadays, modeling of industrial processes considers basic issues to majority of the operations such as design, control and optimization. Both model simplification and model reduction are found in process system engineering (PSE) literature, specifically in process control applications. They help to ease computational burdens of the simulation by gaining insight into models of the processes [4]. Furthermore, simplified models sometimes can give better estimations and predictions than extended models when the data have a lack of information and calculating values of the mean square error for both simplified and extended models. Simplified models were developed and used in many different fields in chemical engineering such as process control, design, and optimization [4], [5]. Simplified models are more reliable and less expensive in usage since they do not contain many unknown variables [6]. The solution of any simulation of the dynamic or steady state problems requires choosing correct numerical methods with special calculation features. By simplification model, both complexity and nonlinearity of the models can be reduced. Finally, the aim of using model reduction is not only to reduce the number of the equations but also to reduce their difficulty. Because of the complexities that are associated with deriving the models, the engineers almost should use simplified models along with choosing the correct assumptions such as neglecting terms in mass/energy balances or making some parameters at reasonable values or fixing temperature dependencies of heat of reactions if the temperature range is narrow. Also, to have accurate results in the simulations, the modelers should have sufficient knowledge about the processes, obtain data that represent the best predictions, and select the appropriate simplified models. Many processes are complex and difficult to obtain accurate mechanism, especially with existing unknown parameters and limited of information about the process. The consequences of using simplified models focused on acceptable assumptions during formulation of the model as well as fixing some parameters at fixed appropriate values. Developing those models represents challenges since they are difficult and costly and required sufficient data to predict all the unknown parameters and variables of the model [7].

III. Model Simplification: State Space Analysis

State space analysis is a method that is used in multi-influencing and multi-output (MIMO) dynamic systems to figure out the relationships between influencing variables and output variables. Calculation of the method depends on groups of the matrices that are defined in (1)-(4) [8]:

$$\left\{\begin{matrix} \dot{x}_1 = f_1(x_1, x_1, \dots, x_n, u_1, u_1, \dots, u_m) \\ \dot{x}_2 = f_2(x_2, x_2, \dots, x_n, u_2, u_2, \dots, u_m) \\ \cdot \\ \cdot \\ \cdot \\ \dot{x}_n = f_n(x_1, x_2, \dots, x_n, u_1, u_2, \dots, u_m) \end{matrix}\right\} \quad (1)$$

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dots \\ \dot{x}_n \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{12} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1m} \\ b_{12} & b_{22} & \dots & b_{2m} \\ \dots & \dots & \dots & \dots \\ b_{n1} & b_{n2} & \dots & b_{nm} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ \dots \\ u_n \end{bmatrix} \quad (2)$$

where x_1, x_2...x_n are state variables while u_1, u_2...u_n are influencing variables.

$$\dot{x} = Ax + Bu \quad (3)$$

$$y = Cx \quad (4)$$

where y is a vector of the outputs (y_1, y_2…, y_n), A and B are matrixes that represent coefficients of the influencing variables and output variables respectively, while C is an identity matrix. The elements of the A and B matrixes are computed through (5) and (6):

$$a_{nm} = \frac{\partial f_n}{\partial x_m} \quad (5)$$

$$b_{nm} = \frac{\partial f_n}{\partial u_m} \quad (6)$$

where f refers to a right side of the differential equation. After finding the elements of matrixes A, B, and C, (7) is used to find the relationships between influencing and output variables.

$$Y(s) = [C[sI - A]^{-1}B]U(s) \tag{7}$$

Many researchers used state space method to figure out dynamic responses of the MIMO system and to find the transfer functions between influencing and output variables since its calculation is easy and depends on matrix algebra. In opposite side, using this method makes researchers loss some accuracy because it converts the system from nonlinear state to linear one.

IV. Optimization Technique

Optimization is one of the effective tools used by engineers and researchers for solving many relevant management problems. It is concerned with finding the best solutions by minimizing the time required, increasing profits and enhancing operating conditions in the process. Using optimization became easier and more effective since software includes many quantitative optimization methods, leading to more reliable solutions and allowing the researchers to achieve results faster. Basically, optimization problems consist of many mathematical expressions that range from simple to complex depending on the system itself [9]. To achieve a good optimization, simulation models, objective functions and constraints should be presented very well since every optimization problem should include at least one objective function (profit function, cost function, etc.), equality constraints, inequality constraints and side constraints. The framework of an optimization model can be described as the following:

Optimizing objective function: f(x)

Subject to:

- $h(x) = 0$ equality constraints,
- $g(x) \geq 0$ inequality constraints,
- $x_i^L \leq x_i \leq x_i^U$ side constraints.

where x is a vector of the n variables $(x_1, x_2, \ldots, x_n)$, h(x) is a vector of the equations, and g(x) is a vector of the inequalities [9], [10].

V. Simplified Model of the FCCU

In simulation models of various processes, the equations of mass/energy balance and equations of kinetic models should be derived. Some assumptions should be considered to help the researchers reduce the complexity of models and solve them. The aim of dynamic modeling is to predict changes consequence of the system influencing or operating conditions. Worldwide, the FCCU is a principal element in modern refineries. Its object is converting heavy hydrocarbon petroleum fractions into more usable products such as gasoline at high octane number, middle distillates, and light gases. Studying operating conditions that have impact on physical properties of the catalyst makes the operation of the FCCU a big challenge [1]. Heat balances need to be calculated correctly for the process to work. These balances can be employed to study among the process variables (i.e., temperatures and flow rates) and the impact of the heat balances on the FCCU. The heat generated from combustion of coke supplies the heat of all streams in the reactor such as heating the feed temperature to the rector temperature, substituting the heat losses by conduction, radiation, etc., supplying the heat of reaction, and raising the steam temperature the reactor temperature [3]. While in regenerator, it supplies the heat to the streams such as raising coke temperature from reactor temperature to regenerator temperature, and raising air temperature to regenerator temperature, and substituting the heat losses by conduction, radiation, etc. The distribution of combustion heat varies from one stream to another depending on needs of the stream in the process and design considerations to maintain good balances between the reactor and regenerator. The distribution of combustion heat of feed, reaction, air, steam and losses are 40%, 30%, 20%, 8%, and 2% respectively [11].

A. Heat Balance of the Reactor

References [12]-[14] presented detailed models of the FFCU that included mass/heat balances and kinetic reactions in both reactor and regenerator, control system and optimization. Reference [12] described mechanistic models for both reactor and regenerator. The model covered most of dynamic behaviors of the FCCU including interaction between two processes, process control and on-line optimization. They concluded that FCC process has high interactions among the influencing and output variables and high nonlinearities system. Also, [13] presented the FCC models in detail with mentioning the kinetic rates of CO_2 and CO combustion and their effects on the FCC performance. [14] represented a dynamic simulator of the FCCU and studied the dynamic behavior by imposing step changes in manipulated variables. They measured temperature of the reactor and regenerator and regenerator flue gas in both open- and closed loops of the unit and compared these to a simulator. They concluded that the dynamic simulator can serve to develop model-based control and off-line optimization studies. [15] described material/heat balances for the reactor and regenerator at steady state. The reactor model was described as follows by assuming that the specific heats of the variables are constant.

$$F_{feed} \int_{T_{ref}}^{T_{feed}} Cp_{Feed}\, dT + F_{Freshcat} \int_{T_{ref}}^{T_{freshcat}} Cp_{freshcat}\, dT + F_{regcat} \int_{T_{ref}}^{T_{reg}} Cp_{regcat}\, dT + F_{steam} \int_{T_{ref}}^{T_{steam}} Cp_{steam}\, dT - F_{prduct} \int_{T_{ref}}^{T_{product}} Cp_{product}\, dT - F_{spdcat} \int_{T_{ref}}^{T_{spdcat}} Cp_{spdcat}\, dT + \Delta H_{rxn} - Heat\ Losses = \left(M_{spdcat} Cp_{spdcat} + M_{product} Cp_{product}\right) \frac{dT_{rec}}{dt} \tag{8}$$

where heat losses due to convection and radiation in the reactor are equal to 2% of the regenerated catalyst [11], [16]. After integration, (8) can be written as:

$$F_{feed}Cp_{feed}(T_{feed}-T_{ref})+F_{freshcat}Cp_{freshcat}(T_{freshcat}-T_{ref})+F_{regcat}Cp_{regcat}(T_{reg}-T_{ref})+F_{steam}Cp_{steam}(T_{steam}-T_{ref})-F_{product}Cp_{product}(T_{rec}-T_{ref})-F_{spdcat}Cp_{spdcat}(T_{rec}-T_{ref})+F_{feed}\Delta H_{rxn}-0.02\,F_{regcat}Cp_{regcat}(T_{reg}-T_{ref})=(M_{spdcat}Cp_{spdcat}+M_{product}Cp_{product})\frac{dT_{rec}}{dt} \quad (9)$$

B. Heat Balance of Regenerator

The regenerator model is described as follows by assuming that the specific heats as variables are constant:

$$F_{air}\int_{T_{ref}}^{T_{air}}Cp_{air}\,dT+F_{spdcat}\int_{T_{ref}}^{T_{rec}}Cp_{spdcat}dT-F_{fluegas}\int_{T_{ref}}^{T_{reg}}Cp_{fluegas}\,dT-F_{regcat}\int_{T_{ref}}^{T_{reg}}Cp_{regcat}\,dT-F_{coke}\Delta H_{combxn}-Losses=(M_{regcat}Cp_{regcat}+M_{fluegas}Cp_{fluegas})\frac{dT_{reg}}{dt} \quad (10)$$

where heat losses due to convection and radiation in the regenerator are equal to 4% of the combustion heat [11], [16]. After taking integration, (10) can be written as:

$$F_{air}Cp_{air}(T_{air}-T_{ref})+F_{spdcat}Cp_{spdcat}(T_{rec}-T_{ref})-F_{fluegas}Cp_{fluegas}(T_{reg}-T_{ref})-F_{regcat}Cp_{regcat}(T_{reg}-T_{ref})-F_{coke}\Delta H_{combxn}-0.04\,F_{coke}\Delta H_{combxn}=(M_{regcat}Cp_{regcat}+M_{fluegas}Cp_{fluegas})\frac{dT_{reg}}{dt} \quad (11)$$

In case of oxy-combustion systems, two scenarios will be considered in the regenerator. For the first scenario, we substitute the same heat that air supply to the regenerator, i.e.

$$Q_{air}=Q_{oxy} \quad (12)$$

Therefore, the model becomes:

$$Q_{oxy}+F_{spdcat}Cp_{spdcat}(T_{rec}-T_{ref})-F_{fluegas}Cp_{fluegas}(T_{reg}-T_{ref})-F_{regcat}Cp_{regcat}(T_{reg}-T_{ref})-\Delta H_{combxn}-0.04\,F_{coke}\Delta H_{combxn}=(M_{regcat}Cp_{regcat}+M_{fluegas}Cp_{fluegas})\frac{dT_{reg}}{dt} \quad (13)$$

The difference is in calculation of the specific heats and flowrates of both air and oxygen since air contains nitrogen while oxygen is diluted with carbon dioxide [17], so the equation will be as follows:

$$F_{air}Cp_{air}(T_{air}-T_{ref})=F_{oxy}Cp_{oxy}(T_{oxy}-T_{ref}) \quad (14)$$

Those differences will affect dynamic behaviors of both reactor and regenerator since total material and heat balance should be recalculated again. Percentage of oxygen in flue gases values of the lower/upper limits of the flow rates will also be different. For the second one, we substitute the same flow rate that air provides to the regenerator, i.e.

$$F_{air}=F_{oxy} \quad (15)$$

In this case, the heat supplied by air will not be the same heat supplied by oxygen. The reason is differences between the specific heats containing nitrogen and oxygen diluted with carbon dioxide. Therefore, percentage of oxygen in flue gases and lower/upper limits of flow rates will also be different. It is important to mention that the switching from post-combustion to oxy-combustion takes 5-15 min [17]. This gives advantages to the modern FCCUs to be in a flexible design and operation. Studying a simulation behavior of the FCCU represents a challenging research due to high environmental and economic importance, while the optimization involves developing a model which describes the process in detail [14]. Our model will be based on the models presented in literature, but compared to that of [15], the model is not only in a static behavior but also in a dynamic one.

VI. Results and Discussions

A. Dynamic Behavior

For post combustion, Figs. 2–7 show the dynamic responses of positive step changes in the influencing variables to study their effects on the output variables. Some influencing variables have considerable effects, while others have sensible effects. Some increases are with positive step change, while others decrease since majority of the change nature in these types takes step behavior. The aim of taking step change is for knowing nature of the relationship between influencing and output variables and magnitude of the change; therefore, figuring out the allowable lower/upper limits of the influencing variables. Also, the same procedure is for oxy-combustion. Tables II and III show the results of the optimization for both post- and oxy-combustion in the regenerator and reactor.

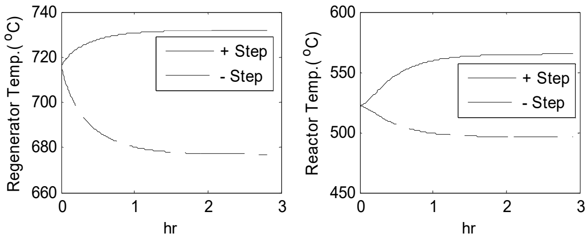

Fig. 2 Effects of a positive/negative step change in the air flow rate on reactor and regenerator temperatures

B. Optimization Technique

Nature of the two reactions taking place inside a FCC unit is different: a reaction inside the reactor is endothermic, while the one inside the regenerator is exothermic. These reactions affect directly the temperatures and other parameters. Keeping appropriate temperatures of both the reactor and regenerator is considered a challenge and plays a key role in maintaining a satisfactory performance of the FCCU. It is should be important to mention that every FCCU has set of the constraints since operations of a FCCU depend on combination of the constrains during optimal operations [18].

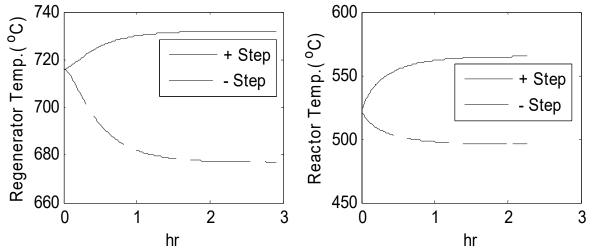

Fig. 3 Effects of a positive/negative step change in the feed flow rate on reactor and regenerator temperatures

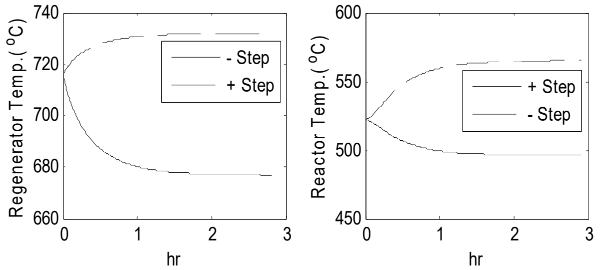

Fig. 4 Effects of a positive/negative step change in the flue gases flow rate on reactor and regenerator temperatures

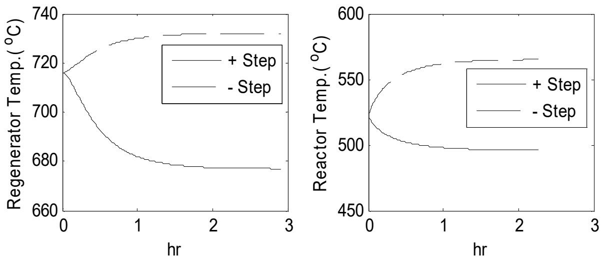

Fig. 5 Effects of a positive/negative step change in the product flow rate on reactor and regenerator temperatures

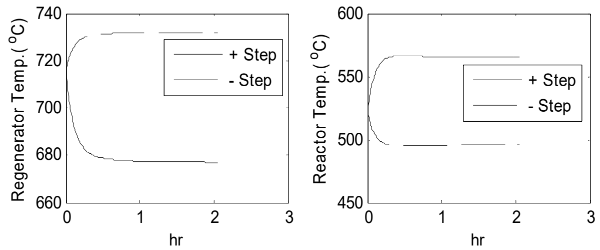

Fig. 6 Effects of a positive/negative step change in the regenerated catalyst flow rate on reactor and regenerator temperatures

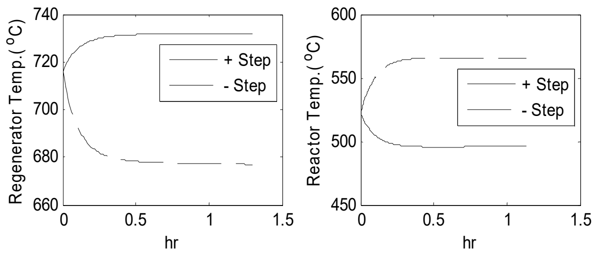

Fig. 7 Effects of a positive/negative step change in the spend flow rate on reactor and regenerator temperatures

For reactor, objective function: maximizing total energy, $Q_{tot} = Q_{in} + Q_{out} + Q_{gen} + Q_{con}$

$$F_{feed}Cp_{feed}(T_{feed} - T_{ref}) + F_{freshcat}Cp_{freshcat}(T_{freshcat} - T_{ref}) + F_{regcat}Cp_{regcat}(T_{reg} - T_{ref}) + F_{steam}Cp_{steam}(T_{steam} - T_{ref}) - F_{product}Cp_{product}(T_{rec} - T_{ref}) - F_{spdcat}Cp_{spdcat}(T_{rec} - T_{ref}) + F_{feed}\Delta H_{rxn} - 0.02\, F_{regcat}Cp_{regcat}(T_{reg} - T_{ref}) \quad (16)$$

Equality constraints:

$$F_{feed} - F_{product} + F_{regcat} + -F_{spdcat} + F_{steam} = 0 \quad (17)$$

Side constraints:

14.953	≤	F_{air}	≤	120.61
73.676	≤	F_{feed}	≤	98.419
12.651	≤	$F_{fluegas}$	≤	85.743
70.017	≤	$F_{product}$	≤	87.36
349.85	≤	F_{regcat}	≤	453.64
308.18	≤	F_{spdcat}	≤	443.31
370	≤	T_{air}	≤	593
204	≤	T_{feed}	≤	400
496	≤	T_{rec}	≤	565
677	≤	T_{reg}	≤	732

For regenerator, objective function: minimizing total energy, $Q_{tot} = Q_{in} + Q_{out} + Q_{gen} + Q_{con}$

$$F_{air}Cp_{air}(T_{air} - T_{ref}) + F_{spdcat}Cp_{spdcat}(T_{rec} - T_{ref}) - F_{fluegas}Cp_{fluegas}(T_{reg} - T_{ref}) - F_{regcat}Cp_{regcat}(T_{reg} - T_{ref}) - F_{coke}\Delta H_{combxn} - 0.04\, F_{coke}\Delta H_{combxn} \quad (18)$$

Equality constraints:

$$F_{air} + F_{spdcat} - F_{feed} - F_{regcat} = 0 \quad (19)$$

Side constraints:

19.225	≤	F_{air}	≤	69.347
61.000	≤	F_{feed}	≤	92.025
48.114	≤	$F_{fluegas}$	≤	82.788
74.498	≤	$F_{product}$	≤	96.245
367.32	≤	F_{regcat}	≤	441.7
317.63	≤	F_{spdcat}	≤	423.06
370	≤	T_{air}	≤	593
204	≤	T_{feed}	≤	400
496	≤	T_{rec}	≤	565
677	≤	T_{reg}	≤	732

VII. Conclusion

With all theoretical conducted since this research commenced, the following simple conclusions can be made thus far about using post- and oxy-combustion schemes: it can be used oxy-combustion in the regenerator since the values of both cases are the same.

TABLE II
OPTIMAL VALUES OF THE POST-COMBUSTION

Optimized Variables	Regenerator	Reactor
Air flow rate	54.76	54.76
Feed flow rate	83.00	98.41
Flue Gases flow rate	58.20	58.19
Product flow rate	80.824	70.017
Regenerated Catalyst flow rate	388.96	414.91
Spend Catalyst flow rate	392.39	443.31
Air Temperature	450.00	-
Feed Temperature	-	400.00

TABLE III
OPTIMAL VALUES OF THE OXY-COMBUSTION

Optimized Variables	Same heat		Same volume	
	Regenerator	Reactor	Regenerator	Reactor
Oxygen	54.76	54.76	54.76	54.76
Feed	98.41	98.41	83	98.41
Flue Gases	58.79	58.79	58.8	58.79
Products	70.01	70.01	80.82	70.01
Regenerated Catalyst	415.22	415.22	388.96	415.22
Spend Catalyst	443.2	443.62	392.39	443.62
Oxygen Temperature	370	-	450	-
Feed Temperature	-	400	-	400

APPENDIX

TABLE IV
DATA

Variables at steady state	Temperature (°C)	Mass flow rates (kg/sec)	Specific heat (kJ/kg.°C)
Reference	25	-	-
Reactor	522	-	-
Regenerator	716	-	-
Coke	522	3.43	1.670
Feed	312	83.0	3.266
Fresh catalyst	312	0.38	1.193
Products	522	80.82	3.639
Regenerated catalyst	720	388.96	1.193
Spent catalyst	522	392.39	1.197
Post-combustion			
Air	450	54.76	1.0153
Flue gases	720	58.20	1.0932
Oxy-combustion/ Constant heat			
Oxygen	450	55.36	1.0466
Flue gases	720	58.80	1.0261
Oxy-combustion/ Constant volume			
Oxygen	450	54.76	1.0461
Flue gases	720	58.20	1.1021

TABLE V
DESIGN VALUES

Design Values	Reactor	Regenerator
Temperature range	496 – 565 (°C)	677 – 732 (°C)
Feed temperature range	204 – 400 (°C)	-
Air/Oxygen temperature range	-	370 – 593 (°C)
Residence time	3 (sec)	15 (min)
Heat of reaction	25,937 (kJ/sec)	-
Heat of combustion	-	141,602.86 (kJ/sec)
Heat losses	2 (%)	4 (%)

TABLE VI
ANALYSIS OF THE AIR/OXYGEN AND FLUE GASES IN THE REGENERATOR

Components	Post-combustion (wt.%)	Oxy-combustion (wt.%)	
		Constant heat	Constant volume
Air/oxygen			
Nitrogen	79	78.5	79
Oxygen	21	21.5	21
Total	100	100	100
Flue gases			
Carbon dioxide	19.35	93.68	93.68
Nitrogen	74.33	-	-
Oxygen	0.95	0.95	0.95
Sulpher dioxide	0.09	0.09	0.09
Water	5.28	5.28	5.28
Total	100	100	100

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