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Opting of an Organic Rankine Cycle Based on Waste Heat Recovery System to Produce Electric Energy in Cement Plant

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Abstract

This study investigates the feasibility of installing a waste heat recovery system (WHR) in a cement factory in Iraq using the organic thermal Rankine cycle (ORC). Heat losses in the cement industries represent high energy consumption percentages of the total energy inputs. The production of clinker is a sub-process in the cement manufacturing plant and consumes three quarters of the total energy used as heat from combustion. The main sources of waste heat in the cement plant are identified, from these sources of waste heat from the kiln surface to the air, hot air coming out of the clinker cooler, and preheating exhaust gases. It is possible to obtain the total waste heat from these sources in the range of 35-40% of the total heat input. This waste heat energy can be exploited by installing a waste heat recovery system in these plants to generate electricity. It is possible to generate electrical energy by 5.9 MW. When using an organic system to recycle hot gases in plants whose daily production is up to 6000 tons, the installation of such a system could lead to saving 82.5 tons of fuel oil consumption per day, and reducing carbon dioxide emissions by 99.12 tons per day.

1. Introduction

This study was prepared to examine the using of waste heat from cement plants and the benefits from it to improve further performance of these plants through the installation of thermoelectric systems that work with organic liquids, especially there is an increasing in demand of fuel and its high prices on the one hand, and an increasing the CO_2 emissions to the atmosphere on the other hand. However, the cement factory contributes to raising this percentage directly when Clinker production and releasing CO_2. And for the purpose of reducing the high consumption of fuel used in cement plants in Iraq. For the continuity of economic growth in light of high fuel prices on the one hand and the environmental threats of pollutants and waste on the other hand, it must have reconsidered the technology of cement production through the installation of systems for recycling surplus heat to produce electricity, for example, as well as to reduce the depletion of natural resources. Especially in cement industry, which is considered as of energy-intensive industries that need to organize their energy management and search for new ways and means in order to preserve the environment and reduce energy expenditures. Where the cement industry is one of the vital industries due to its direct and effective relationship to the development process, and the fact that cement is one of the basics upon which the industrial, agricultural, service and urban development projects are based. Perhaps it is necessary to mention the high rank occupied by the cement industry in the local and regional market in previous years in terms of quality and accuracy of product specifications and the great role played by this industry in serving the Iraqi economy and urbanization [1].

With tightening emission of CO_2 regulation on heavy duty plants and increasing the prices of fuel oil, waste heat recovery (WHR) have been achieved under extensive study for many years ago, in cement sector the major portion of consumed energy is thermal energy and energy correspond to the total cost of operating expenses, wherefore the projects planner utilized (WHR) scenario to diminishing the total operating cost in cement plants and an appreciable amount of energy can be conserved by optimizing the plant operation. Expecting on the type of process, (WHR) can be rejected at substantially any high temperature waste gases from kiln industrial furnace. Usually higher the temperature, higher the quality and more cost effective [1]. Worreli and Galitsky studied the attempts of improving energy efficiency for a cement plant and mentioned some technologies for energy saving in clinker process [2]. Ozawa and Sheinbaum specified that use of the waste heat and improvement in the process decreased the rate of carbon dioxide emission by 17% in and energy density by 28% in the cement sector [3]. Liu et al. declared that recondition the process and the energy density improves energy efficiency between (10) % and (30) % in the cement sector in China [4]. Khuara et al. conducted a study in energy levels of Mexican cement industry and its CO_2 emissions percentage, and suggested to set up a cogeneration system [5]. Sathaye and Schumacher investigated the CO_2 and energy productivity [6]. Ahmed et al. selected an Organic Rankine cycle (ORC) in cement plant and evaluated the feasibility of (1) MW power production for the proposed system [7]. B. Saleh et al designed and studied the performance of an ORC system nonetheless depends on the selection of the working fluid and its specifications in terms of thermodynamics and environmental and safety criteria [8]. The (ORC) occupies on the principle of the Clausius-Rankine cycle, so that the system that used organic fluid with low boiling temperature and high vapour pressures as the thermal working fluid to generate power instead of water or steam. Although the recovered heat can be transformed into several useful forms such as electricity and district heating, the priority should be given to the direct use of energy sources such as geothermal and solar applications to avoid further losses [9].

The aim of this work is to improve the cement plants by using the surplus heat from cement process industry and from clinker cooling and to convert it to another type of energy like an electric energy by using waste heat recovery system. And the work assumed the amount of electrical energy for a cement plant daily capacity of 6000 tons can generate about 5.9 MW. And daily reduce CO_2 daily emissions amount 99.12 Tons.

2. Theoretical Part

2.1. Waste Heat Recovery Option

Capturing and transforming the amount of flue gases heat energy process always the first step in a well-planning energy reservation program to gain extra energy source. The energy source can be used this additional heat to generate electrical power. Once that target has been met, take into consideration the next level – waste heat recovery. WHR increase performance efficiency to higher levels, by kiln furnace and by air quenching cooler because those extract energies from the exhaust gases and recycle it to the process. Impressive efficiency improvements can be made even on furnaces that operate with properly tuned ratio and temperature controls.

The quantity of the available of flue gas can be measured by using equation (1) [10]:

$$\boldsymbol{Q} = \boldsymbol{V} \times \boldsymbol{\rho} \times \boldsymbol{C}_{P} \times \Delta T \qquad \textbf{(1)}$$

where: *ΔT:* is the difference in gases temperature (ºC) between the final highest temperature in the outlet and the initial temperature in the inlet of system, Cp: is the specific heat of the gases (kJ/kg.ºC), ρ : is density V is the flow rate of the flue gases (m^3/s)of the flue gas (kg/m^3), *Q* (kJ): is the potential heat content.

The waste flue gases can be recognized of two main branches of the heat dissipation from cement process, the first is coming from pre-heating row materials and the other from cooler exhaust gas. The feasibility of waste heat energy can vary significantly; the gain of the heat recovery energy can be shown in Figure (1) while using the heat source as a power input for waste heat boiling working media in heat exchanger to transfer the heat from source to heat sink.

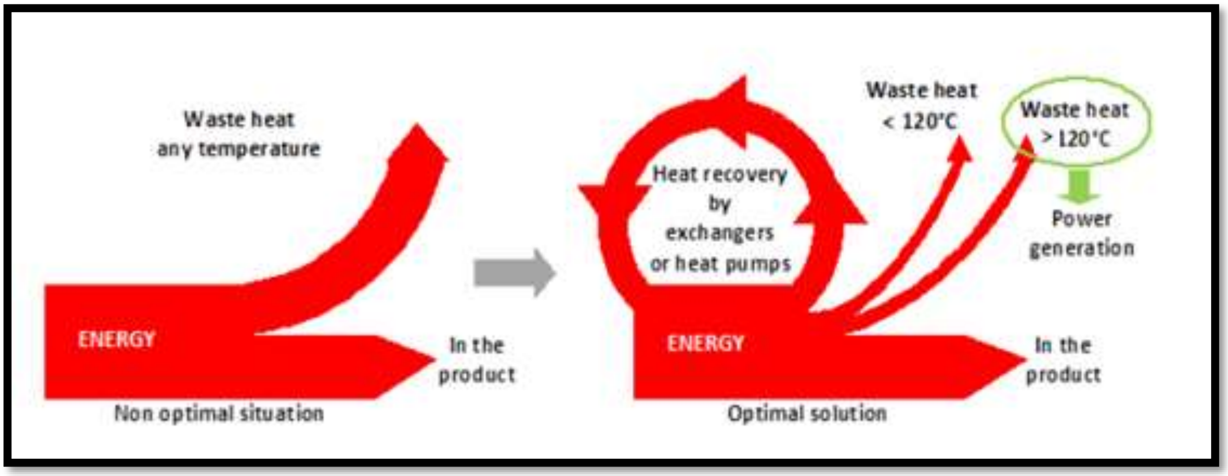

Figure (1). Simple scheme shows heat recovery flow without and with using waste heat recovery system [11].

There are three main workout systems: Clausius Rankune cycle system, Organic Rankine cycle system and Kalina cycle system, each one of them has its own disadvantages and advantages and superior system for each implementation depends upon the specifications of the particular plant.

2.2 Description of Main Mechanical Equipment

2.2.1 Preheater Heat Exchanger

The heat exchanger is a combined of pre-heater, flue gas conveys heat to thermal oil circuit that flowing throw tubes were built in the process system and can be depicted as recuperates [11].

2.2.2 Clinker Cooler Heat Exchanger

Another part of waste heat recovery available in cement plant is cooler exhaust air where outrageous from clinker cooler and is mostly exhausted to the surrounding air. The typical function of the clinker cooler is to dissipate the heat from the hot clinker discharged from kiln so that it can be handle by the posterior equipment and does not rise any impediment to moreover processing that is cement grinding, swift cooling also improves the quality. For analyzing this system, energy balance is applied in the control volume of every component and various efficiencies are calculated. The efficiency of heat exchange system is defined [12]:

$$\eta \mathbf{hex} = \frac{Qf}{Qhs} \qquad \textbf{(2)}$$

Q_{hs} is the heat source energy given by:

$$Qhs = mg(hg.1 - hg.amb) + ma(ha.1 - ha.amb) \qquad \textbf{(3)}$$

where: mg and ma are mass flow rate of flue gas and hot air respectively, and h is the enthalpy, Qf is the heat that the working fluid absorb it from the heat carrier source via the HCF circuit given by:

$$Qf = mf\,(hg - ht) \qquad \textbf{(4)}$$

2.2.3. Organic Rankine Cycle Based on Waste Heat Recovery

A suitable technique to recapture the surplus heat from clinkerization process is indirect ORC in medium temperature energy sources because of its low critical point of an organic fluid. The Organic Rankine cycle

(ORC) it's named for using of an organic, high molecular weight fluid with a liquid-vapor phase change, or its boiling point, occurring at a lower temperature than the Clausius Rankine Cycle barriers. In the optimal design, three partial systems should co-act dependably, efficiently and economically with respect to three partial systems. The basic theory of organic Rankine cycle that a heating medium is chosen for its convenience. The heat is fed to the heat exchanger by feed pump, expands through turbine, then condensates through condenser and feeds back again to the heat exchanger. A cycle will be assumed working in steady state conditions with less pressure drop in the system expected cross the turbine vanes, while the kinetic and prospect energies will be neglected [13].

For safety reason it's necessary in the indirect ORC based heat recovery system used a moderate heat convey fluid as heat carrier fluid (HCF) from the heat source to the working fluid system because most organic fluids are flammable and in case of failure of heat exchanger the hot medium of the heat source and the ORC fluid would get in contact in an explosion. There are two different closed loops scheme, one with the working fluid and the other with HCF. The HCF circuit soaks up heat from the flue gases and from the hot air, by using two heat exchangers in parallel (one for each waste heat stream), in order to transfer this heat to the organic fluid. The HCF absorbs the axcess heat to the extent that the temperature of both the surplus heat streams falls to 140 ^{O}C. The heat is then exchanged from HCF to the working fluid during the heat exchangers, which are the preheater, the evaporator and the superheater. At the inlet of the turbine, the working fluid has a maximum temperature 185^{O}C. The turbine exhaust enters the regenerator, before the condenser, in order to preheat the working fluid. This way the system recovers some of the energy released to environment through the condenser. The maximum pressure at the inlet of turbine (evaporation pressure) depends on the exit temperature of waste heat streams determined by a slight change of temperature difference of 10^{O}C is also set between the waste heat streams and HCF in the waste heat exchangers. The minimum pressure is the condensing pressure at the condensation temperature of 45^{O}C. The thermal efficiency of the cycle is defined:

$$\eta th = \frac{Wel}{Qf} \qquad (5)$$

where: *Wel* mean generated electric power after taking in to account the isentropic, mechanical and electrical efficiencies. The overall efficiency of the system is defined:

$$\eta sys = \frac{Wel}{Qhs} \qquad (6)$$

2.2.4. Feed Pump

The enthalpies increase though the pressure difference across the pump and the power could be assumed by equations 7 and 8, respectively [13]:

$$H2 - H1 = V(P2 - P1) \qquad (7)$$

$$Wp = m(h2 - h1) = \frac{m(h2 - h1)}{\eta} \qquad (8)$$

h2 and *h1* represent heating medium enthalpies at feed pump outlet and inlet, respectively, *v* represents a specific volume, and *P1* and *P2* are pressure values of outlet and inlet sides of the pump, respectively.

2.2.5. Turbine

In a turbine the energy will be extracted from ORC fluid isentropic enthalpy raise cross the turbine according to [14]:

$$WT = \eta\, m(h3 - h4) \qquad (9)$$

where: *h3 and h4* represent inlet, outlet of turbine and η is the efficiency of turbine, the turbine efficiency is given by the industrialist designer and it is a ratio between the real inlet enthalpy changes through the turbine to the largest possible enthalpy change (isentropic process) [13].

2.2.6. Energy Analysis for ORC Working Fluid

After the energy analysis of the both flue gas and hot air systems, an ORC analysis is performed. Power output is a maximum quantity of work that can be achieved by a system when a heat stream is brought to equilibrium in relation to the ambient conditions (P_o & T_o). In sum, turbine will be always working in the dry area. the ideal working fluid will be that has saturated vapor line is parallel to the expansion of the turbine line, ensuring maximum efficiency, lines converge, the turbine would operate in the wet region. In order to avoid this entire issue, it must restraint the working fluid to go through superheat region before the expansion occurs. Although, the lines mentioned above were divergent, the output working fluid of the turbine be overheated. This will increase significantly the size of the condenser surface area, that an aspect of related to the operating pressure system [12]. ORC analysis is a very valuable appliance for analyzing thermodynamic system parameters, as it's conceivable to determine the performance of each component by considering its behaviors due to losses. Figure (2) shows the T-S diagram of various ORC fluids. The calculation of ORC working fluid analysis depended on the four thermodynamic properties:

(Temperature (T), the pressure (P), the enthalpy (h) and the entropy (s).

The expression that gives the thermodynamically analysis at each point of the working fluid is considered in the following formula [12]:

$$\boldsymbol{Ei = (hi - ho) - To(Si - So)} \qquad \textbf{(10)}$$

Where: *ho & So* are the enthalpy and entropy at ambient condition for organic working fluid, *Ei* is the energy or ORC working fluid. The ORC cycle losses due to mechanical and electrical inefficiencies are taken in consideration but the heat losses of the system units are ignored. Hence for ORC system cycle efficiency can be applied equation (5) for ORC cycle [13]:

$$\eta \mathbf{t} = \frac{\mathbf{Wt - Wp}}{\mathbf{Qf}} \qquad \textbf{(11)}$$

Where: W_t is the power generated in turbine, Wp is the power consumed in the pump.

2.2.7. Selection of working fluid

There are many different organic fluids that can be used according to the feasibility limited barriers and regarding to the thermodynamic performance of each fluid for giving temperature limits. The working fluids are selected from the optimizing out power view and the value of superheat for any considers working fluid and the critical temperature requirements. Table (1) shows the critical temperature and pressure for some working fluids applied in an ORC cycle which absorb heat from the HCF circuit. Working fluids include synthetic organic refrigerants as well as hydrocarbons, wet, dry and isentropic types [14]. Opting the working fluids studies in the scientific fields cover wide range of working fluids and only few fluids are actually used in commercial ORC systems.

Table (1). Critical temperature and pressure for opting working fluids [12].

Name	Critical temp (°C)	Critical Pressure *Bar*	Expansion type	Application field
n-hexane	234.7	3.058	Dry	High WHR
n-pentene	196.5	3.364	Dry	WHR
Isopentane	187.2	3.37	Dry	Solar
R245f	154	3.651	Isentropic	WHR
n-butane	152	3.796	Dry	WHR

Isobutene	135	3.64	Dry	Geothermal
R236fa	124.9	3.2	Dry	WHR

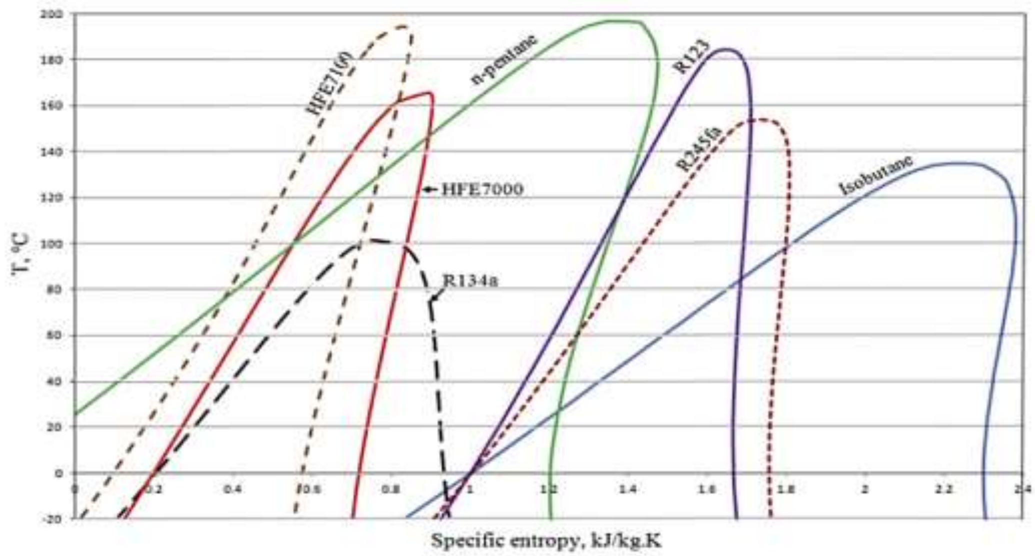

Figure 2. T-S diagram of various ORC fluids [17].

3. Results and Discussion

The volumetric flow rates of the waste heat gas streams from the cooler exhaust and the preheater exit were measured as well as their operating conditions like temperatures and static pressures. The determination of the volumetric flow rate required the knowledge of the density of the gas stream, dust concentration, gas temperature, barometric pressure, duct cross-section area, and gas velocity. The computation of the gas density was based on the measured volumetric gas composition. The process instruments that were used in the determination of the waste flue gases' volumetric flow rates were Pitot tubes and "S" tube, and Flue Gas Analyzer (O_2, SO_2, N, and CO). The average measured volume of flue gases was 7880 m^3/min at 180°C and 4010 m^3/min. at 260 °C for the kiln preheater and the cooler, respectively. The results are shown in Tables (2). The thermal energy analysis of the cooler exhaust waste gas stream was conducted and it was found that it contains 12.2 MW of thermal energy per hour, which is 38.4% of whole thermal power as shown in Table (3). The volumetric flow rate of the preheater exit gases, characterization parameters, measured gas composition, and their respective thermodynamic properties was utilized in the determination of the thermal energy content of the gases exiting the preheater tower as shown in Table (2). The thermal energy analysis of the waste flue gas stream was conducted and it was found that it contains 19.55 MW of thermal energy per hour, which is 61.6% of whole thermal power as shown in Table (3), the summation of both sides it will be 31.75 MW thermal power. The main objective of the theoretical assessment was to calculate the mass and energy balances required to conduct theoretical study of using ORC cycle to generate electric power from waste heat energy in cement plant, and estimate CO_2 emission reduction per ton of clicker as well. All parameters that used in this work were recorded from Kar cement plant as indicate in Table (2), and the Table (3) shows the thermal heat analysis that gained from the flue gases and hot air .and according to flue gas and hot air proprieties the theoretical thermal power of each branch at 25°C are 19.55 MW and 12.2 MW respectively and the percentage of each branch to the total thermal power are61.6% and 38.4%, respectively.

Table (2). Heat Source.

	Flue gas	**Hot air**
Available waste heat pressure M.Bar	23.5	6.1
Outlet temperature of Stack °C	180	260

Gas flow rate M^3/min	7880	4010

Table (3). Estimated Thermal Power Potential from Flue Gas Flow and hot air [15], [16].

Outlet Temp. °C	Gas Flow m^3/min	Gas/Air Density kg/m^3	Heat Capacity KJ/Kg K	Thermal Power MW*at Ambient Temp. °C		
				5 °C	55 °C	25°C
180	7880	0.9096(Gas)	1.091	22.82 63.5%	16.29 60.7%	19.55 61.6%
260	4010	0.6959(Air)	1.112	13.18 36.5%	10.59 39.3%	12.2 38.4%
Total energy				36	26.88	31.75

**Theoretical maximum heat energy available for ORC system*

A pinch point temperature difference of 10 °C is also set between the waste heat stream and HCF in the heat exchanger, and the maximum pressure turbine inlet depend on the exit temperature of waste heat stream determined by the setting a minimum pinch point temperature between HCF and working fluid in the evaporator.

According to Table (1) the suitable working fluid that can be use in ORC system is R245f and the results of energy analysis are mentioned in Table (4). The approximate system efficiency of 18% producing 5.9MW of electric power. The main losses are the heat rejected in the condenser, the other energy loss is in the flue gas stream to the air, the presence intermediate of HCF cycle in ORC causes additional energy losses. Another useful idea for the thermodynamic analysis of the ORC system is Sankey diagram which is presented in Figure (3) for ORC system, from this diagram it is clear that main energy loss is in the condenser and in flue gas exchanger.

Table (4). Energy balance of total energy system at 25 °C.

Energy sources	MW	(%)
Flue gases	19.55	61.6%
Hot air	12.2	38.4%
Total	31.75	100%
Energy transfer	MW	%
Energy loss: flue gases	10.3	32.47%
Energy loss: hot air	4.06	12.87%
Energy loss: condenser	11.27	35.5%
Energy loss: pumps	0.177	0.56%
Electrical power	5.9	18,6%
Total	31.75	100%
Energy exchange		
Flue gases HX	13.12	41.35%
Hot air HX	4.22	13.31%
Net energy	17.35	54.66%
losses	14.39	45.34%

Total	31.75	100%

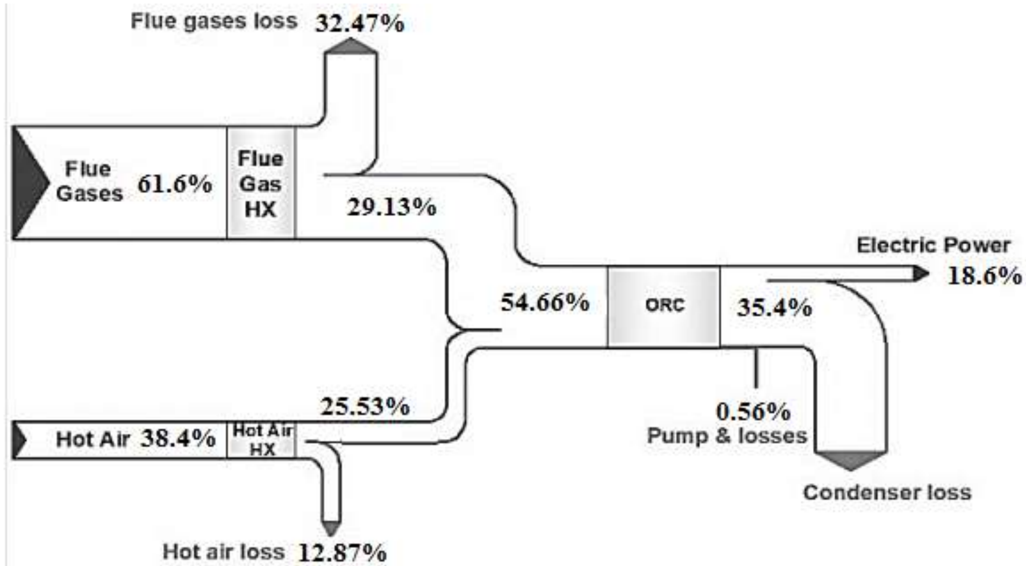

Figure (3). Snakey diagram for the system.

And according to this amount of power generation, the quantity of CO_2 emission reduction will estimated 99.12 tons per day computed by the equivalent CO_2 percentage is 0.7 kg CO_2/KW.hr.

4. Conclusions

The evaluation shows an interesting potential of electricity generation from waste heat recovery in cement sector in Iraqi industries. There are already working examples of plants around the world in many of the most interesting sectors considered. Many of these plants employ organic Rankin cycle turbogenerators which demonstrated their suitability for this application and their reliability. And the future is promising thanks to the attention for industrial heat recovery in the national energy planning and to the support of the “renewed” green certificates system. The latter, with the novelties introduced at the end of 2022 represents a very interesting incentive, hopefully capable to boost the diffusion of electricity generation from waste heat recovery. In addition to the appropriate economic feasibility from an economic and environmental point of view in this industrial sector, it will be admired when the payback period is reduced. In general, WHR are a small part of a large national ecosystem that increases the reliability of industrial projects in global organizations.

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