Modeling and investigation of gas turbines heat recovery in the semnan oil pumping station for heating gas-oil to reduce energy consumption of pumping

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This paper proposed the effect of using a heat recovery system in the gas turbines of Semnan to Shahroud oil pumping station in energy conservation point of view. Heating the transferred fluids is one of the common approaches to reduce fluids viscosity and energy consumption, respectively. Due to the low efficiency of station turbines compared to modern turbines, it is expected that the use of heat recovery has a positive effect on improving station performance. By analyzing the combustion products of the gas turbine at the station, the heat extracted from the exhaust gas flow has been calculated, which is consumed in the recovery boiler. The pipeline application process, including recovery boiler and main equipment of Semnan and Shahroud pumping stations, have been modeled. By applying the model, it found that the amount of energy savings by gas-oil heating using a heat exchanger equals 395311 m3 natural gas annually. Therefore, optimal points of using combustion heat in the gas turbine output were obtained. In addition, the reduction of power consumption in the presented station has been calculated. Economic calculations were carried out for different countries, including Iran, Scandinavian countries, China, and the Europian Union average, based on their energy prices and bank interest rates.

keywords: *Oil Pumping Station, Pipeline, Energy Saving, Gas Turbine, Heat Recovery.*

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NOMENCLATURE

ATK Aviation turbine kerosene.
i, j, k Index of cluster.
boe Barrel of oil equivalent.
Cp Specific heat at constant pressure.
GO Gas Oil.
GHV Gross Heat Value.
MS Motor spirit.
NG Natural Gas.
KER Kerosene.
API American Petroleum Institute index.

1. INTRODUCTION

As the use of electricity grows more and more in modern life, increasing the average consumption and peak demand is an unavoidable fact. Global demand for oil has risen sharply over the past two decades and in recent years has grown 1.5% annually. Studies show that in the next 20 years, at least 80% of the world's energy demand will meet by oil and gas. Therefore hydrocarbons will still play a key role in world energy [1, 2]. Oil pumping stations are one of the most energy-intensive industries in Iran. The potential for energy savings on oil pipelines is 0.16 mboe/year, equivalent to a reduction of 60000 tons CO2 per year [3]. One of the ways to reduce energy consumption in oil pumping stations is to reduce fluid viscosity. The purpose of this study was to investigate the use of heat in the exhaust gas stream from the gas turbine for heating gas oil to reduce the viscosity and power consumption of the pumps. One of the principal problems in the pipeline, especially for heavy crude oil, is the high viscosity. Therefore, different methods have been used to reduce the viscosity of crude oil for pipeline transmission. For example, diluting with lighter substances or alcohol, heating and surfactant usage to stabilize emulsions are some of these common methods [4]. In one study, electromagnetic heating of crude oil was used as a solution to reduce viscosity and energy consumption. The absorbed electromagnetic energy is converted to heat and can significantly reduce the viscosity of crude oil. Reducing fluid viscosity has reduced pressure losses and reduced the number of pumping stations and increased the distance of pumping stations installed in pipelines by 30% [5]. One major drawback of using hot pipelines is the high capital and operating costs of such long-distance pipelines [6].

Most of the studies on oil heating to reduce viscosity relates to crude oil transmission lines using a separate heat source. Boilers or electromagnetic temperature rise systems have used. Most of the papers study the benefits of this method to reduce energy consumption and increase the flow for heavy crude oil pipelines. A comprehensive study of the mentioned method application in refinery products pipelines has not been published yet.

There are more than 3.5 million kilometers of oil and gas and refineries pipelines in the world [7], the governmental oil pipeline in Iran is 14,000 km long and transports more than 123 billion liters of oil and petroleum products annually [8]. In terms of the length of oil and gas pipelines in the world, America, Russia, Canada ranked first to third, China with 87,000 kilometers in fourth place and Iran with 38,000 kilometers in eighth place. In 2017, 720 million cubic meters of oil and petroleum products shipped in Europe [9]. This study investigates this method in the gas-oil pipeline as one of the main outputs of refineries and one of the most consumed fuels in Iran. The average gas oil consumption is about 83 million liters per day [10]. Heat recovery from gas turbines at the station also has been used to supply the heat needed to save more energy. Given the structure of energy pricing in Iran, economic calculations have also been made for several countries from the European Union and Asia compared.

Given the increasing energy consumption in the world and the potential for energy consumption reduction in the Iranian pipelines mentioned above, this article could have a beneficial effect on reducing energy consumption in gas turbine oil stations in Iran.

2. METHODOLOGY

Semnan - Shahroud Oil Pipeline Transmission Line is one of the main pipelines of Tehran Mashhad, 189 km long, and 22-inch Diameter, This station supplies the energy needed to the northeast of the country and four provinces more cost-effectively than other modes of transport. Semnan pumping station has three main pumps with TB-4000 Ruston gas turbine drivers. The station pumps a variety of petroleum products, including GO, KER, MS, and ATK. The main workflow of the station is GO, so because of its higher viscosity than other petroleum products, the most energy consumption of station is for that. Figures 1 and 2 show a view of pumps and gas turbines in the Semnan oil pumping station.

Viscosity is one of the factors affecting pump power consumption. Reducing viscosity increases the Reynolds number (Reynolds is the ratio of inertia to viscose forces). Therefore, according to Moody's diagram, the coefficient of friction and, consequently, the pressure drop inside the pipe decreases. Increasing the API index or average line temperature reduces the viscosity, resulting in higher Reynolds numbers, less friction and less pumping energy. Reducing pump power consumption means increasing efficiency and increasing transmission capacity due to lower pressure drop [11].

According to Figs. 3 and 4 [12], studies show that the efficiency of station turbines are 20% less than present-day turbines. Therefore, the use of heat recovery was considered to improve

Fig. 1. A view of the station's turbines.

Fig. 2. View of the pumping station.

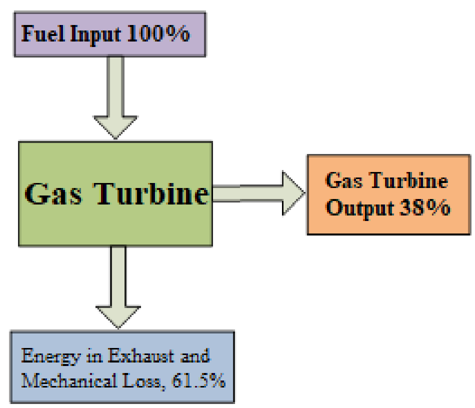

Fig. 3. The energy flow of today's turbines.

the performance of the station.

According to the Iranian Oil Pipeline Standard, ISIRI 13377 [13], this station is in the F category in terms of energy consumption index, this standard attempts to categorize oil pumping stations in Iran at different levels in terms of energy consumption.

There are generally two main methods to reduce the viscosity of the oil, mixing it with lighter materials and heating it. Heating is one of the attractive solutions, especially for crude oil, due to the rapid decrease in viscosity with temperature. It should note that oil heating is not an easy task and requires many consid-

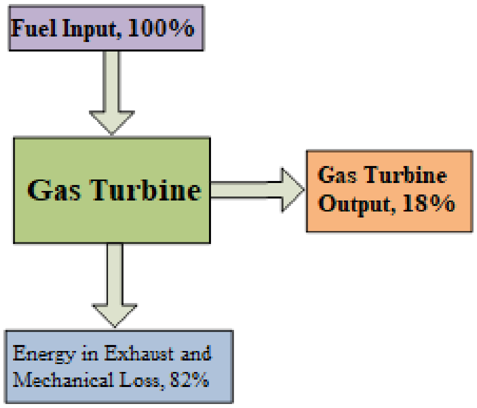

Fig. 4. The energy flow of the station's turbines.

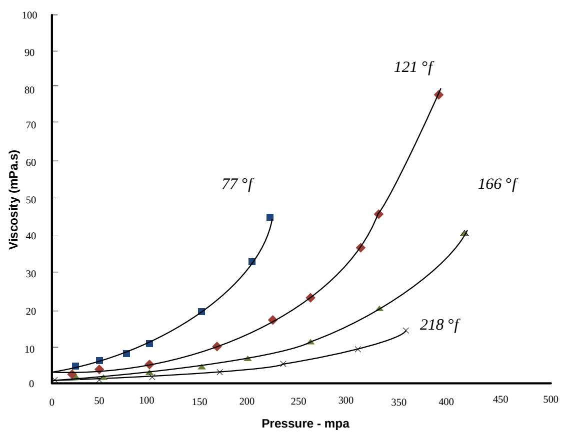

Fig. 5. Viscosity changes of a gas oil sample with temperature.

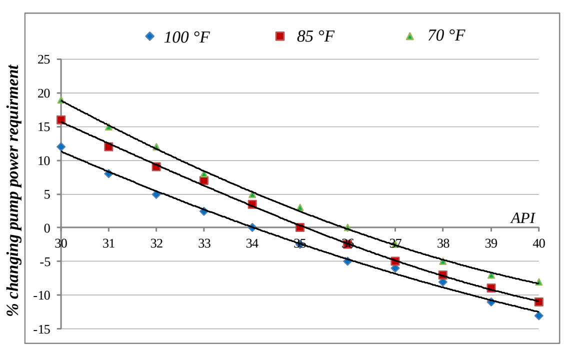

Fig. 6. Changes in pumping power to temperature and density variations for a 16-inch diameter pipeline and a length of 161 km.

erations, including line expansion. Heat loss, changing pump performance curves and high corrosion rates [14]. Its disadvantages are its high cost due to energy consumption and insulation of the pipeline. Fig. 5 shows the viscosity changes of crude oil with temperature [15], Fig. 6 shows the effect of viscosity changes on pumping power consumption for a 16-inch diameter pipeline and a length of 161 with a capacity of 1126 m^3/hr.

Crude oil heating also increases the transfer capacity of a 48-inch, the 800-mile pipeline in Alaska. It is one of the most famous in Alaska, using three heaters to raise oil temperatures from 20 °C to 50 °C. With this method and the addition of multi-loop rings with an investment of $48 million, the transfer capacity increased to 146,000 barrels per day [16]. Another well-known pipeline is a 200-km, 36-inch pipeline in Venezuela, which crude oil mixed with naphtha before pumping and then heated to 19 °F. This method, along with the addition of an intermediate pumping station, has increased the transfer capacity by 200,000 barrels per day [17].

3. CALCULATE THE HEAT OUTPUT OF THE TURBINES

The dew point of the gas-vapor mixture is the temperature at constant pressure becomes liquid. This point is significantly important in boilers because the condensation of steam causes acid boilers to corrode. At the end of the recovery boiler, the smoke temperature is more likely to reach the dew point. The combustion pressure in this area is equal to the local site pressure plus the stack pressure drop. The dew point temperature well approximated with the saturation temperature at the partial pressure of water in the combustion products. To calculate the partial pressure of water in the combustion products, so must burn the station's consumed natural gas with Table 1, Specifications [18].

Table 1. Station gas analysis data

$iC_4\&nC_4$	C_3H_8	C_2H_6	CH_4
96.63%	1.27%	0.14%	0.07%
GHV	CO_2	N_2	$i-C_5\&n-C_5\&C_6$
8847 $kCal/m^3$	0.1%	0.56%	1.23%

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.5N_2$$
$$C_2H_6 + 3.5(O_2 + 3.76N_2) \rightarrow CO_2 + 3H_2O + 13.16N_2$$
$$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 18.8N_2$$
$$C_4H_{10} + 6.5(O_2 + 3.76N_2) \rightarrow 4CO_2 + 5H_2O + 24.4N_2$$
$$C_5H_{12} + 8(O_2 + 3.76N_2) \rightarrow 5CO_2 + 6H_2O + 30.08N_2$$

Since the smoke temperature is more likely to reach the dew point at the end of the recovery boiler, the gas pressure in this area can be assumed to be the sum of the site pressure and the chimney pressure drop, and eventually the dew point is equal to the saturation temperature at the relative pressure of the water vapor in the combustion products.

Using Eq. (1), and analysis of the combustion products in Table 2, the dew point temperature of the combustion products calculated at 60.1 °C.

$$P_v = (W/(0.622 + w)) \times P_t \tag{1}$$

P_v- Partial pressure of water in combustion products
W- % of the water in combustion products
P_t- the pressure of combustion products

To calculate the heat capacity of the turbine exhaust flow, Eq. (2), and Table 3, (exhaust gas components) used. The specific heat of combustion products calculated 1.070 kJ/kg K. The data required to calculate the thermal power available in the exhaust gas flow presented in Table 4. Using this table and Eq. (3), the thermal power output of the exhaust gas was 6591 kJ/s.

$$C_{p,mix} = \sum_i C_i \times C_{p,i} \tag{2}$$

$$Q = \dot{m} \times C_{p,\text{mix}} \Delta T \tag{3}$$

Table 2. Station gas analysis data

Components	CO_2 kmol	%mol	O_2 kmol	H_2O kmol	N_2 kmol
CH_4	96.63	96.63	193.2	193.2	726.4
C_2H_6	2.54	1.27	4.44	3.81	16.69
C_3H_8	0.42	0.14	0.7	0.56	2.63
C_4H_{10}	0.28	0.07	0.45	0.35	1.69
C_5H_{12}	0.5	0.1	0.8	0.6	3
N_2	-	0.56	-	-	0.56
CO_2	1.23	1.23	-	-	-
total	101.6	100	199.6	198.5	786.9

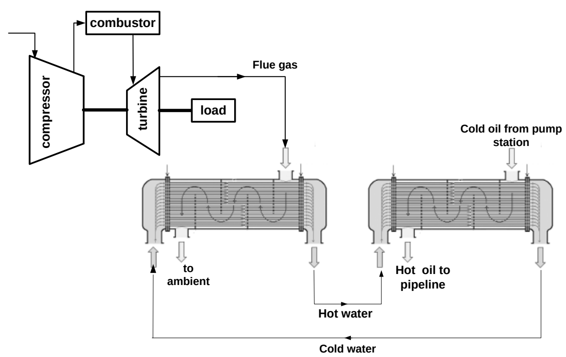

Fig. 7. Schematic of the heat recovery system.

Q- Thermal power output of the exhaust gas – KJ
$\dot{m}$– mass flow rate – kg/s
C- the pressure of combustion products

Table 3. Components of exhaust gases

Flue gas components	$Vol.$ %	mas %	$C_p\ kJ/kg.K$
H_2O (vapor)	15.4	9.7	1.872
CO_2	7.9	12.2	0.846
N_2	61.1	60.4	1.039
O_2	15.5	17.5	0.918

A. Design of heat exchanger

With the purpose of modeling of the fluid heating and to avoid the risks operational of gas-oil heating by combustion products, as it is shown in Fig. 7, two primary and secondary heat exchangers have been used. The primary heat exchanger aims to heat the water with combustion products, and the secondary is to heat oil with hot water.

B. Calculate the pressure drop in the secondary heat exchanger

The secondary heat exchanger pressure drop calculate according to Table 5 [19].

4. MODELING

The calculations for the secondary heat exchanger show that the pressure drop is 14.1 psi for each turbopump. The pumping station and pipeline model with shell and tube heat exchangers. Table 6 presents the model specifications. The model first implemented in the boiler shutdown mode and then switched on by increasing the amount of fluid pressure drop inside the heater.

As shown in Fig. 8, using this model reduced the viscosity, specific energy and it has increased the flow rate from 656 m^3/hr to 674 m^3/hr. Then the specific energy began to increase with increasing losses in the secondary heat exchanger. With losses within the heater reaching 27 psi, the specific energy value is similar to the boiler shutdown state, i.e., the effects of increased power consumption due to pressure drop over power loss due to reduced viscosity. Calculations showed that the internal losses of the secondary heat exchanger were 14.6 psi.

Using the results of the model and total oil transmitted by the pipeline over a year shows that using the shell and tube heat exchanger saves 95311 m^3 natural gas without additional insulation on the pipe. Under these conditions, by adding 51 mm of fiberglass insulation, the savings will be 151349 m^3.

Table 5. Design specifications of shell and tube heat exchanger

Fluid name	-	Water	Gas oil
Flow rate	kg/s	34.5	145
Temp. range	°C	80 to 40	44 to 125
Specific heat	J/kg K	4179	2200
Dynamic viscosity	$N.S/m^3$	0.00072	0.00189
Density	Kg	995	830
Fouling factor	W/m^2K	0.00025	0.00025
Tube wall resistance	$\{W/m^2K\}^{-1}$	0.00004	
Overall U-initial	W/m^2K	450	
ΔT_{lm}	°C	24	
Heat load	5858 kW		
Tubes	OD= 19.05 mm	Thk = 2.11 mm	
Material	Carbon steel		
Shell Dia. ID	m	1.524	
A requirement	m^2	591	
Shell side pressure loss - Pa			
Nozzle loss	15.4		
Total central loss	41245.73		
Tow win-loss	53302.17		
End space loss	6345.49		
Total	100909		

5. ECONOMIC CALCULATIONS

Economic calculations are in Table 7. These calculations made for different countries, including Iran, Finland, France, Sweden, China and the EU average based on their energy prices and bank interest rates. For each one, Net Present Value (NPV) and return period calculated. NPV index or net present value aggregate the value of all annual cash flows over the life of a project with Eq. (4). Costs as negative values and savings presented as positive values. Higher NPV in a project, the more attractive the project is. The return period is the time when all project capital costs obtained by taking into account the bank interest rate. Other savings income can consider as net profit [20]. Equation (5) is used to estimate the cost of heat exchanger construction

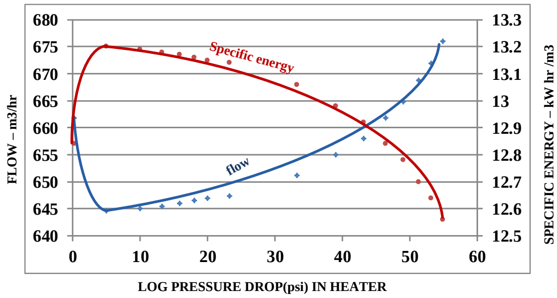

Fig. 8. Specific energy and flow changes by pressure drop within the heat exchanger.

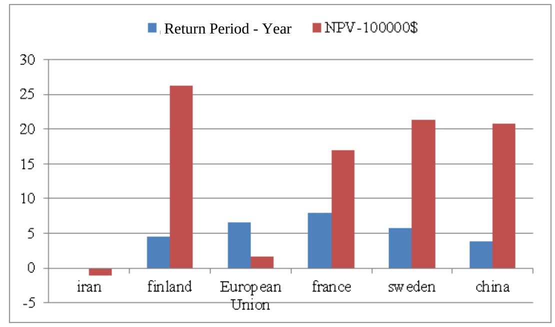

Fig. 9. Comparison of NPV and return period in different countries.

Table 6. Specifications of pipeline model with heat exchanger

-	1	2
Boiler efficiency	88%	
Input power	6591 kW	
Pipeline type	Burial	
Depth of pipe	1.2 m	
Insulation	Bitumen 5 mm	Fiberglass 55 mm
Ambient temp	15 °C	
Working fluid	Gas oil	
Specific gravity	0.835	
Hours of operation per year	8760	

[21]. Since oil prices are one of the fundamental causes of the devaluation of the dollar and other commodities, this equation presents the cost of producing a heat exchanger based on the price of a barrel of oil.

$$\mathrm{NPV} = \sum_{t=0}^{n} \left(\frac{\mathrm{R_t}}{(1+\mathrm{i})^{\mathrm{t}}} \right) \quad (4)$$

R_t– Net cash inflow- outflow in period t
t- Number of time period
i=Discount rate

$$C = 43 + 12.18A^{0.78} \quad (5)$$

A is the heat transfer area, and C is the cost of heat exchanger based on the price of a barrel of oil.

Initially, the cost of construction and maintenance of the heat exchanger is calculated and then compared with the annual revenue from energy savings and the cost of downtime after the useful life, then the costs and revenues are converted to present values.

Table 7 and Fig. 9, compares the results of the NPV and the period of return on investment, as can be seen in all the countries studied except Iran this project has an economic justification. The least return period is for China, and most for France, the main reason for the project being non-economic in Iran is energy subsidies. In Iran, large amounts of energy subsidies are spent annually, the price of all forms of energy set by parliament being low compared to the basic costs of providing them. Household fuel prices are kept particularly low to make them more affordable.

Despite consumer resistance, experts acknowledge that pricing reform is a key element in improving energy efficiency and supply [25]. That is why the targeted subsidies law has been adopted to bring energy costs closer to international rates by reducing energy subsidies. With the implementation of this law and the realization of the prices of energy carriers, it seems that the project will also have a good economic justification.

6. CONCLUSION

The recoverable energy from the output of the gas turbine is equivalent to 6591 kW. This value is suitable for changing the operating temperature of the pumping station from 25 °C to 44 °C. Using the heat recovery turbine in this method, reducing the viscosity of the gas-oil and also the energy required for pumping. This amount of energy savings is equivalent to 95311m3 of natural gas per year without pipe insulation. Also, by adding insulation to the pipeline, the savings will be approximately 151349 of natural gas. Therefore, in addition to optimally utilizing the heat available in the gas turbine combustion products, it also reduces the power consumption of the pump station. Economic calculations performed for different countries including Iran, Finland, France, Sweden, China, and the EU average, based on their energy prices and bank interest rates, In all of the considered countries except Iran, this project has an economic justification. The least return period is for China and most for France. The main reason for this project being non-economic in Iran is the energy subsidy. It seems to have reasonable economic justification with the implementation of targeted subsidies law and realization of prices of energy carriers. The limitation of this design is the head loss caused by the heat exchanger, which reduces the energy benefits.

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Table 4. Data needed to calculate the thermal power available in the exhaust gas stream

$\dot{m}_{air}$	$C_{p,mix}$	Share of H_2O in combustion products	Partial press. of water	Dew point temp.	temp. of exhaust gases
lb/s	kJ/kg.K	%	kPa	°C	°C
34	1.070	15.4	16.5	56	456

Table 7. Economic calculations

-	China	Sweden	France	Average EU	Finland	Iran
Cost of construction	$ 199211					
Annual maintenance cost	$100					
Useful life	20 year					
Sacrificial value	25% of the initial investment					
Saved fuel per year	95311 cubic meters of natural gas equivalent to 96023 liters of Gas oil					
First Year Fuel Price [22, 23]	0.909$/$ltrGO$	0.548$/$m^3NG$	0.445$/$m^3NG$	0.366$/$m^3NG$	0.668$/$m^3NG$	0.1$/$m^3NG$
Interest rate (%) [24]	4.2	0	0	1.8	0	18
NPV index- $	2080357	2130466	1698313	167064	2629106	-114416
Return Period- Year	3.9	5.8	7.9	6.6	4.5	-