Economical aspects of the CCS technology integration in the conventional power plant

Nela SLAVU

University Politehnica of Bucharest, Bucharest, Romania

Cristian DINCA

University Politehnica of Bucharest, Bucharest, Romania

crisflor75@yahoo.com

Abstract. *One of the way to reduce the greenhouses gases emissions generated by the fossil fuels combustion consists in the Carbon Capture, Transport and Storage (CCS) technologies utilization. The integration of CCS technologies in the coal fired power plants increases the cost of the energy generation. The CCS technology could be a feasible solution in the case of a high value of a CO₂ certificate but for the present value an optimization of the CCS technology integration in the power plants is expected. However, for reducing the cost of the energy generated in the case of CCS integration in the power plants, a parametrical study optimization of the CO₂ capture process is required. In this study, the chemical absorption process was used and the monoethanolamine with 30 wt. %. The objective of this paper is to analyze the effects of the package type used in the absorption column on the size of the equipment used and, on the energy cost of the power plant with CO₂ capture process consequently. The packages types analyzed in this paper are metal Pall rings with different sizes and the rings are made of different metals: aluminum, nickel, cooper, and brass. In the case of metal Pall rings, the utilization of different material has an impact on the absorption column weight. Also, Pall rings made of plastics (polypropylene and polyethylene) were analyzed. The comparative assessment was achieved for a coal fired power plant with an installed power of 100 MW and considering the CO₂ capture process efficiency of 90 %.*

Keywords: coal, power plant, CCS, chemical absorption, monoethanolamine.

Introduction

In the last years, an important growing of carbon dioxide concentration in the atmosphere was observed. This tendency is caused by the industry development and the raising of global living standards. The International Energy Agency (IEA) recommends the diminishing at least 80 % of carbon dioxide emissions from the energy sector until 2050, for reducing the climate change effect. Nowadays, only the fossil fuels and nuclear energy primary resources are not enough to respond of the global energy requirements (Rahman et al., 2017, Badea et al., 2010).

Nowadays, the development of the energy sector only by using both the renewable energy and nuclear power plants is not sufficient to assure the electricity requirements at the global scale. On the other hand, the utilization of the fossil fuels for electricity production generate in the environment a large amount of emissions (Dinca, 2013). For example, the amount of the CO₂ emissions generated in the environment depends on the combustion technology type (e.g. Circulated Fluidized Bed Combustion technology, Pulverized technology, etc.), on the fuel type (e.g. in the case of lignite combustion, 850 kg_CO₂/MWh is generated, but for natural gas utilization, 450 kg_CO₂ are emitted for each MWh) (Dinca, 2016). In order to avoid the increasement of the power plant environmental impact, the CCS (Carbon Capture, Transport and Storage) technologies are required to be integrated in the fossil fuels power plants (Norisor et al.,

2012). In the last decades, a lot of CCS technologies was developed but not all are mature to be applied both in the energy or industrial sector. However, the post-combustion technologies are the most developed today comparing to the others (Porter et al., 2016). In this context, one technology, the chemical absorption process, could be applied both for new or existing power plants. Despite of its flexibility, the chemical absorption process integration in a power plant has a negative impact on the power plant global efficiency due to the amount of steam required for chemical solvents regeneration (Dinca and Badea, 2013). Additionally, the integration of the chemical absorption process leads to the electricity cost increase with 30-70 % (according to the power plant used) (Liang et al., 2016).

In this way, in the present study the authors studied the equipment of the chemical absorption process in order to optimize them and to reduce the electricity cost. Consequently, the power installed in the coal fired power plant analyzed in the paper is 100 MW, and in the chemical absorption process used for CO₂ separation the monoethanolamine 30 wt.% is assumed to be used.

Coal fired power plant

The chemical absorption technology is integrated into a power plant with a power installed of 100 MW. In Table 1 is presented the lignite and flue gases composition, the flue gases composition is for dry and wet gases.

Table 1. *Lignite and flue gases composition*

Elementary lignite composition							
C ⁱ [%]	H ⁱ [%]	S ⁱ [%]	O ⁱ [%]	N ⁱ [%]	W ⁱ [%]	A ⁱ [%]	LHV [kJ/kg]
35	1	1	2	2	27	32	12110
Flue gases composition							
	Dry gases			Wet gases			
CO ₂ , [%]	12.6306			11.6255			
SO ₂ , [%]	0.1352			0.1244			
N ₂ , [%]	79.6352			73.2984			
O ₂ , [%]	7.5991			6.9944			
H ₂ O, [%]	-			7.9573			

Source: Authors' own research.

Table 2. *Main data of the power plant*

Parameter	Values	U.M.
Power installed	100	[MW]
Pressure steam	190	[bar]
HP steam	550	[°C]
MP steam	550	[°C]
Average annual temperature river water	15	[°C]
Average annual temperature water from cooling tower	22	[°C]
River water share in total flow cooling water	25	[%]
Net power plant efficiency	39.23	[%]
Flow rate fuel	66.45	[t/h]
Mass flow rate flue gases	372968	[kg/h]
Volumetric flow rate flue gases	381159	[Nm ³ /h]
Electricity generated	485649	[TWh/an]

Source: Authors' own research.

The main data of the lignite power plant are shown in Table 2. It was calculated the flow rate fuel, the flow rate flue gases for an excess air of 1.56 and the amount of electricity produced for an annual power plant operation of 6000 h/year. In the case of determining the net power plant efficiency was used thermodynamic cycle diagram

shown in Figure 1. In this case, the thermodynamic cycle is composed of 3 preheaters for low/high pressure and a degasser. The fuel combustion efficiency is of 85.87 %.

Figure 1. Power plant with CO₂ capture

Source: Dinca and Badea, 2013.

The technology for CO₂ capture by chemical absorption consists of passing the flue gases in countercurrent through an absorption column (Figure 2) where the flue gases are mixed with the amines solution. The flue gases treated leaving the absorption column at the top, while the CO₂ rich solvent exits at the bottom. The CO₂ rich solvent enters a heat exchanger which recovers a part of the heat transferred by the CO₂ lean solvent. The regeneration of the CO₂ rich solvent is performed in the desorption column. The amount of thermal energy required for the rich solvent regeneration is obtained by using a steam ratio from the low pressure steam turbine. The CO₂ lean solvent enters in the absorption column at the top, not before to transfer a part of heat the CO₂ rich solvent. In order to meet the requirements of the mass concentrations of solvent in the amine solution is added a new amount of amine. The process pressure is obtained by using pumps (Dinca and Badea, 2013).

In the process of CO₂ capture by chemical absorption are encountered the following equipment: flue gases ventilator, system of cooling flue gases, two heat exchangers (liquid/liquid), absorption column, desorption column, pumps used to transport the solvent or the water cooling, monitoring equipment of the different parameters of the process, chemical solvent recycling system, recipient with new chemical solvent in order to maintain the same mass concentrations of the solvent.

In the Table 3 are shown the entry data for the fin-and-tube heat exchanger. The primary agent is represented of the flue gases and the secondary agent of water. The obtained results are presented in the Table 4.

Table 3. Entry data fin-and-tube heat exchanger

Parameter	Notation	Value		U.M
		HX1	HX2	
Mass flow rate primary agent	$\dot{m}_1$	51.8	51.8	[kg/s]
Inlet temperature primary agent	T_1'	155	120	[°C]
Outlet temperature primary agent	T_1''	120	50	[°C]
Inlet temperature secondary agent	T_2'	10	10	[°C]
Outlet temperature secondary agent	T_2''	43	43	[°C]
Pressure primary agent	p_1	2.25	1.75	[bar]
Pressure secondary agent	p_2	1.4	1.4	[bar]
Outer diameter tube	d_e	0.04	0.04	[m]
Inner diameter tube	d_i	0.035	0.035	[m]
Diameter fin	d_a	0.06	0.06	[m]
Pitch fin	b	0.005	0.005	[m]
Thickness fin	δ_a	0.0005	0.0005	[m]
Pinch transversal bundle tubes	x_t	0.065	0.065	[m]
Pinch in depth bundle tubes	x_a	0.075	0.075	[m]
Velocity primary agent in free section	w_1	7	7	[m/s]
Velocity secondary agent in free section	w_2	0.5	0.5	[m/s]
Efficiency heat exchanger	η_{sch}	97	97	[%]

Source: Authors' own research.

Table 4. Fin-and-tube heat exchanger

Parameter	Equation	Value		U.M
		HX1	HX2	
Thermal load	$\dot{Q}_1 = \dot{m}_1 \cdot c_{p1} \cdot (T_1' - T_1'')$	2.148	4.312	[W]
Amount heat transferred secondary agent	$\dot{Q}_2 = \dot{m}_2 \cdot c_{p2} \cdot (T_2'' - T_2')$ $\dot{Q}_2 = \eta_{sch} \cdot \dot{Q}_1 = \dot{Q}$	2.084	4.183	[W]
Logarithmic mean temperature difference (ε -factor correction, according to P and R)	$\Delta T_m = \varepsilon \cdot \Delta T_{mc}$ $\Delta T_{mc} = \frac{(T_1'' - T_2') - (T_1' - T_2'')}{\ln \frac{(T_1'' - T_2')}{(T_1' - T_2'')}}$	105	46.6	[K]
Length fin	$h_a = \frac{d_a - d_e}{2}$	0.01	0.01	[m]
Degree of filling	$\gamma = 1 - \frac{d_e}{x_t} \cdot (1 + 2 \cdot \frac{h_a}{b} \cdot \frac{\delta_a}{d_e})$	0.354	0.354	-
Volumetric flow rate primary agent	$\dot{V}_1 = \frac{\dot{m}_1}{\rho_1}$	26.313	22.367	[m ³ /s]
Free section	$S_1 = \frac{\dot{V}_1}{w_1}$	3.759	3.338	[m ²]

Parameter	Equation	Value		U.M
		HX1	HX2	
Minimum section	$S_{\min} = \gamma \cdot S_1$	1.33	1.181	[m ²]
Maximum velocity primary agent	$w_{\max} = \frac{\dot{V}_1}{S_{\min}}$	19.78	19.78	[m/s]
Reynolds number primary agent	$Re_1 = \frac{w_{\max} \cdot b}{\nu_1}$	9134.7	11454.7	-
Nusselt number primary agent	Nu_1	24.7	28.6	-
Heat transfer coefficient primary agent	$\alpha_1 = Nu_1 \cdot \frac{\lambda_1}{b}$	156.8	161.5	[W/(m ² ·s)]
Mass flow rate secondary agent	$\dot{m}_2 = \frac{\dot{Q}}{c_{p2} \cdot (T_2'' - T_2')}$	14.72	29.55	[kg/s]
Volumetric flow rate secondary agent	$\dot{V}_2 = \frac{\dot{m}_2}{\rho_2}$	0.015	0.03	[m ³ /s]
Total flow section secondary agent	$S_2 = \frac{\dot{V}_2}{w_2}$	0.03	0.059	[m ²]
Tubes section	$S_t = \frac{\pi \cdot d_e^2}{4}$	0.001257	0.001257	[m ²]
Maximum number calculated of tubes	$N_{\max, \text{calculat}} = \frac{S_2}{S_t}$	24	48	-
Total section tubes	$S_{\text{total}} = N_{\max} \cdot S_t$	0.03	0.06	[m ²]
Reynolds number secondary agent	$Re_2 = \frac{w_2 \cdot d_i}{\nu_2}$	20277.5	20277.5	-
Nusselt number secondary agent	Nu_2	161.4	146.2	-
Heat transfer coefficient secondary agent	$\alpha_2 = Nu_2 \cdot \frac{\lambda_2}{d_i}$	2814.8	2549.3	[W/(m ² ·s)]
Overall heat transfer coefficient	$k = \frac{1}{\frac{1}{\alpha_1} + \frac{\delta}{\lambda_{\text{otel}}} + \frac{1}{\alpha_2}}$	147.22	150.6	[W/(m ² ·s)]
Heat exchange area	$S = \frac{\dot{Q}}{k \cdot \Delta T_{\text{med}}} [m^2]$	134.8	596.4	[m ²]
Length tube (Choose a number of passes n_{tr})	$l = \frac{S}{\pi \cdot d_e \cdot N_{\max} \cdot n_{tr}}$	7.44	16.5	[m]
Number fins	$n_a = \frac{l}{b + \delta_a}$	1354	2996	-

Source: Authors' own research.

Absorption column

The chemical absorption process requires the existence of two phases: liquid and gas. In this case, the gas phases is represented of the flue gases and the liquid phases of the chemical solvent (Hadri et al., 2017). The chemical solvent is a mixture of

monoethanolamine (MEA) and water in a different weight ratios (MEA-30 %, H₂O-70 %).

The equilibrium absorption of carbon dioxide varies according to the height of the absorption column because the kinetics of the chemical reactions between the carbon dioxide and the chemical solvent is a function of temperature, and the temperature profile varies along the absorption column (Pascu et al., 2016). The flue gases velocity through the column is limited by a condition imposed by entrainment gas and liquid phase (Wang et al., 2015). On the other hand, the absorption column is designed for the highest value of the velocity so that the acquisition costs be as low. Considering the large amount of circulated flue gases, the absorption column represents the largest equipment used in the CO₂ capture technology. In the column are different packing which are designed to increase the area of the contact between the chemical solvent and the carbon dioxide from flue gases.

The material streams balance in and out of the column is represented by the following equation (Dinca et al., 2015):

$$N_{CO_2} = G \cdot (Y_i - Y_e) = L \cdot (X_e - X_i) \text{ [kmol}_{CO_2} / h] \quad (1)$$

where: N_{CO_2} - is the CO₂ flow transferred from the gas phase in the liquid phase, in [kmol_{CO₂}/h]; G - is the flow rate of the flue gases, at in/out from the column, in [kmol_{ga}/h]; L - is the flow rate of the chemical solvent, at in/out from the column, in [kmol_{solvent}/h]; Y_i, Y_e - is the CO₂ concentration in the flue gases, at in/out from the column, in [kmol_{CO₂}/kmol_{ga}]; X_i, X_e - is the CO₂ concentration in the chemical solvent, at in/out from the column, in [kmol_{CO₂}/kmol_{solvent}].

In order to characterize the chemical absorption process, the CO₂ capture efficiency was considered of 90 %.

The point of view the thermal condition, the chemical absorption can be performed the isothermal and non-isothermal condition. In the isothermal condition the concentration of the solute in the gas phase is small, and absorption is performed in a high amount of absorbent. In the non-isothermal condition, the concentration of the solute in the gas phase is high, and absorption is performed in a small amount of absorbent. In this case the integral heat of dissolution can increase the liquid phase temperature up to a value at which the desorption process starts. To prevent this situation is realized the cooling of the liquid phase inside or outside column (Wang et al., 2015).

Enthalpy of absorption for MEA at a temperature of 40 °C is – 50 kJ for each mole of solvent (Dinca, 2016).

The output optimum temperature of the flue gases and of the chemical solvent is calculated with the following equation (Badea and Dinca, 2012):

$$T_e = \frac{Q_{gi} + Q_{li} + Q_{ab} - Q_p}{(1 + \bar{Y}_e) \cdot G_m \cdot c_{p_{ge}} + (1 + \bar{X}_e) \cdot L_m \cdot c_{p_{le}}} = 56.7 [^{\circ}C] \quad (2)$$

where: Q_{gi} - is the heat of the flue gases the column entry, in [W]; Q_{li} - is the heat of the chemical solvent the column entry, in [W]; Q_{ab} - is the heat of the absorption, in [W]; Q_p - are the heat losses; G_m - is the mass flow rate flue gases, in [kg_{ga}/s]; L_m - is the mass flow rate chemical solvent, in [kg_{solvent}/s]; $\bar{Y}_e$ - is the CO₂ weight concentration in the flue gases at the column exit, in [kg_{CO₂}/kg_{ga}]; $\bar{X}_e$ - is the CO₂ weight concentration in the chemical solvent at the column exit, in [kg_{CO₂}/kg_{solvent}]; $c_{p_{ge}}, c_{p_{le}}$ - are the specific heats at the constant pressure for flue gases/chemical solvent at the column exit, in [J/(kg·K)].

The diameter of the absorption column is a factor that influences the velocity of the phases. The optimal functioning of the column is performed at determinate ratios between the amount the chemical solvent and the velocity (amount) of the gases circulating in countercurrent. To calculating the absorption column diameter with packing is applied Kafarov equation (Kim and Lee, 2017):

$$\lg \left(\frac{w_{ic}^2 \cdot \sigma \cdot \rho_g \cdot \eta_l^{0.16}}{g \cdot V_l^3 \cdot \rho_l} \right) = A - 1.75 \cdot \left(\frac{L}{G} \right)^{0.25} \cdot \left(\frac{\rho_g}{\rho_l} \right)^{0.125} \quad (3)$$

where: w_{in} - is the flooding vapor velocity, in [m/s]; σ - is the surface area of the packing, in [m²/m³]; g is the gravitational acceleration, in [m/s²]; V_l - is free volume of the packing, in [m³/m³]; ρ_g and ρ_l - are the densities of the flue gases and the chemical solvent, in [kg/m³]; η_l - is the dynamic viscosity of the chemical solvent, in [Pa·s]; L and G - are the mass flow rate of the flue gases and chemical, in [kg/s]; $A = 0.022$, for packing rings and spirals.

The type of the packing influences the absorber column size and implicitly the acquisition costs. In the table below are presented the characteristics of different types of packing studied in this article.

Table 5. Operational data PALL-Rings

Type PALL-Rings	Size	Weight	Number	Specific Surface	Free volume
	[mm]	[kg/m ³]	[per m ³]	[m ² /m ³]	[%]
Metal	25 x 25 x 0.6	460	51000	215	95
Stoneware/porcelain	25 x 25 x 3	620	39900	220	75
Plastics	25 x 25	75	54600	220	91

Source: Pascu et al., 2016.

The height of the absorption column with packing is determined by the height of the layer packing. The height of the layer packing resulted from the equation of the effective mass transfer area (Liang et al., 2016).

The effective height of the absorption column is calculated by the equation [13]:

$$H_{col.abs} = n_{str} \cdot h_u + (n_{str} - 1) \cdot h_1 + h_2 + h_3 = 38.4 \text{ m} \quad (4)$$

where: h_1 - is the distance between two layers of packing (0.5 ÷ 1 m); $h_1 = 0.5 \text{ m}$; h_2 - is the distance from the top of the first layer of packing to the top of the column (1 ÷ 1.5 m); $h_2 = 1 \text{ m}$; h_3 - is the distance from the bottom of the last layer of packing up the bottom of the column (1 ÷ 2 m); $h_3 = 1 \text{ m}$.

In the Table 6 are presented results obtained for the size of the absorption column according to the type of the packing used.

Table 6. Sizes absorption column

Type PALL-Rings	Flooding velocity	Diameter column	Packing height	Column height	Mass column
	[m/s]	[m]	[m]	[m]	[t]
Metal	2.728	10.3	35.9	40.4	1462.7
Stoneware/porcelain	1.892	12.4	25.1	29.5	1948.3
Plastics	2.529	10.7	33.4	37.9	296.6

Source: Authors' own research.

Desorption column

Order to the desorption process using a column to which sizing is performed the same as that of the absorption column. Thus, for desorption column (Figure 4), we only calculated the necessary stripping steam.

Figure 4. Heat balance of desorption column

Source: Hadri et al., 2017.

The general equation of the heat flow balance to the desorption column is:

$$Q_{initial_solvent} + Q_{steam_stripping} = Q_{CO_2} + Q_{steam_drive} + Q_{desorption} + Q_{absorbent+condens} + Q_p \quad (5)$$

Table 7. Equations to calculate the steam ratio for solvent regeneration

Parameter	Notation	U.M
Mass flow rate CO ₂ rich solvent	L	[kg/s]
Maximum flow rate steam	$\dot{m}_{steam}$	[kg/s]
Mass flow rate CO ₂	$\dot{m}_{CO_2}$	[kg/s]
Mass flow rate steam drive	$\dot{m}_{steam_drive}$	[kg/s]
Inlet temperature CO ₂ rich solvent	$T_{i,solvent}$	[K]
Outlet temperature CO ₂ rich solvent	T_{e,CO_2}	[K]
Outlet temperature absorbent and condense	T_e	[K]
Specific heat CO ₂ rich solvent	$c_{p,solvent}$	[J/(kg·K)]
Specific heat CO ₂ at outlet temperature	c_{p,CO_2}	[J/(kg·K)]
Specific heat H ₂ O	c_{p,H_2O}	[J/(kg·K)]
Enthalpy steam at temperature in column	i_{steam}	[J/kg]
Heat dissolution CO ₂	$-\Delta H_{ab}$	[J/kg]
Overall heat transfer coefficient	k	[W/(m ² ·K)]
Heat exchange area insulation	S_{iz}	[m ²]
Mean temperature difference	ΔT_m	[K]
Parameter	Equation	U.M
Heat flow introduced to chemical solvent	$Q_{initial_solvent} = L \cdot c_{p,solvent} \cdot T_{i,solvent}$	[J/s]
Heat flow introduced to steam stripping	$Q_{steam_stripping} = \dot{m}_{steam} \cdot i_{steam}$	[J/s]
Heat flow of CO ₂ output	$Q_{CO_2} = \dot{m}_{CO_2} \cdot c_{p,CO_2} \cdot T_{e,CO_2}$	[J/s]
Heat flow steam drive	$Q_{steam_drive} = \dot{m}_{steam_drive} \cdot i_{steam}$	[J/s]
Heat flow desorption	$Q_{desorption} = -\Delta H_{ab} \cdot \dot{m}_{CO_2} [W]$	[J/s]
Heat flow absorbent and condense	$Q_{absorbent+condens} = (L + \dot{m}_{steam} - \dot{m}_{steam_drive}) \cdot c_{p,H_2O} \cdot T_e$	[J/s]
Losses heat flow insulation layer	$Q_p = k \cdot S_{iz} \cdot \Delta T_{med}$	[J/s]

Source: Kim and Lee, 2017.

The steam ratio for solvent regeneration ($\dot{m}_{steam}$ [kg / s]) resulted of the equation of the heat balance (Table 7) for which the steam index is of 0.775 t_{steam}/t_{CO_2} . Also, it was

calculated the consumption index to capture a ton of CO₂, it is of 2.95 GJ/t_{CO2}. The result obtained is validated by the results of the scientific literature.

Results

The type of the packing influences the size of the absorption column and implicitly the cost of investment. We analyzed different type packing PALL-Rings: metal, stoneware/porcelain and plastics. In the case we used the PALL-Rings of metal the diameter of the absorption column (Figure 5) obtained was of 10.3 m, the higher value for diameter is in the case we used the PALL-Rings of stoneware/porcelain (12.4 m). The diameter of the column varies with the flooding vapor velocity, in the Figure 6 it is observed that with increasing the flooding velocity the diameter is smaller.

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Figure 5. Diameter column absorption according to type packing

Source: Authors' own research.

Figure 6. Flooding vapor velocity according to type packing

Source: Authors' own research.

The packing and the effective column height (Figure 7) varies according to the characteristics of the type packing used. The packing height for the stoneware/porcelain is of 25.1 m, for the plastics is of 33.4 m and for the metal is of 35.9. The characteristic which influences this values is the free volume for all of them. In the Figure 8 is represented the packing height according to the free volume. It is observed that in the case of the packing stoneware/porcelain the free volume is of 75 %, for the plastics is of 91 % and for the metal is of 95 %.

In the Figure 9 are shown the mass absorption column for the packings studied in this study. The weight is small for the plastics and bigger for the stoneware/porcelain. The cost of the absorption column varies (Figure 10) according to the mass of the absorption column. The least cost investment is for an absorption column with packing of plastics.

Figure 7. Packing and effective column absorption height according to type packing

Source: Authors' own research.

Figure 8. Packing column height according to free volume of type packing

Source: Authors' own research.

Figure 9. Mass absorption column according to type packing

Source: Authors' own research.

Figure 10. Cost absorption column according to type packing

Source: Authors' own research.

Conclusions

In this study we analyzed the CO₂ capture technology by chemical absorption, it was integrated in a power plant with power installed of 100 MW. The amine used was monoethanolamine in weight 30 %. The efficiency of CO₂ capture was considered of 90 %. The capturing a ton of CO₂ requires 2.95 GJ, this amount of thermal energy for the solvent regeneration is obtained by using a steam ratio from the low pressure steam turbine. The size of the equipments depends the flow rate of the flue gases, the CO₂ concentration in the flue gases, the CO₂ capture efficiency and the type amine used.

The size of the absorption column varies according to the characteristics of the type packing used. We analyzed different packings, respectively PALL-Rings made of metal, stoneware/porcelain and plastics. After the economical evaluation, the best option for the type of the packing resulted PALL-Rings of plastics.

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