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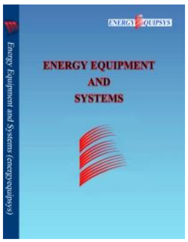

# A feasibility study and economic analysis for application of nanofluids in waste heat recovery

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## ABSTRACT

*This paper presents a comprehensive theoretical, experimental, and economic study on the application of nanofluids as heat transfer fluid in waste heat recovery systems. The research work was conducted in a steel-making complex in which a plate heat exchanger had been used to recover heat from hot process water. The system was theoretically modelled and the effects of using nanofluids as heat transfer fluid were investigated. Nanofluids with ZnO,* $Al_2O_3$*,* $SiO_2$*, and CuO as nanoparticles and water as base fluid were used in the analysis. It was found that the best performance is obtained with* $Al_2O_3$ *nanofluid. This can increase the effectiveness of the plate heat exchanger by up to four per cent. Based on this analysis, the existing heat transfer fluid (demineralized water) was replaced by* $Al_2O_3$ *nanofluid. The experiment confirmed the theoretically predicted increase of the heat exchanger's effectiveness but this increase was a little lower than what was expected. Finally, an economic analysis was done using the net present value method. This economic analysis was performed twice: once with local market prices and once with global market prices. The results show that the project is economical based on global market prices.*

**Keywords:** Economic Analysis, Net Present Value, Heat Recovery Nanofluid, Case Study, Nanofluid.

## 1. Introduction

Nanofluids are a relatively new class of fluids produced by dispersion of nano-scale materials (typically nanoparticles and nanofibres) in a fluid called basic fluid. Nanofluids have attracted great interest in recent years because of their enhanced thermophysical properties, such as thermal conductivity, viscosity, and convective heat transfer coefficients.

Up to now, there have been many studies on the heat transfer properties of nanofluids. Some researchers investigated thermal conductivity of nanofluids—for example, Murshed et al. [1], Patel et al. [2], Chandrasekar et al. [3] Vajjha et al. [4], and Duangthongsuk and Wongwises [5] reported enhancement of nanofluids' thermal conductivity compared to base fluids. Some other researchers, such as Sundar et al. [6], Hussain et al. [7], Wen and Ding [8], and Rea et al. [9], reported enhancement of nanofluids' convective heat transfer. As a result of improved heat transfer properties, in recent years there have been considerable studies on application of nanofluids for heat transfer purposes—for example, Kulkarni et al. [10] studied application of nanofluids in heating buildings, Rennie et al. [11] performed a numerical simulation for fluid flow and heat transfer in a double-pipe heat exchanger, and Kazemi-Beydokhti and Zeinali Heris [12] studied application of nanofluids in combined heat and power systems.

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The present research work focuses on the effects of using nanofluids as heat transfer fluid in waste heat recovery. The work was conducted in a steel-making complex located in the east of Iran in which a plate heat exchanger had been used to recover thermal energy from hot process water and transferring it to demineralized water. The system was theoretically modelled and the effects of using nanofluids instead of demineralized water as heat transfer fluid were determined. Based on the results of theoretical investigations, a nanofluid was selected and used in the system instead of water.

## Nomenclature

| | |
|---|---|
| $\emptyset$ | Volumetric concentration |
| $\emptyset_m$ | Mass concentration |
| $\rho_f$ | Base fluid density |
| $\rho_s$ | Nanoparticle density |
| $\rho_{nf}$ | Nanofluid density |
| $\rho_{f,0}$ | Density of the base fluid at T=293 K. |
| $\mu_f$ | Base fluid viscosity |
| $\mu_{nf}$ | Nanofluid viscosity |
| $(C_p)_f$ | Base fluid specific heat |
| $(C_p)_s$ | Nanoparticle specific heat |
| $(C_p)_{nf}$ | Nanofluid specific heat |
| $(C_p)_{cf}$ | Cold fluid specific heat |
| $(C_p)_{hf}$ | Hot fluid specific heat |
| $k_f$ | Base fluid thermal conductivity |
| $k_s$ | Nanoparticle thermal conductivity |
| $k_{nf}$ | Nanofluid thermal conductivity |
| $h_{cf}$ | Convective heat transfer coefficient between cold fluid and heat transfer surface |
| $k_p$ | Conduction heat transfer coefficient of plate |
| $P$ | Heat exchanger heat load |
| $T$ | Temperature |
| $T_{cf,i}$ | Cold fluid temperature at the heat exchanger inlet |
| $T_{hf,i}$ | Hot fluid temperature at the heat exchanger inlet |
| $T_{cf,o}$ | Cold fluid temperature at the heat exchanger outlet |
| $T_{hf,o}$ | Hot fluid temperature at the heat exchanger outlet |
| $R$ | Heat transfer resistance |
| $R_T$ | Total heat transfer resistance |
| $\mathrm{d_p}$ | Nanoparticle diameter |
| $\mathrm{d_f}$ | Equivalent diameter of a base fluid molecule |
| $A$ | Area |
| $m$ | Mass flow rate |
| $m_{cf}$ | Cold fluid mass flow rate |
| $m_{hf}$ | Hot fluid mass flow rate |
| $q$ | Heat transfer rate |
| $LMTD$ | Log mean temperature difference |
| $NTU$ | Number of transfer units |
| $\varepsilon$ | Plate heat exchanger effectiveness |
| $\Theta$ | Theta value |
| C | Heat capacity |
| $\mathrm{C_r}$ | Heat capacity ratio |
| $Nu$ | Nusselt number |
| $Re$ | Reynolds number |
| $Pr$ | Prandtl number |
| $Pe$ | Peclet number |
| M | Molecular weight of the base fluid |
| $h_{hf}$ | Convective heat transfer coefficient between hot fluid and heat transfer surface |
| N | Avogadro number |
| IC | Installed capacity |
| CMC | Consumable material cost |
| AI | Annual income |
| OMC | Operation and maintenance cost |
| AWH | Annual working hour |
| EPC | Energy production capacity |
| COE | Cost of energy |
| $CF$ | Cash flow |
| $CF_t$ | Cash flow at the time of t |
| i | Opportunity cost of a capital |
| t | Time |
| n | Number of years of operation |

* All units are in SI, and all costs and cash flows are in US dollar.

## 2.Plate heat exchanger

Plate heat exchangers are the most common type of compact heat exchangers. The first patent for a plate heat exchanger was granted to Albretch Dracke, a German inventor, and the first commercial plate heat exchanger became available in 1923 from the APV Company [13]. A plate heat exchanger consists of a series of corrugated plates. These plates are gasketed, welded, or brazed depending on the application. Figure 1 shows a schematic of a plate heat exchanger.

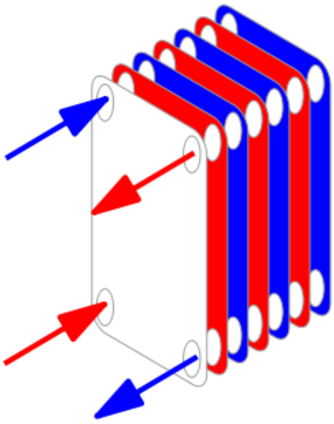

**Fig.1.** Schematic of a plate heat exchanger

There have been many studies about heat transfer and flow in plate heat exchangers. Hesselgreaves [14], Shah et al. [15], Wang and Sunden [16], and Guo et al. [17] proposed and described design methods for plate heat exchangers. Vlasogiannis et al. [18], Galeazzo et al., [19], Bassiouny and Martin [20,21], Tsai et al. [22], Zhang and Li [23], Prabhakara et al. [24], and Li XW et al. [25] studied heat transfer characteristics and related flow mechanisms in plate heat exchangers. Durmus et al. [26], Muley and Manglik [27], Dovic et al. [28], Khan T.S. et al. [29], Tinaut et al. [30], and so many others proposed various thermal and hydraulic correlations for plate heat exchangers.

In a plate heat exchanger, the hydraulic diameter is small, and the interaction between the flow inside the channel and over the corrugation crest is strong. So, both heat transfer and pressure drop are high. For heat recovery purposes, plate heat exchangers have a number of advantages over shell and tube heat exchangers as the most common type of non-compact heat exchangers. The first advantage is its compactness. In addition to requiring less space, compactness results in less material use for heat transfer surfaces and, therefore, leads to low cost. In 2011, Alfalaval Company compared the heat recovery per invested dollar of a plate heat exchanger (Alfanova) with a shell and tube heat exchanger (BEM) [31]. The result showed that heat recovery efficiency of the plate heat exchanger is up to 25 per cent higher than for shell and tube at a comparable cost. Figure 2 shows the heat recovery percentage versus the cost unit for the plate heat exchanger vis-à-vis the shell and tube heat exchanger. The study showed that to obtain the same levels of heat recovery, the shell and tube heat exchanger becomes several times more expensive—for example, to reach heat recovery of 95 per cent, the plate heat exchanger is about five times more efficient. Another advantage of plate heat exchangers is their flexibility. The heat transfer surface can be changed by adding or reducing plates. Another major advantage that is important in heat recovery is a close temperature approach. Usually in heat recovery systems, it is necessary to consider the minimum temperature difference in a heat exchanger. Such conditions can be satisfied by a plate heat exchanger.

The main challenge is the pressure drop, which is relatively high. This challenge becomes more important when using nanofluids because they have higher viscosity, which leads to a greater pressure drop.

## 3.Theory

### 3.1. Nanofluid

Most of the thermophysical properties of nanofluids can be calculated by knowing the volume concentration, properties of the nanoparticles, and properties of the base fluid. The equation for the volumetric concentration is [32]:

$$\emptyset = \frac{\rho_f \emptyset_m}{\rho_f \emptyset_{\mathrm{m}} + \mathrm{\rho_s}(1 - \emptyset_{\mathrm{m}})} \quad (1)$$

The density of nanofluid can be calculated as [33]:

$$\rho_{nf} = \emptyset \rho_s + (1 - \emptyset)\rho_f \quad (2)$$

For the effective dynamic viscosity of nanofluid, different models have been proposed. Here, the recent model of Corcione[34] is considered,

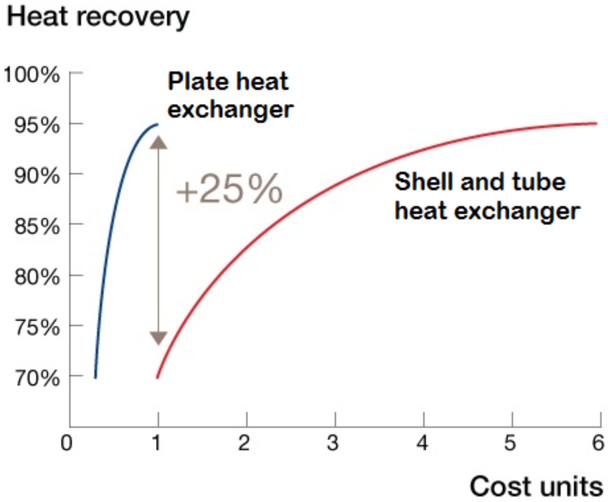

**Fig.2.** Heat recovery versus cost units for plate, shell, and tube heat exchanger. The blue line represents the plate heat exchanger heat recovery percent, and the red line the shell and tube

$$\frac{\mu_{nf}}{\mu_f} = \frac{1}{1 - 34.87\,(d_p/d_f)^{-0.3}\,\emptyset^{1.03}} \tag{3}$$

where $d_f$ is the equivalent diameter of a base fluid molecule:

$$\left(\frac{6M}{N\pi\rho_{f,0}}\right)^{0.33} \tag{4}$$

The heat capacity of nanofluids is [35]:

$$(\rho C_p)_{nf} = \emptyset(\rho C_p)_s + (1-\emptyset)(\rho C_p)_f \tag{5}$$

The thermal conductivity of oxide and metallic nanofluids can be obtained from the following equation [36]:

$$\frac{k_{nf}}{k_f} = 1 + 0.135\left(\frac{k_s}{k_f}\right)^{0.273}\emptyset^{0.467}\left(\frac{T}{20}\right)^{0.547}\left(\frac{100}{d_p}\right)^{0.234} \tag{6}$$

## 3.2. Plate heat exchanger

The heat load of a heat exchanger can be calculated from the following equations:

$$P = mC_p\Delta T \tag{7}$$

$$P = \frac{A\,LMTD}{R_T} \tag{8}$$

LMTD is the log mean temperature difference and it is defined as:

$$LMTD = \frac{\Delta T1 - \Delta T2}{\ln\left(\frac{\Delta T1}{\Delta T2}\right)} \tag{9}$$

where $\Delta T1$ is the difference between hot fluid inlet temperature and cold fluid outlet temperature, and $\Delta T2$ is the difference between cold fluid inlet temperature and hot fluid outlet temperature.

To determine the effectiveness of a heat exchanger, the maximum possible heat transfer rate must be determined first. The maximum possible heat transfer rate is:

$$q_{max} = C_{min}(T_{hf,i} - T_{cf,i}) \tag{10}$$

The $C_{min}$ is equal to $m_{cf}(C_p)_{cf}$ or $m_{hf}(C_p)_{hf}$, whichever is smaller, and the $C_{max}$ is equal to whichever is larger. The effectiveness of a plate heat exchanger is defined as actual heat transfer divided by maximum possible heat transfer. It is calculated as:

$$\varepsilon = \frac{1 - \exp(NTU\,C_r - NTU)}{1 - C_r\exp(NTU\,C_r - NTU)} \tag{11}$$

where NTU and $C_r$ are the number of transfer units and heat capacity ratio:

$$NTU = \frac{UA}{C_{min}} \tag{12}$$

$$C_r = \frac{C_{min}}{C_{max}} \tag{13}$$

The total heat transfer resistance, RT, is the summation of convection heat transfer resistance between cold fluid and heat transfer surface ($R_1$), conduction heat transfer resistance of heat transfer surface ($R_2$), and convection heat transfer resistance between hot fluid and heat transfer surface ($R_3$). It can be calculated from the following equation:

$$R_T = R_1 + R_2 + R_3 \tag{14}$$

where:

$$R_1 = \frac{1}{h_{cf}A} \tag{15}$$

$$R_2 = \frac{1}{k_pA} \tag{16}$$

$$R_3 = \frac{1}{h_{hf}A} \tag{17}$$

The convection heat transfer coefficient for the turbulent flow can be calculated from the following correlation [37]:

$$Nu = 0.0059\,(1 + 7.6286\,\emptyset^{0.6886}\,Pe^{0.001})\,Re^{0.9238}\,Pr^{0.4} \tag{18}$$

For laminar flow, the following correlation can be used [37]:

$$Nu = 0.4328\,(1 + 11.285\,\emptyset^{0.754}\,Pe^{0.218})Re^{0.333}Pr^{0.4} \tag{19}$$

For evaluating the temperature approach in a heat exchanger, the theta value is used. Theta is defined as in Eq.(20). It is a parameter that refers to the temperature difference between hot and cold fluid. Small values of theta represent a large temperature difference in the heat exchanger between hot and cold fluids, whereas large values of theta represent a small temperature difference in a heat exchanger.

$$\Theta = \frac{\delta T}{LMTD} = \frac{A}{m\,R_TC_p} \tag{20}$$

where $\delta T$ is the temperature difference between inlet and outlet on one side.

## 4.Model and results

In the heat recovery system, 3.6 $m^3/h$ of process water with the temperature of 95°C enters the plate heat exchanger and heats 2.88 $m^3/h$ of demineralized water, which has an inlet temperature of 15°C and is used for building heating. The pressure of both fluids is 3 bar. Table 1 shows the characteristics of the plate heat exchanger.

To understand the results of using nanofluids instead of demineralized water, the plate heat exchanger was modelled hydraulically and thermally based on the relations mentioned in the previous section. Nanofluids with ZnO, $Al_2O_3$, $SiO_2$, and CuO as nanoparticles and water as base fluid were used in the analysis. In the normal operation of the system, the demineralized water with the temperature of 15°C enters the heat exchanger and leaves it with a temperature of 61.1°C. In the operational condition of the system, the hydraulic regime is laminar.

The theta value in the normal operation condition is about 1.25. The study showed that application of nanofluids could increase the water outlet temperature by about 1 to 3°C. For investigating larger theta values, the analysis was repeated with lower fluid flow rates. In this case, the hot and cold fluid flow rates were considered as 1.44 and 0.94 $m^3/h$, respectively. In this condition, the theta value is about 2.25. Figures 3 and 4 shows the increase of the nanofluids' outlet temperature versus volumetric concentration for two mentioned theta values.

The temperature does not completely represent the absorbed heat because, in addition to temperature rise, the absorbed heat is related to nanofluid heat capacity. The effectiveness of the heat exchanger that is directly related to absorbed heat can show the the performance of nanofluid in a better way. Figures 5 and 6 shows the plate heat exchanger effectiveness versus volume concentration for nanofluids at two mentioned theta values.

It can be observed that use of nanofluids with the volume concentration of five per cent can increase the heat exchanger effectiveness by one to four per cent. The best performance

**Table 1.** Technical specifications of a plate heat exchanger

| | |
|---|---|
| Number of plates | 14 |
| Plate width | 140 mm |
| Vertical distance between centres of ports | 640 mm |
| Plate thickness | 2 mm |
| Plate spacing | 3 mm |
| Plate material | Titanium |
| Plate thermal conductivity | 20.9 ($W/m^2k$) |
| Effective area of single plate | 0.089 $m^2$ |

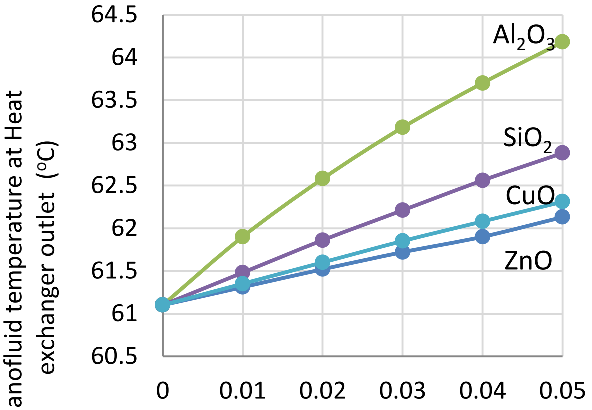

**Fig. 3.** Nanofluid temperature at heat exchanger outlet (For Θ= 1.25).
The lines represent the outlet temperature of Al2O3, SiO2, CuO, and ZnO nanofluids, respectively

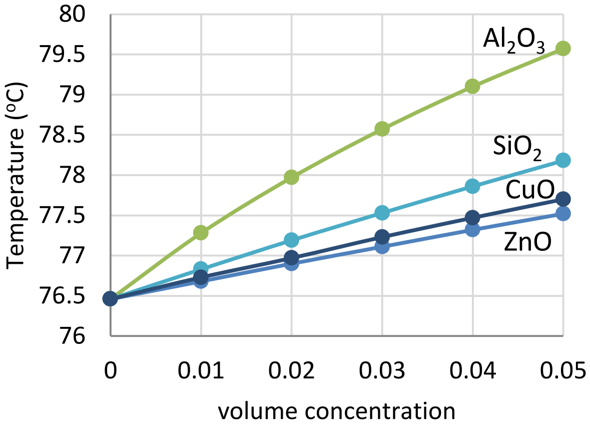

**Fig.4.** Nanofluid temperature at heat exchanger outlet (For Θ= 2.25).
The lines represent the outlet temperature of Al2O3, SiO2, CuO, and ZnO nanofluids, respectively

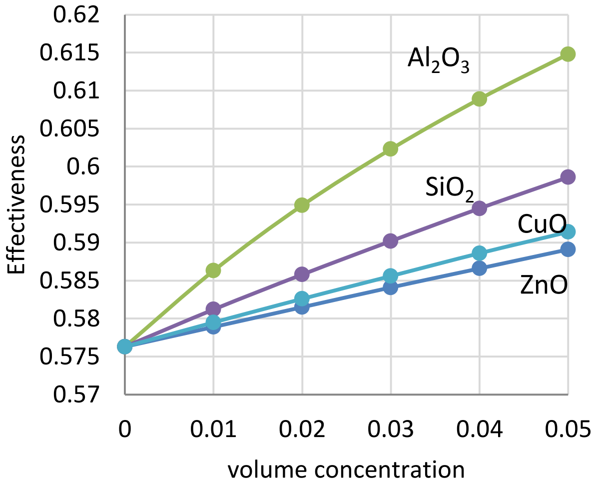

**Fig.5.** The plate heat exchanger effectiveness (For Θ= 1.25).
The lines represent the heat exchanger effectiveness when using Al2O3, SiO2, CuO, and ZnO nanofluids, respectively

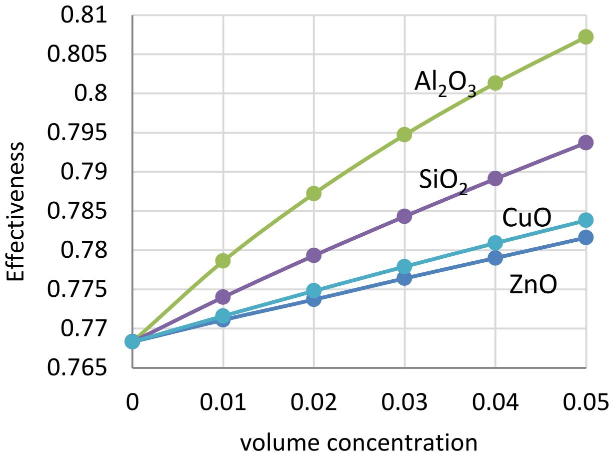

**Fig. 6.** The plate heat exchanger effectiveness (For Θ = 2.25).
The lines represent the heat exchanger effectiveness when using Al2O3, SiO2, CuO, and ZnO nanofluids, respectively.

belongs to $Al_2O_3$ nanofluid. It enhances the plate heat exchanger effectiveness up to four per cent at both theta values. The temperature of $Al_2O_3$ at the plate heat exchanger outlet is 3.2°C more than demineralized water at Θ = 1.25 and 3.1°C more at Θ = 2.25.

As mentioned, nanofluids increase pump power in the plate heat exchanger. But the study showed that in this case the pump power increase resulting from application of nanofluids is less than 0.1 of the absorbed heat increase.

## 5.Experimental work

Based on the theoretical study, the demineralized water was replaced by nanofluid with $Al_2O_3$ as nanoparticle and water as base fluid. The nanofluid samples were prepared by dispersing the nanoparticles in water. To improve the dispersion of nanoparticles, the nanofluids were ultrasonicated for two hours using a 20 kHz ultrasonic processor. Four samples with one to four per cent volume concentration were used in the system. Figure 7 shows the experimental results of nanofluid temperature at the heat exchanger outlet in comparison with the theoretical results. It can be observed that experimental temperature values are less than the values expected from theoretical studies.

## 6.Economic analysis

In this section, the economic benefit gained by using the nanofluid in the system is evaluated. For this purpose, the net present

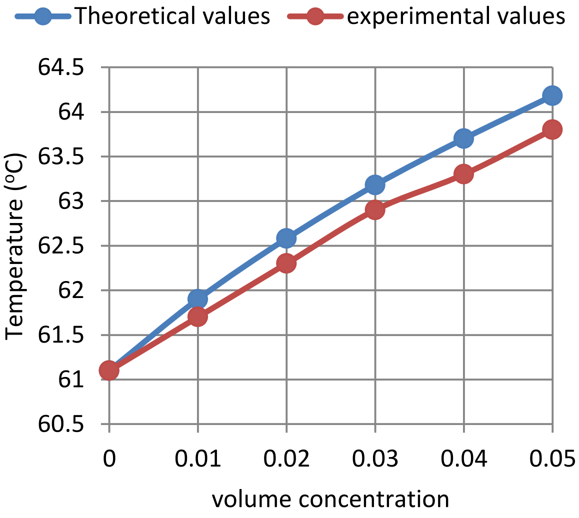

**Fig.7.** Comparison of theoretical and experimental results of Al2O3 nanofluid temperature at heat exchanger outlet. The blue line represents the theoretical values and the red line represents the experimental values.

value (NPV) method is used. In this method, each cash income or outcome is discounted back to its present value, and then all terms are summed.

The present value of a cash flow after n years is calculated as:

$$PV = \frac{\pm CF}{(1+i)^n} \quad (21)$$

The plus sign is used for income and the minus sign is used for outcome. The NPV is the summation of all income and outcome present values. If NPV is a positive value in a particular time, it means that total income from the beginning of the project until that time is more than total outcome and the project is currently a profit-making one. The NPV is calculated as:

$$NPV = \sum_{t=0}^{t=\mathrm{n}} \frac{\pm CF_t}{(1+i)^t} \quad (22)$$

In this study, to compare the system before and after use of nanofluid, the relative cost approach is used. In other words, the incomes and outcomes of the heat recovery system before use of nanofluid is considered zero, and the changes caused by application of the nanofluid are taken into account. The total benefit of the system during the n years of operation is:

$$TB = n \times AI - IC - n \times CMC - n \times OMC \quad (23)$$

The annual income is equal to:

$$AI = AWH \times PEC \times COE \quad (24)$$

The economic analysis was performed twice: once with Iranian market prices and once with global market prices (average of prices in New Zealand, Japan, UK, France, and US). Table 2 shows values used in the analysis, and Tables 3 and 4 provide the results of the economic analysis based on the NPV method. The analysis is performed for $Al_2O_3$ nanofluid with four per cent volumetric concentration. The annual working hours and number of life years of the system is considered 4,000 hours and 10 years, respectively.

According to the results of Table 3, it is clear that using nanofluid instead of demineralized water is economical based on world prices. The capital recovery period is less than two years. In the next eight years, the total benefit of $27,231 is achieved. The average annual income is $2,723 per year. The results of Table 4 also show that because

**Table 2.** Cost values used in the analysis

| Item | Cost (US$) | |
|---|---|---|
| Market | Global | Local |
| Nanofluid preparation equipment | 7,100 | 7,100 |
| Consumable material (per year) | 510 | 330 |
| Operation and manual (per year) | 355 | 355 |
| Number of life years | 10 | 10 |
| Opportunity cost of a capital | 0.06 | 0.2 |
| Cost of energy | 0.16 | 0.025 |

**Table 3.** Results of the economic analysis with global market prices

| Year | Present value of cash flow | Net present value |
|---|---|---|
| 0 | -7,100 | -7,100 |
| 1 | 4,400.56 | -2,699.43 |
| 2 | 4,151.47 | 1,452.04 |
| 3 | 3,916.48 | 5,368.53 |
| 4 | 3,694.80 | 9,063.33 |
| 5 | 3,485.66 | 12,548.99 |
| 6 | 3,288.35 | 15,837.35 |
| 7 | 3,102.22 | 18,939.57 |
| 8 | 2,926.62 | 21,866.20 |
| 9 | 2,760.96 | 24,627.17 |
| 10 | 2,604.68 | 27,231.8 |

that because of the low energy prices the project is not economical in the local market.

## 7.Conclusion

The study demonstrates that use of nanofluids as heat transfer fluids can increase the heat transfer and, therefore, the efficiency of the system.

At first, a theoretical study was conducted to assess the performance of four nanofluids in the heat recovery system. It showed that $Al_2O_3$ nanofluid performs better than the others. This can increase the system effectiveness up to four per cent. Then an experimental work was carried out to verify the theoretical results. The experiment confirmed the theoretically predicted increase of the heat exchanger effectiveness but this increase was a little lower than what was expected. Finally, an economic analysis was done using the NPV method. The results show that the project is economical based on global market prices.

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