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Nanoparticles concentration and environmental effects on cogeneration system in cement industry

Ali Amer A. Hadi

Department of Materials Engineering. Faculty of Engineering

University of Kufa, 21- Kufa-Najaf, Iraq

Abstract- Cement production considers one of the most intensiveenergy consumingand largest carbon emitting industrial sectorsaccording to very high temperature required to produce cement clinker. This paperhighlights the importance of the waste heat recovery in the clinker cooler of cement industry via indirect approach to reheat the working fluid of cogeneration cycle. Diverse base fluids with Al_2O_3nanoparticlesas a working fluid were used in a closed recoverycycle.The effect of inlet working fluid temperatureand volume fraction of nanoparticles on the energy saving, emission reductions and cost saving werestudied.It was found that the utilization of Al_2O_3-engine oil as a working fluid for a closed recovery cycle gave the best indication as a comparison with Al_2O_3-water and Al_2O_3-ethylene glycol. As well as, it was found that the energy saving, emissions reduction and cost saving increase as a result of increasing in nanoparticles concentration and inlet working fluid temperature.

Keywords: Energy saving; Al_2O_3 nanoparticles; cogeneration system; cement industry.

Nomenclature	
Cp	Specific heat at constant pressure, kJ/kg K
CS	Cost savings, USD/yr
E	Energy, kJ
EC	Energy cost, USD
EF	Emission factor, tCO_2/MWh
ER	Emission reduction, tCO_2/year
ES	Energy saving kW
FP	Feed pump
G	Generator
$\dot{m}$	Mass flow rate, kg/s
Q	Heat transfer. KJ
ST	Steam turbine
T	Temperature. K
$\dot{V}$	Volume flow rate, m^3/s
WHRSG	Waste heat recovery steam generator
Greek symbols	
φ	Volume fraction
Subscripts	
ca	Cooling air

cc	Cooled clinker
ch	Hot clinker
conv.	Heat losses due to convection
ha	Hot air (Exhaust)
in	Input
nf	Nanofluid
rad.	Heat losses due to radiation
s	Solid particles
sa	Secondary air
ta	Tertiary air
out	Output

1. Introduction

Energy conservation has come to the forefront as a key priority for the well-being of the global economy and is expected to remain so in the foreseeable future. The most effectual approach to reduce the demand of energy is to use energy more competently [1].The current global energy consumption is between 4 and 5 GJ per tonne of cement. The industry has turned to progressively developing technologies for efficient energy use to improve its profitability and competitiveness [2].A considerable number of studies have focused on energy use and analysis in the cement industry. Madlool*et al*. [3] reported that the cement industry consumed about 12% and 15% of total energy in Malaysia and Iran respectively. Doheim*et al*. [4] examined the consumption of thermal energy, losses and the potential of heat saving. Engin*et al*. [5] focused on the energy audit of rotary kiln system and discussed the probable approaches of heat recovery from some major sources of heat loss. Kabir*et al*. [6] evaluated the consumption of thermal energy for the dry process.Khurana*et al*. [7] presented thermodynamic analysis and cogeneration for a cement plant. Rasul*et al*. [2] evaluated the thermal performance and investigated the opportunities of energy conservation in Indonesia.

In the grate cooler, almost 70 % of the clinker released heat can be recovered through its recirculation as secondary air to the kiln. While the tertiary air and vent air at 300^{o}C and 275^{o}C, respectively, are filtered in the hot electrostatic precipitators (ESP) in addition to releasing both of them to the atmosphere without being used [8]. From the pre-heater and grate cooler exit gases, approximately 40% of the total heat input is expelled as waste heat. The heat lost from grate cooler exit gases is about 334.72 to 543.92 kJ/ kg clinker at a temperature range of 200 to 300^{o}C. These waste heats can be used in diverse applications such as to dry raw materials and preheat the air required for the coal combustion and cogeneration [9].Madlool*et al.* [10] investigated the waste heat recovery in cement industry g a by studying case study in addition to estimate the energy saving.

Saneipoor*et al*. [11] examined the performance of a new Marnoch Heat Engine (MHE) which was used to recover the waste heat from a typical cement plant. Sogut*et al*. [12] studied the heat recovery from rotary kiln for a cement plant in Turkey. Caputo *et al*. [13] evolved a mathematical model for heat exchange sizing and estimation of performance to recover the waste heat from the external surfaces of rotating kilns. Wang *et al*. [14] examined the performances of cogeneration power plants using four kinds of cycles for a cement plant.

The most effective ways to increase the energy efficiency and reduce CO_2 emissions are a consequence of improving the cement production process. However, the consumption of energy and the emissions of CO_2 can also be reduced by improving the operation of available cement plants. The training of the plant operator plays an essential role in this respect [11, 15].

The majority of the studies about waste heat recovery are limited to the rejected gases from pre-heating and clinker cooling systems. There is a need forintensive research to reduce the losses caused byradiationand convectionin the clinker cooler. Recovering these losses can contribute to increasing the efficiency of the clinker cooler.

However, far too little attention has been paid to the losses due to radiation and convection in the grate cooler. This paper attempts to show that the waste heat lost through radiation and convection in the grate cooler can be recovered via an indirect approach. In this work, different working fluids were used in another cycle to recover waste heat and then to heat the working fluid of the cogeneration cycle. The comparison was carried out at different volume fraction of nanoparticles and inlet temperature of working fluid of closed recovery cycle for the same conditions of waste heat.

2. Energy analysis of a grate cooler

The conventional industrial process energy analysis is based on the first law of thermodynamics. This analysis involves a simple energy accounting, by quantifying the input and output energy to and from the clinker cooler. Fig. 1 shows the input energy which consists of energy of hot clinker and energy of cooled air, whereas, the output energy represents the energies of cool clinker, secondary air, tertiary air and hot air.

In order to thermodynamically analyze the cooler system, the following assumptions were made to simplify the analysis:

- Steady state working conditions.
- Leakage of cold air into the system is negligible.
- Clinker compositions do not change.
- Changes of kinetic and potential energy for input and output materials are negligible.
- Grate work in addition to energy losses which take place in the connections of pipeline among units are ignored.
- Assuming all gas streams are ideal gases.

For a general steady state, the equation of mass balance is applied as shown belowin the rate form [17]. The following balance equations are also applied [18]:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (1)$$

The energy balance in general form:

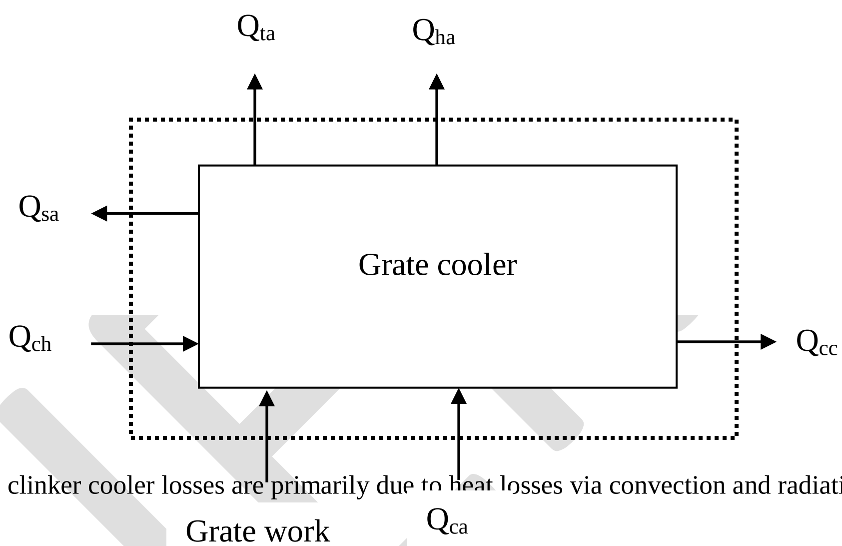
$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \quad (2)$$

Heat input into the clinker cooler:

$$\dot{Q}_{in} = \dot{Q}_{ch} + \dot{Q}_{ca} \quad (3)$$

Heat output from the clinker cooler:

$$\dot{Q}_{out} = \dot{Q}_{sa} + \dot{Q}_{ta} + \dot{Q}_{cc} + \dot{Q}_{ha} \quad (4)$$



The unaccountable clinker cooler losses are primarily due to heat losses via convection and radiation heat transfers.

3. Nanofluid as a working fluid for a closed recovery cycle

Over thepast few decades, many attempts by scientists and engineers have been made to develop fluids which can offer better performance of cooling or heating for a variety of thermal systems, compared to fluids of conventional heat transfer. Nanofluidswere engineered by dispersing solid particles of nanometer-size in fluids of conventional heat transfer such as water, engine oil and ethylene glycol. The enhancement of the fluids heat transfer capability with suspended nanoparticles makes fluid use in convection loops and thermosyphons an interesting option, leading to better performance of the system and resulting in improvement of energy efficiency [19].

The heat exchanger is a general apparatus for process heating in the industry. It is used to transfer thermal energy between two or more media at different levels of heat capacity. It is widely applied to power engineering, chemical industries, petroleum refineries, food industries etc[20].Mapa and Sana [21] demonstrated heat transfer using nanofluids in a mini heat exchanger. Vijjha and Das [22] presented measurements of specific heat for three nanofluids containing particles of zinc oxide, aluminum oxide, and silicon dioxide.

The process ofnanofluid production may be accomplished in either a one-step or two-step method. Both methods are sophisticated andrequireadvanced equipment.In fact,the high cost ofnanofluidsis an obstacle toits utilizationin the industry. While the physical analysis does not entail losses in the closed cycle, they are bound to be present in a real setting. The quantity of nanofluids used in this work was chosen to suffice the needs of a closed recovery cycle for a year.

4. 1 Equation of specific heat and density for nanofluids.

According to the dispersion of solid particles in a liquid, the specific heat and density equations for the two-phase mixture are a function of the particle concentration [23].

$$Cp_{nf} = (1-\varphi)Cp_{bf} + \varphi Cp_s \tag{5}$$

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_s \tag{6}$$

Table 1 presents the thermophysical properties of differenttypes of working fluids which were used in a closed cycle to recover the heat losses.

Table 1.Specific heat of base fluid and nanoparticles of closed recovery cycle.

Working fluid	Specific heat, Cp (J/kg.K)	Density, ρ (kg/m^3)	Refrence
Water	4190	1000	[24]
Engine oil	1910	884	
Ethylene glycol	2415	1114	[25]
Al_2O_3	775	3970	

5. Utilizing radiation and convection losses to heat the working fluid of cogeneration cycle indirectly

The unaccounted loss is a fairly high value of 324.21 kJ/kg clinker, mostly caused due to the convection and radiation losses from the uninsulated cooler [2]. The constraints of the cement quality and the corresponding effects on secondary and tertiary air impede the recovery of these losses. After the author’s personal consultation with experts in the industry, it was discovered that the abovementioned constraints can be overcome by passing a nanofluid inside the pipe which traverses compartments 3 to 8 of a grate cooler as shown in Fig. 2. This pipe will act as a heat exchanger with a grate cooler and absorb a portion of the heat losses. If 50% of the heat loss is attributed to radiation and convection heat losses and half of this proportion may be recovered, the temperature of thenanofluid will increase by 80% with the pipe technique.

The heat exchange capacity of the pipe withnanofluids that functions as a heat exchangeris based on the measured temperatures of the inlet and outlet, the mass flow rate and the specific heat of nanofluid and can be expressed as follows [26]:

$$Q_{rad.+conv.} = \dot{m}_{nf}\, Cp_{nf}\,(T_{out_{nf}} - T_{in_{nf}}) \qquad (7)$$

The working fluid is directed to the heat exchanger to exchange heat with water, which enters the cogeneration cycle as shown in Fig. 2.

The source of waste heat in the cement plant comprises of the exhaust gases from suspension pre-heater (SP) and the discharge hot air from the clinker cooler. For cogeneration power plant, these two sources which have different temperature levels may be used either separately or in combination. The hot air temperature from the cooler discharge is 220^{o}C and the temperature of exhaust gases from the suspension pre-heater is 325^{o}C. These waste heats can generate steam if directed to WHRSG. The steam generated would be used to power a steam turbine driven electric generator.

The sensible and latent heat of exhaust gases and hot air that are recovered substitute the purchased energy in a cement production plant and thus make it more efficient.The energy saving with respect to the net output power which is generated by the steam turbine can be estimated according to the following equation:

$$ES = \text{Net output power} \times \text{Working hours} \qquad (8)$$

As a result, a reduction in emissions from the fuels used by the cogeneration power plant is made possible.

The emission reductionthat brings about energy savings can be expressed by the following equation [28]:

$$ER = ES \times EF \qquad (9)$$

where EF is the *electricity emission factor*, which for Iraq can be taken as 0.744 tCO2/MWh[27].

With reduced energy consumption comes reduced cost. The average of the unit price of electricity is 0.07 USD/kWh [5]. The predictable cost savings can be estimated as follows:

$$CS = ES \times EC \qquad (10)$$

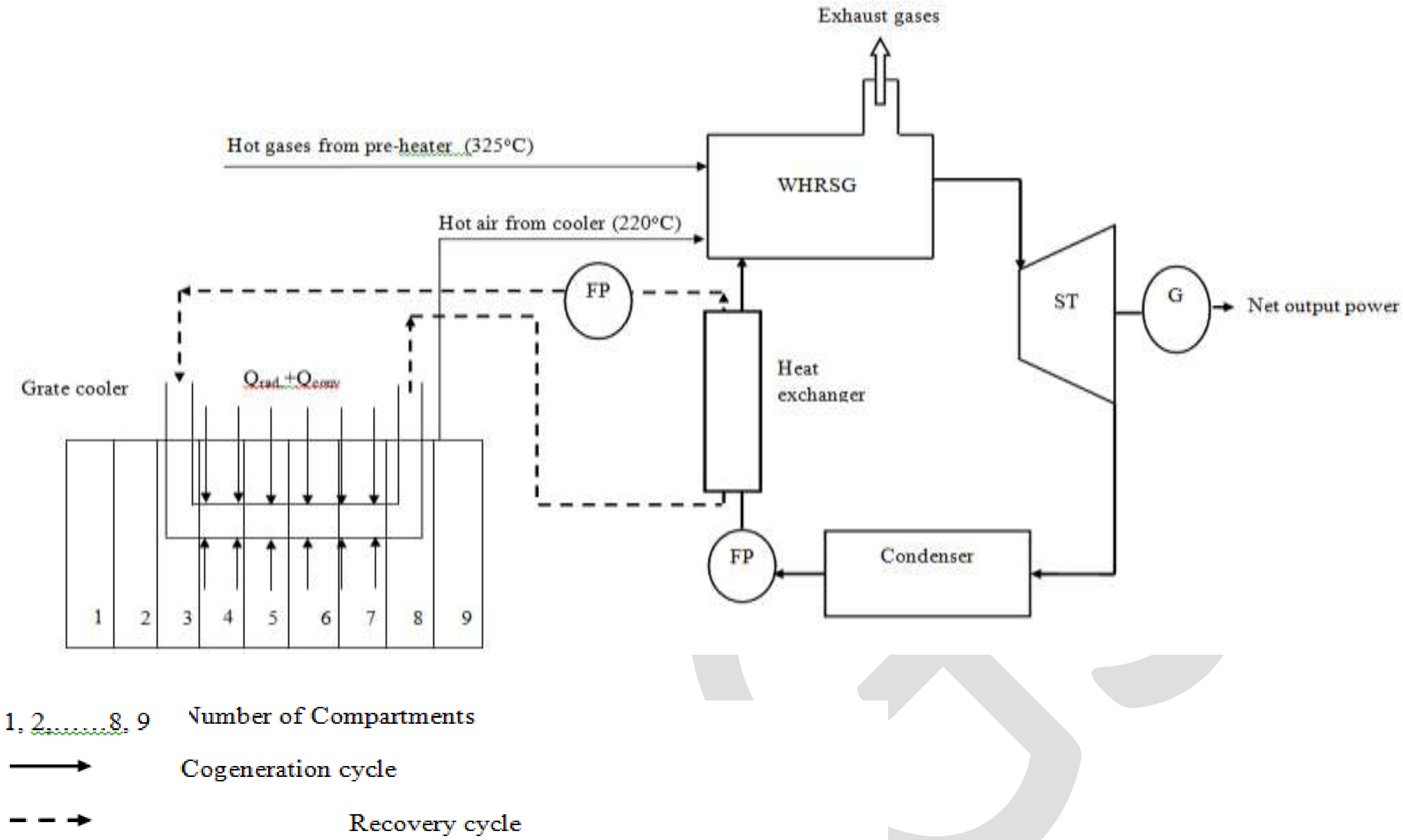


Fig. 2.Schematic of cogeneration cycle with recovery cycle.

6. Results and discussion

6.1 Energy savings

For a closed recovery cycle, the heat capacity of nanofluids should be minimized to get maximum heat transfer. A maximum possible temperature difference of nanofluids is needed to increase the temperature of the working fluid for the cogeneration cycle. Al_2O_3-engine oil has the smallest heat capacity among nanofluids, which enables maximum heat transfer and thus increases themean temperature of heat addition in the cogeneration cycle. Consequently, a high net output power is obtained which contributes significantly to energy savings.Increasing nanoparticles concentration will lead to increase the rate of heat exchange between the nanofluid of closed recovery cycle and the working fluid of steam generation cycle. And this will be affected in more energy saving as shown in Fig. 3.

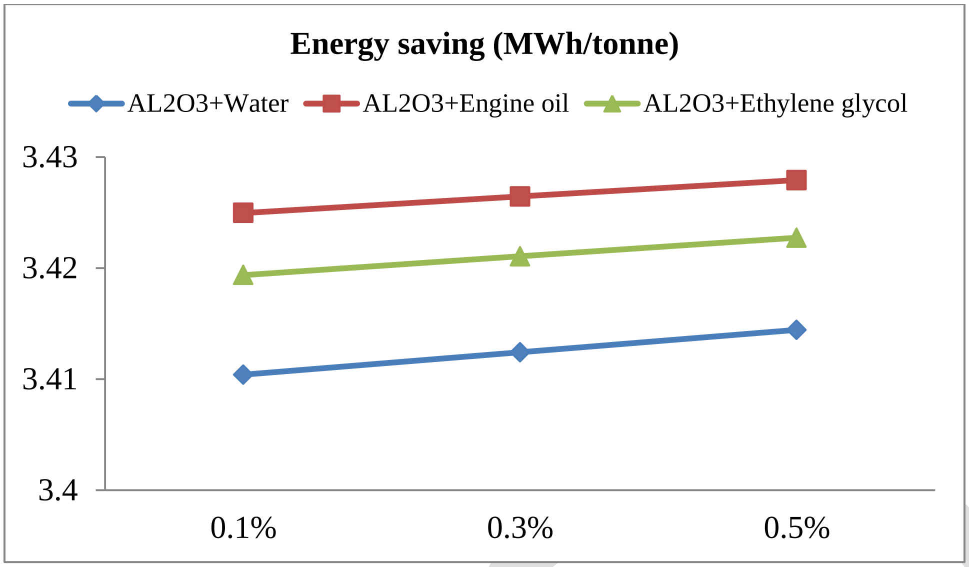


Fig. 3. Effect of nanoparticlesconcentration in closed recovery cycle on the energy saving.

Increase of inlet temperature of working fluid of closed recovery cycle increases the maximum heat transfer and leads to high outlet temperature of the nanofluid in a closed recovery cycle. Al_2O_3-engine oil as a working fluid in the closed recovery cycle causes the highest energy saving due to its low heat capacity. Fig. 4 shows the effect of inlet temperature on energy savings. On the other hand, Al_2O_3-water has the highest heat capacity and therefore the lowest improvement in energy savings, which increase with rising inlet temperature.

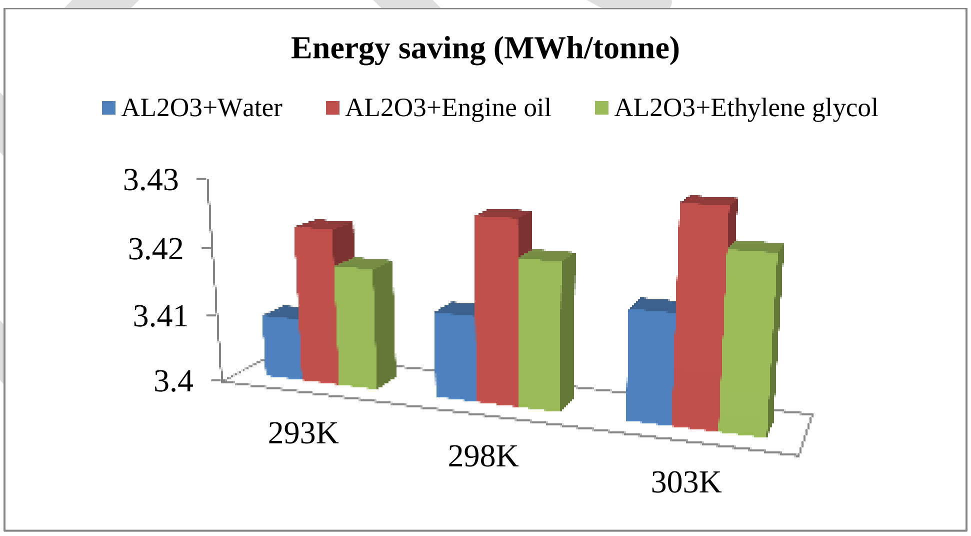


Fig. 4. Effect of inlet nanofluids temperatures in closed recovery cycle on the energy saving.

6.2 Emission reductions

The emissions reduction is estimated by using eq. (9). The emissions reduction increases in direct proportion to the energy savings.In Fig. 5, Al_2O_3-engine oil as a working fluid caused the highest emission reductions of CO_2 as a result of highest energy saving when it was utilized in a closed recovery cycle.

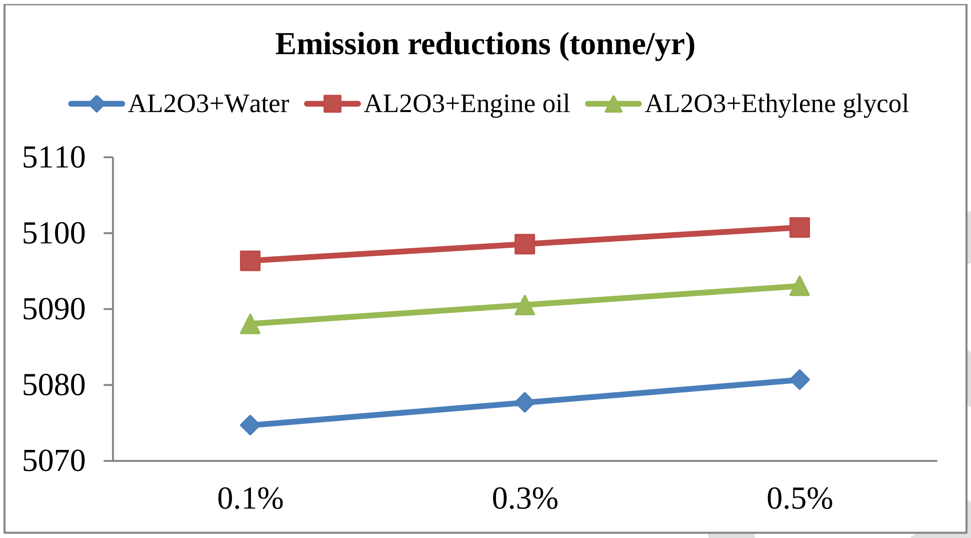


Fig. 5. Effect of different volume fraction of nanofluids in closed recovery cycle on emissions reduction.

As shown in Fig. 6, an increase of inlet temperature of the nanofluid increases the emissions reduction. Increasing of emissions reduction behaves the same with respect to energy savings as the increase of inlet temperature of nanofluids in a closed recovery cycle. Al_2O_3-engine oilin a closed recovery cycle causes the highest emissions reduction of $CO_2$and emissions reduction increases with increase of inlet temperature.

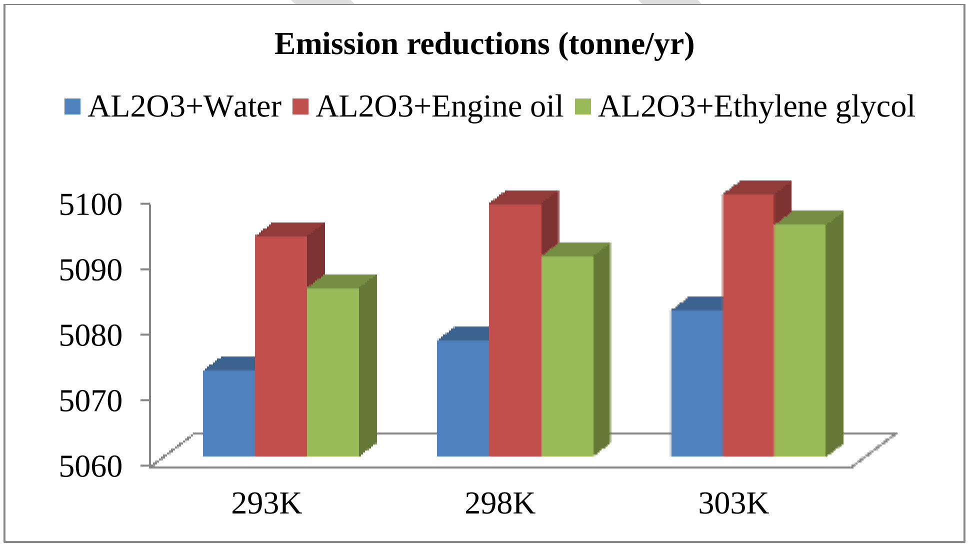


Fig. 6. Inlet temperature effect of nanfluids in closed recovery cycle on the emissions reduction.

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6.3 Cost saving

Eq. (10) can be used to estimate the cost saving. Fig. 7 presented the cost saving by using the nanofluid in a closed recovery cycle. It was noticed that use of Al_2O_3-water leads to the lowest cost saving, due the low heat capacity allowing only low energy saving. As noticed in eq.(10), the cost saving can be determined according to the amount of energy saving and the energy cost.

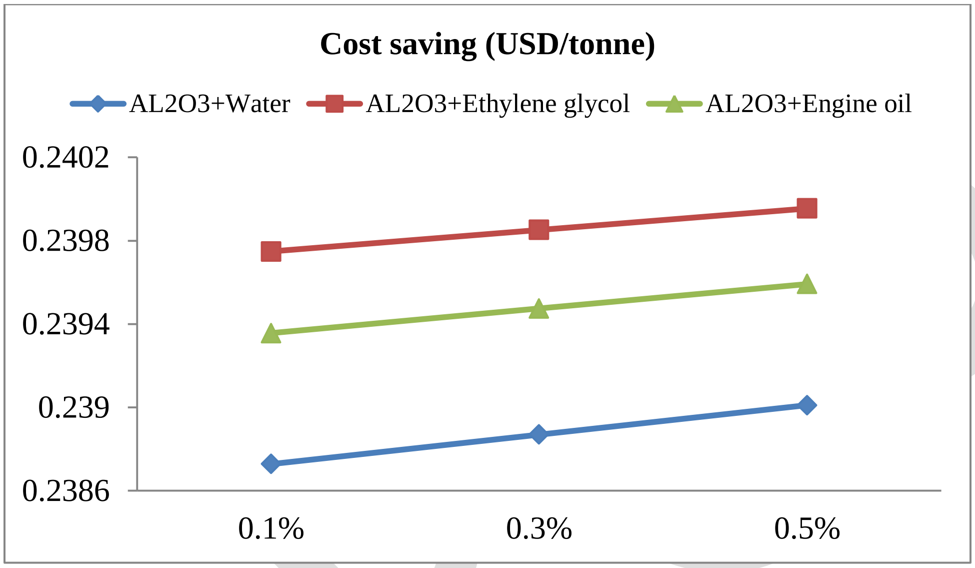

Fig. 7 Influence of nanofluids concentration in closed recovery cycle on the cost saving.

Fig. 8 shows the effect of changing the inlet temperature of nanofluid on the cost saving as a result of using cogeneration system in conjunctionwith closed recovery cycle. It was found that the increase of inlet temperature for Al_2O_3-engine oil provides the highest value of cost saving. The highest cost saving follows the highest energy saving. It increases with increase of inlet temperature of nanofluids in a closed recovery cycle.

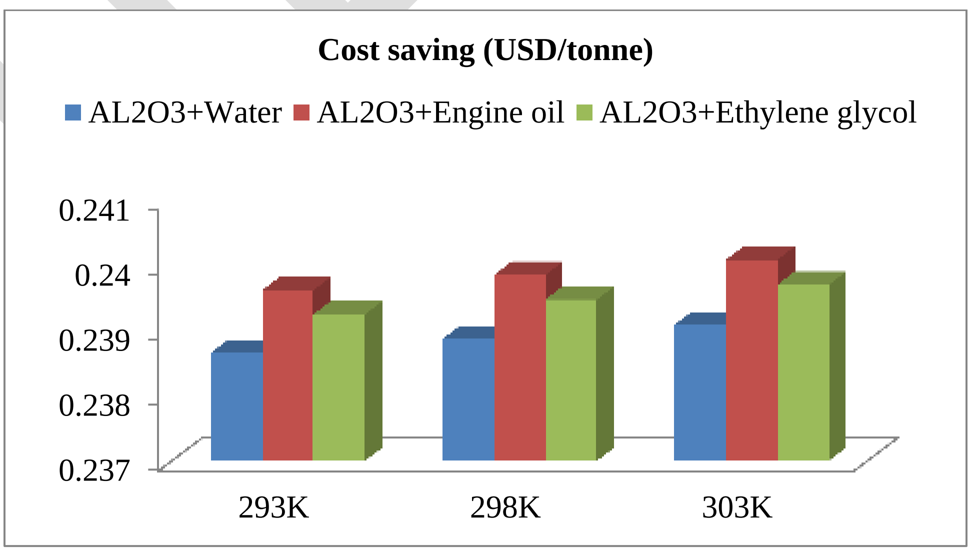

Fig. 8. Cost saving improvement as a result of different inlet temperature of nanfluids in closed recovery cycle.

7. Conclusions

The following conclusions are drawn from this work:

1. Low specific heat capacity produces high heat transfer between working fluids.
2. Al_2O_3-engine oil gives the highest values of energy saving, cost saving and emissions reduction compared to Al_2O_3-ethylene glycol and Al_2O_3-water.
3. Al_2O_3-water is the lowest in efficiency among the tested nanofluids.
4. Increase of working fluid inlet temperature and volume fraction of nanofluids in a closed recovery cycle causes an increase in energy saving, cost saving and emissions reduction for each type of nanofluid.

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