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About the Possibilities of the Heat Exchangers Network Retrofit for Post-Combustion CO_2 Capture Unit Without Stream Split

Oleksandr Yu. Perevertaylenko[a], Andrii O. Gariev*[a],Theodoros Damartzis[b], Leonid L. Tovazhnyanskyy[a], Petro O. Kapustenko[a], Olga P. Arsenyeva[a]

[a]National Technical University “Kharkiv Polytechnic Institute”, Frunze str. 21, 61002 Kharkiv, Ukraine
[b]Chemical Process and Energy Resourses Institute (CPERI), Center of Research and Technology Hellas (CERTH), Thermi , 57001, Thessaloniki, Greece
sodrut@gmail.com

There is an increasing interest in post-combustion CO_2 capture connected with climate change and further use of captured CO_2 in enhanced oil and gas recovery and as a feed to produce such products as methanol, dimethylether and others, use in hot dry rock technologies etc.

The currently used post-combustion method with monoethanolamine (MEA) absorption without stream split has two shortcomings: significant steam consumption to regenerate amine solution and relatively high cost of heat exchange equipment of absorption unit or Heat Exchange Network of Absorption Unit (HEN AU).

The variation of temperature differences on rich/lean heat exchanger was considered and its influence on heat supply, cost of HEN AU and cold utility consumption was searched. The high effective plate heat exchangers are proposed as components of HEN AU to decrease its cost. The possibility of flue gas stream heat integration for heat supply to the desorber was searched too.

1. Introduction

Today is an increasing interest in post-combustion CO_2 capture connected with climate change. The number of possibilities of captured CO_2 use as raw and as saleable product now increases. Except the traditional applications CO_2 is widely used in enhanced oil recovery, it is estimated as perspective heat carrier for hot dry rock technologies and suitable fluid for enhanced natural and shale gas and coal bed methane recovery. Olah et al. (2009) proposed to use captured CO_2 as key component for methanol synthesis as the base for dimethyl ether and gasoline production. The industrial scale plant was constructed in 2012 in Iceland for methanol synthesis from CO_2 extracted from geothermic sources and hydrogen obtained by electrolysis of water (Richter, 2012).

The method of CO_2 capture according to absorption process is not new and is known during about seventy years. It had been used for small scale carbon dioxide extraction from flue gas of boiler-houses for food industry. With highly increased demands of post combustion CO_2 capture it is necessary to use high effective and economically feasible technologies.

2. State-of-art review

Modern industrial-scale technologies of post combustion CO_2 capture are amine solvent based absorption processes (Global CCS Institute, 2012). Now mostly used processes with monoethanolamine (MEA) solutions as absorbents are: Kerr-McGee&ABB process (15-20 % wt. MEA+inhibitor) and Fluor Daniel (Econamine FG^{TM}, 30 % wt. MEA + inhibitor). These processes are successfully used for CO_2 post combustion capture from coal fired sources and gas turbine exhausts. The main drawbacks of use the MEA solutions, such as solvent loss, degradation, corrosion activity and relatively high heat demand for

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regeneration, led to development of another absorbents and appropriate processes: Mitsubishi Heavy Industry KM-CDR industrial scale process (KS-1 sterically hindered amine solution), Powerspan ECO_2^{TM} process ready for scale-up (mixture of aqueous amines), Siemens POSTCAP ^{TM} pilot scale process (amino acid salts solution),(Sandell,2010).

The processes mentioned above have similar principles of units, flowsheets and equipment item. The unit consists of two parts: one part is flue gas cooling and SO_x scrubbing (in case of high SO_x content the “warm” scrubber is used) and another part is absorption unit with absorber, desorber and appropriate heat exchangers network of absorption unit (HEN AU). HEN AU consists of boiler that supplies the heat to the bottom of desorber, rich/lean heat exchanger to recuperate the heat of hot lean absorbent by cold rich absorbent, top condenser for water vapour/ CO_2 mixture and cooler of lean absorbent before the absorber. There is single stream of rich absorbent and single stream of lean absorbent.

The number of researches are dedicated to enhance the energy efficiency of post-combustion capture with process modifications and AU integration. Feron (2009) presented the results of analysis of single stream AU for various chemical absorbents to achieve a reduced energy use for solvent regeneration. He estimates minimal possible temperature approach for rich/lean recuperative heat exchanger but not mentioned about the cost of this position depending on temperature approach value and kind of absorbent. Le Moullec and Kanniche (2010) made the evaluation of flowsheet modifications of monoethanolamine AU for post-combustion CO_2 capture. They considered such modifications as the staged feed of the desorber, the lean solvent vapour compression and the overhead compression. Authors supposed that lean solvent vapour compression is the most effective way for heat consumption decreasing with AU but the cost of HEN AU increased and additional power for vapours compression. For the flow splitting approach it is noticed that heat consumption may be decreased on about 27-30 %. For further effect these processes has to be coupled with more effective solvents and the Process integration of HEN AU with another part of post-combustion unit and power plant is necessary. Neveux et al. (2013) focused their researches on the improvement of AU process flow scheme to reduce the energy consumption. They searched five amine-based solvents including monoethanolamine. In particular they considered the use of heat pumps for lean solvent vapour compression and overhead desorber vapour compression. Authors noticed that process modifications using heat pumpsare always better when the associated coefficient of performance is higher, meaning that for lean solvent vapour compression heat pump use is more efficient when the solvent regeneration take place at higher pressure.

Two possibilities of heat integration were discussed. First possibility considered by Cousins et al.(2010) related to inside HEN AU heat integration and was connected with use of top condenser for water vapor/CO_2 as the preheater of rich absorbent before rich/lean recuperative heat exchanger. Another case mentioned by Feron (2009) related to fossil fuel power station total site integration where the heat ejected in top condenser and lean absorbent cooler may be used for preheating of boiler feed water.

The recuperation of heat of lean solvent after desorber with rich solvent going to desorber is the key technological position that influence on the heat consumption of HEN AU of the post-combustion unit and thecold utility consumption.

This work is focused on the investigation of the rich/lean recuperative heat exchanger temperature approach influence on heat consumption of HEN AU, cold utility consumption with lean absorbent cooler and in parallel the cost of the rich/lean heat exchanger depending on temperature approach for plate and shell-and tube heat exchangers. Some alternative options of HEN AU integration are discussed.

3. Possibilities of HEN AU improvement

3.1 General

HEN AU efficiency is an important factor of effective duty of whole capture unit. From the other side the cost of equipment is another significant factor that influences on the selection of capture unit design. Cost factor depends on capacity of post-combustion capture unit, of percentage of CO_2 captured from flue gas, nature of absorbent, absorbent flowrate and others. So the cost factor for HEN AU should be considered together with energy efficiency.

The heat consumption for MEA-solution regeneration which is supplied to boiler may be expressed as:

$$Q = Qdes + Qh + Qev + Qlosses \qquad (1)$$

,Where $Qdes$ – heat of carbon dioxide desorption,

Qh - heat for MEA solution heating in desorber,

Qev - heat for evaporation of water at the top of the desorber,

$Qlosses$ – heat losses in HEN AU, approximately not more than 5%;

$$Qdes = Gcd * Hd \tag{2}$$

Where Gcd – mass flowrate of captured carbon dioxide,
Hd – specific heat of desorption;

$$Qh = Gmea * Cmea * (t1-t2) \tag{3}$$

Where $Gmea$ – mass flowrate of MEA solution circulated,
$Cmea$ – overall specific heat capacity of MEA solution circulated,
$t1$ – outlet temperature of lean MEA solution from desorber,
$t2$ – outlet temperature of rich MEA solution from rich/lean recuperative heat exchanger.

This temperature difference may be called as temperature approach at “hot end” of the rich/lean recuperative heat exchanger. Because of single stream flowsheet of HEN AU the temperature approach at “hot end” is actually equal to the temperature approach at “cold end” of the recuperative heat exchanger:

$$(t1-t2) = (t3-t4) \tag{4}$$

Where $t3$ – outlet temperature of lean MEA solution from rich/lean recuperative heat exchanger,
$t4$ - outlet temperature of rich MEA solution from absorber.

For single stream flowsheet of HEN AU this value may be called as temperature approach at rich/lean recuperative heat exchanger (ARHE).

$$Qev = h * Gvgm \tag{5}$$

Where h – specific enthalpy of the mixture of carbon dioxide and water vapour mixture at the top of desorber,
$Gvgm$ – mass flow rate of the vapour-gas mixture.

With use of this mathematical model the influence of ARHE on total heat consumption of the absorption unit with circulated MEA solution as absorbent and on the rich/lean recuperative heat exchanger cost may be estimated.

3.2 Case study

The case study is the post-combustion capture unit of coal fired power plant with capacity of 7,700 kg/h of CO$_2$. The flowsheet is traditional single stream with 20 % wt. MEA solution circulated as absorbent. The principal flowsheet is presented in Figure 1.

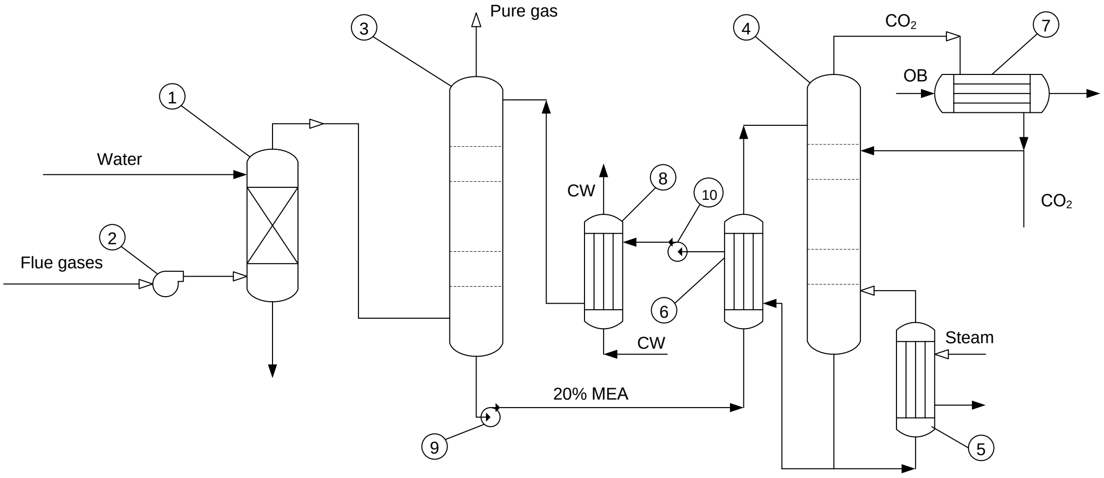

Figure 1. The principal flowsheet for simulated case study

Table 1. Fixed streams data for simulated HEN AU

Parameter	Value
1. Circulated absorbent flowrate	279 t/h
2 .Outlet temperature of lean MEA solution from desorber (*t1*)	126 ^{o}C
3. Inlet temperature of lean MEA solution to absorber	40 ^{o}C
4. Outlet temperature of rich MEA solution from absorber (*t4*)	60 ^{o}C
5. Flue gas supply temperature	300 ^{o}C
6. Inlet temperature of flue gas to absorber	40 ^{o}C
7.Flue gas mass flowrate	19.5 t/h
8. Cooling water (CW) supply and return temperature	20 ^{o}C; 45 ^{o}C
9. Saturated steam to boiler	130 -150 ^{o}C
10. Minimal permissible pressure drop in recuperative heat exchanger for lean MEA solution	5 m of water gauge

In Figure 1 the positions are: 1- flue gas water scrubber, 2- exhauster, 3- absorber, 4- desorber, 5- boiler, 6- rich/lean recuperative heat exchanger,7- top condenser, 8- lean MEA solution cooler, 9- rich solution pump, 10- lean solution pump. The fixed streams data are presented in Table 1.

The range of ARHE variation was selected from 15 °C to 30 °C. For each selected ARHE the heat consumption of AU (Q), heat duty of rich/lean recuperative heat exchanger(Q_{rec}) and heat duty of lean MEA solution cooler (Q_{cl}) were calculated. The plate and shell-and-tube heat exchangers were calculated with use of special software. The results are presented in Tables 2 and 3.

Table 2. The heat consumption of AU and heat duty of recuperative heat exchanger and lean MEA solution cooler

ARHE ,^{o}C	Q,kW	Q_{rec},kW	Q_{cl},kW
30	15,627	10,332	16,107
24	14,574	12,054	14,174
20	14,456	13,200	12,852
18	14,374	13,776	12,210
15	14,294	14,631	11,246

Table 3. Heat exchange area and cost of rich/lean recuperative heat exchanger for different ARHE: plate and shell-and-tube units

Type of heat exchanger	ARHE, ºC	Q_{rec}, kW	Heat exchange area, m^2	Cost, $
Plate heat exchanger	30	10,332	70	39,060
	24	12,054	96	53,568
	20	13,,200	130	72,540
	18	13,776	154	85,832
	15	14,631	200	111,600
Shell and tube heat exchanger	30	10,332	704	102,784
	24	12,054	1,020	148,,920
	20	13,200	1,432	210,504
	18	13,776	1,541	224,986
	15	14,631	1,951	284,846

As a plate units the plate-and-frame heat exchangers were selected with stainless steel AISI 316 plates and as a shell-and-tube units - the standard heat exchangers with carbon steel tubes and shells were selected. The lean MEA solution is directed inside tubes for possibility of cleaning.

The small decreasing of energy consumption with capture unit, only 9 %, is obtained with ARHE decreasing from 30 ^{o}C to 15 ^{o}C. It is resulted by repartition of components of the equation (1).*Qdes* is not significantly changed and practically not influenced on changing the energy consumption; *Qh* decreases proportionally to ARHE reduction. The value of *Qev* is dependent on reflux ratio at the top of desorber and significantly increases when the temperature of rich MEA solution after rich/lean heat exchanger is more than 102 °C.

The increasing of heat duty of rich/lean recuperative heat exchanger lead to increasing of its heat transfer area demand that causes the increasing of heat exchanger position cost and the cost of whole AU unit. (Klemeš et al. 2005) pointed to importance of capital cost estimation in total capital requirement of carbon capture unit. To reduce capital cost of the rich/lean heat exchanger position it is reasonable to consider different types of heat exchangers use: plate-and-frame and shell-and-tube, as mentioned above.

Plate heat exchangers are one of the efficient types of heat exchangers with intensified heat transfer caused by enhanced turbulent parameters in channels (Arsenyeva et al., 2013). As it is seen from Table 2 the cost of plate heat exchangers for ARHE range 15 °C-18 °C is 2.5-2.6 times less than cost of shell-and-tube heat exchangers.

Decreasing the ARHE on recuperative heat exchanger causes the decreasing of lean MEA solution cooler duty i.e. reduction of heat ejection into environment. The optimal ARHE on recuperative rich/lean heat exchanger is around 18 °C, but for well - grounded optimization it is necessary to perform more detail techno-economic modelling.

3.3 Flue gas heat integration.

The heat of flue gas before water scrubber may be used for MEA solution boiling. In this case the flue gas may be co and H_2SO_4 that present as reaction products between water vapours and SO_x in flue gas that demands the use of stainless steel made heat exchanger and increases the capital cost of this position. Additional blowers for hot flue gas are necessary too. For case study described above the heat recuperated from flue gas is 979.2 kW. It is 6.8 % of AU energy consumption.

3.4 Total site and other integration possibilities

Much of low-potential heat is ejected from lean MEA solution cooler and top condenser with cooling water. The part of this heat may be used for water heating in water make-up unit instead of steam. For power station the water consumption to demineralization is not big, so this possibility of integration is limited. It is more promising for CO_2 capture from furnaces in chemical plants where large amounts of demineralized water are necessary particularly in big capacity ammonia and methanol plants.

A multi-objective regional total site integration conception (Čuček et al. 2013) in scope of considered problem may be a forward-looking.

4. Conclusions

The rich/lean recuperative heat exchanger position was searched. The influence of the temperature approach on the cost of this position is significant but decreasing of energy consumption by desorber is only 9 % in searched temperature approach range. So the possibilities in heat consumption reduction by temperature approach on rich/lean heat exchanger decrease for HEN AU without streams splitting is limited. The future search may be focused on another topology of rich and lean solutions in rich/lean recuperation position. Another significant thing is the evident advantage of plate heat exchangers use as cost saving equipment.

Possibilities of external integration were considered and may be the subjects of further researches.

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References

Olah G.A., Goeppel A., Surya Prakash G.K., 2009, Chemical Recycling of Carbon Dioxide To Methanol and Dimethyl Ether :From Greenhouse Gas to Renewable Environmentally Carbon Neutral Fuels and Synthetic Hydrocarbons, “Journal of Organic Chemistry”, 742,487-498

Richter A., Opening of CO_2 to Methanol plant at Svartsengi geothermal plant, April, 2012, <thinkgeoenergy.com/archives/10711> accessed 30.07.2014

Global CCS Institute. CO_2 Capture Technologies. Post Combustion Capture (PCC), January 2012, 1-17

Sandell M.A., 2010, An Overview of the Current Status of the Siemens POSTCAP process. Siemens Environmental Systems & Service Presentation, 1-7

Feron P.H.M., 2009, The potential for improvement of the energy performance of pulverized coal fired power stations with post-combustion capture of carbon dioxide, Energy Procedia, 1, 1067-1074

Le Moullec Y., Kanniche M., 2010, Description and evaluation of flowsheet modifications and their interaction for an efficient monoethanolamine based post-combustion CO_2 capture, Chemical Engineering Transactions, 21, 175-180

Neveux T., Le Moullec Y. ,Cornou J.P. ,Favre E.,2013, Energy Performance of CO_2 Capture processes Interaction Between Process Design and Solvent, Chemical Engineering Transactions, 35, 337-343

Cousins A., Wardhaugh L.T., Feron P.H.M., 2010, Preliminary analysis of process flow sheet modifications for energy efficient CO_2 capture from flue gases using chemical absorption, Proceedings of Distillation & Absorption Conference, Eindhoven, Netherlands, 187-192

Klemeš J., Bulatov I., Cockerill T., 2007, Techno-Economic Modelling and Cost Functions of $CO_{2,}$ Capture Process; Computers & Chemical Engineering, 31 (5–6) 445-455

Arsenyeva O.P., Tovazhnyanskyy L.L., Kapustenko P.O., Demirskiy O.V., 2013, The Modified Analogy of Heat and Momentum Transfers for Turbulent Flows in Channels of Plate Heat Exchangers, Chemical Engineering Transactions, 35, 487-492

Čuček L., Varbanov P.S., Klemeš J.J., Kravanja Z., 2013, Multi-Objective Regional Total Site Integration, Chemical Engineering Transactions,35,97-102.