

Applied Research of Solar Heating System for Crude Oil Transportation

Xuesheng Wang, Xiaoyong Tan, Ming Zhu

School of Mechanical & Power Engineering, East China University of Science and Technology, Shanghai, China

Abstract: The crude oil was usually heated and insulated to keep better flowability during the transportation because the flowability of crude oil with high solidification point and viscosity value is worse at ambient temperature. Utilization of solar energy instead of general energy for heating fuel oil can save a great part of energy consumption. According to the process conditions and operating characteristic of crude oil, a solar energy system for oil field has been designed. It consists of solar collector array, heat exchanger, hot water storage tanks and control system. In this system, through a heat exchanger the crude oil is heated indirectly by hot water, which is provided from solar energy collectors. The system can provide hot water for 6~8 hours per day, and the temperature of heated crude oil is increased by 25~30°C. It is expected that the nature gas consumption have been saved up to $9 \times 10^4 \text{ m}^3$ annually.

Keywords: Solar Energy, heating crude oil, solar energy collector, heat exchanger

NOMENCLATURE

A	Collector area [m^2]
C_p	Specific heat [$\text{kJ/kg} \cdot ^\circ\text{C}$]
I	Solar radiation intensity [MJ/m^2]
m	Mass rate of water [kg/h]
Q	Heat transfer rate [kJ/h]
t	Temperature [$^\circ\text{C}$]
T	Temperature of water [$^\circ\text{C}$]
W	Mass rate of hot water [kg/h]
η	Thermal efficiency [$^\circ\text{C}$]
Δt	Difference of temperature [$^\circ\text{C}$]

Subscripts

a	ambient
g	nature gas
i	inlet of water
o	oil or outlet of water
T	total
w	water

1. INTRODUCTION

The crude oil in China usually has high solidification point and viscosity value and low flowability at ambient temperature. When it is transported continuously to the next oil stations, it must be heated and insulated to keep better flowability. It has a great significance in the aspects of energy-saving and environmental protection to combine the solar utilization technology with the heating of the crude oil and replace part of the general energy with solar energy. In recent year, reports about utilizing solar energy to heat fuel oil in storage and crude oil during its transportation have been made continuously abroad ^{[1][2][3]}. Research on the utilization of solar energy into the industry of fuel

oil heating was made by Badran, A. A. etc, from Jordan University, in 1998 and two types of fuel oil primary heater units with solar energy were designed by them, which can heat up the fuel oil from ambient temperature to 50°C and store it at this temperature. In 1999, one solar energy company from Australia realized the application of solar thermal diode technology to heat up the crude oil during its transportation in pipe in order to reduce the viscosity value by adopting transparent/opaque materials and spectrally selective coating to increase the value of solar energy absorption coefficient and depression the elimination of heat in the ways of convection and radiation. However, there is still no precedent of utilizing technology in the transportation processes of oil fields in China. Take a measurement station of one oil production factory of Liaohe oil field for an instance, the temperature of the crude oil from this measurement station must be increased by 25~30 °C when it is transported to the next station. The natural gas consumption reaches about 1000 m^3 per day. A great deal of natural gas could be saved up if solar energy is used to heat the crude oil from this station. In this paper, a set of solar energy system for heating crude oil of transportation has been designed according to the conditions of the crude oil heating during the transportation of a measurement station of one oil production factory of Liaohe oil field and researches on the construction, operating principle and performance of the system has been made.

2. SYSTEM SUMMARIZING

2.1 Meteorologic condition on the site

According to the meteorologic data provided by the local meteorologic station, the average duration of sunshine is 2750 hours annually; There are about 300

days with a duration of sunshine of 8–9 hours per day in this region; The average solar energy available in the whole year reaches about 6925MJ/m² and the average day radiant exposure in the whole year is about 19 MJ/m², that is 659 W/m². The level of the solar radiation resource of this area nearly reaches that of the second class region for solar energy utilization of the whole country.

2.2 Scheme selecting

There are two kinds of designing ways for utilizing solar energy to heat the transported crude oil, which are the direct heating and the indirect heating. For the way of direct heating method, the crude oil enters the solar energy collector and is heated directly. It has a high efficiency during the process of crude oil heating. For the way of indirect heating, heat quantity is provided to one heat medium and then transferred to the crude oil from the heat medium through heat exchanger.

There are some disadvantages for direct heating. First, the crude oil transportation system is a system with pressure. But the collector used today doesn't have enough pressure-bearing capability. The reliability of its pressure-bearing is not very high even after its redesigning. Second, the temperature in the collector of direct heating will reach a high point sometimes due to the change of radiant of sunshine and a high temperature may cause the caking of the crude oil in the collector. Third, there exists deposition in the collector because the transported crude oil usually has a high viscosity and the fouling is hard to clean in the collector. At present, the key technology for using solar energy direct heating way to heat the crude oil is still not mature now.

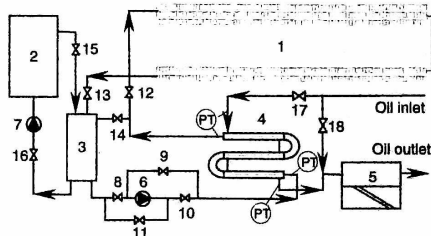
There are no disadvantages mentioned above for indirect heating way. Compared with the direct heating way, the system of indirect heating way must have a heat exchanger additionally and has lower efficiency because the solar energy collected must be transferred two times before it reaches to the crude oil during transportation. But from the aspects of the safety and reliability of the system and the convince of maintenance, overhaul and installation, the adoption of indirect heating way can take the best use of the current mature technology of solar collecting and heat exchanging. Therefore, this kind of programme is reliable and stable.

2.3 The construction and operating principle of the system

According to the above conditions, we have carried out a lot of work both in the deep theory analysis and experimental research and completed the designing of the solar energy system for heating crude oil of transportation. It mainly consists of solar energy collectors and their array, crude oil heat exchanger, hot water storage tanks and control system, etc. The main procedure of the whole system is shown in Fig. 1.

The operating principle of the system can be briefly described as follows: Under the conditions of normal radiation of sunshine, the circulating pump 6 is started with the valves 9 and 11 closed, the solar hot water is drawn from the small-size hot water storage

tank into the heat exchanger 4 through self-control valve 8 and 10 to heat the crude oil in the shell side, and then the cooled water is transported through the self-control valve 12 to the collector array and enters into the small-size hot water storage tanks through the self-control valve 13 with the valve 14 closed. The hot water exchanges heat with the crude oil in the heat exchanger 4 and heat up the crude oil. The heated crude oil enters into the water jacket stove through export on the side of oil transportation. The heater 5 was activated or not depends on the crude oil temperature.



1. Solar collector field 2. Large-size water tank 3. Small-size water tank 4. Oil heat exchanger 5. Water jacket stove 6, 7. Circulating pump 8–18. Control valves

Figure 1: Flowchart of solar systems for heating crude oil

When the temperature in the small-size hot water storage tank is found to be very high, the incident solar radiation is sufficient to provide thermal energy. Then the circulating pump 7 is self-started, the hot water enters into the big-size hot water storage tank through the self-control valve 16 and is transported back to the small-size hot water storage tank after the superfluous energy is stored up. When the temperature in the collector is too low to increase the temperature of water, the hot water enters into the small-size hot water storage tank through self-control valve 14 after exchanging heat with the crude oil in heat exchanger. At this time, the self-control valve is close and the big-size hot water storage tank supplies the heat quantity to the small-size hot water storage tank.

If the water temperature at the outlet of the heat exchanger approaches the water temperature at the inlet, the valve 17 at the side of the inlet is self-closed and the crude oil is transported through the valve 18 to the heat stove to be heated. Under the conditions such as the night time in the winter or that the systems is being repaired or stop, etc, the water in the system is transported back to heat return water tank through the self-control valves 9 and 11, with the self-control valve 8 and 10 closed.

3. SYSTEM DESIGN

3.1 Weather condition on the site

The crude oil from the measurement station of the petroleum production factory is composed of water,

oil and gas. When transported to the next measurement station, it is heated up from 25–30 °C to 50–55 °C with a operating pressure of 0.6 MPa. The qualitative temperature for the calculation is 40°C. Other technological conditions and physical performance parameters of crude oil which will be needed in calculation are shown in table 1.

Table 1: Process conditions and physical parameters of crude oil

Crude oil composition	Water	Oil	gas	Average
Volume flow (m ³ /d)	140	60	12360	523
Mass flow (kg/h)	5833	2210	1931	9974
Mass ratio	0.5848	0.2216	0.1936	1
Density (kg/m ³)	1000	884	3.75	19.07
Specific heat (kJ/kg°C)	4.174	2.582	2.156	3.43
Coefficient of heat conductivity (W/m°C)	0.6333	0.14	0.035	0.408
Viscosity (kg/m.s) ×10 ⁻⁵	65.32	400	1.133	127

3.2 Heat quantity accounting of the system

The load of the system reaches its peak when crude oil is heated up and the temperature of the crude oil is increased by $\Delta t=30^{\circ}\text{C}$. The required heat quantity is:

$$Q_w = W_w \times C_{pw} \times \Delta t = 5833 \times 4.174 \times 30 = 720407 \text{ kJ/h}$$

$$Q_o = W_o \times C_{po} \times \Delta t = 2210 \times 2.582 \times 30 = 171186 \text{ kJ/h}$$

$$Q_g = W_g \times C_{pg} \times \Delta t = 1931 \times 2.156 \times 30 = 124890 \text{ kJ/h}$$

The total heat load is:

$$Q_T = Q_w + Q_o + Q_g = 1026485 \text{ kJ/h} = 285 \text{ KW}$$

Suppose that the temperature of water in solar collector can be increased by 20°C. Then, without consideration of heat loss, the required hot water mass flow is:

$$W = Q_T / (C_p \times \Delta t) = 12.3 \times 10^3 \text{ kg/h}$$

3.3 Solar collector

The evacuated tubular collector with heat pipe is choose by us after a careful analysis of lots of engineering practices of applying solar collector and with a considering of the climate characteristic and temperature rising characteristic of the northeast region of China. The evacuated tubular collector with heat pipe is a type of metal absorber developed successfully by China, which was put into market in 1990s. The evacuated tubular collector has many merits as follow: Firstly, it has high heat transfer efficiency for the working substance inside heat tube has a high coefficient of heat transfer during process of phase change. Secondly, it has strong anti-freeze ability for the solar collector can work at an ambient temperature of -30°C and even below with a proper selection of the suitable working substance. Lastly, it has steady working performances and long operating life because it can not be affected by scaling and corrosion resulting from bad water quality [4].

A systematic experiment research on heat performance of one commercial evacuated tubular collector with heat pipe selected has been done by us.

The thermal collecting efficiency of experimental point can be obtained according to the following formula:

$$\eta = \frac{m C_p (T_o - T_i)}{A \cdot I} \quad (1)$$

Where, m is mass rate of water, C_p is specific heat of water; T_i , T_o is temperature of inlet, outlet of solar collector, A is collector area, I is solar radiation intensity.

The computing formula for momentary thermal efficiency of solar collector is obtained based on the experimental data, which is:

$$\eta = 0.667 - 2.28 \frac{T_i - T_a}{I} \quad (2)$$

Where, T_a is ambient temperature, η momentary collecting efficiency.

The temperature growth of the heat catalysis water inside the evacuated tubular solar collector with heat tube can be calculated by referencing the meteorologic data of solar radiation of Liaohe oil field and the design requirements by combining the test data from experiment and the computing formula above. The changes of water temperature response to the change of solar radiation intensity with collecting efficiencies of 40% and 50% respectively are shown in figure 2.

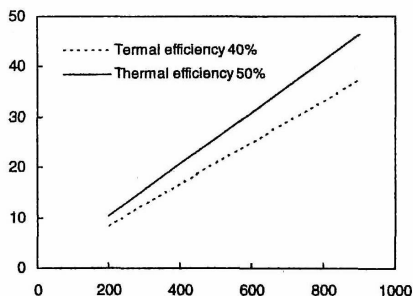


Figure 2: Temperature difference between inlet and outlet of solar collection versus radiant intensity of solar energy

It can be seen from Fig. 2 that by adopting the evacuated tubular collector with heat pipe to heat recycled water, if the collecting efficiency of collector is from 40% to 50%, the water temperature difference can generally reach as high as 20–30 °C according to climatic conditions in Liaohe region. That is to say, when the inlet water temperature in collector is 50–60 °C, the outlet water temperature can be kept above 70–80°C. With such working condition, it can be realized that the crude oil can be heated by heat exchanger using the hot water from outlet of the collector, and the designing of crude oil heat exchanger is directly based on this calculating result.

The heating source of the system is made up of a collector array consisting of 1280 sets of solar evacuated tubular collectors with heat tube. The gross collector area of collector array is 1280m². The

collectors are divided into 16 rows. In order to reduce flow resistance, the disposing fashion that each 8 of the total 16 rows collectors are set in parallel into two group and then the two groups are placed in series is adopted in collector array. The Disposal of field can see from Fig. 1. The total area of collector field is about $50\text{m} \times 35\text{m} = 1750\text{m}^2$.

3.4 Heat exchanger

Although shell-and-tube exchanger is not as good as other new style highly efficient heat-exchange equipment in the aspects such as heat exchanging efficiency, equipment volume, metal material wastage, etc. it is widely used in all kinds of projects for its merits like solid structure, great elastic performance, reliability and wide range of use. Usually, the crude oil transfer pipes have certain pressure and the crude oil in them has high viscosity value, easily scaling characteristics, certain corrosive characteristics. Therefore, shell-and-tube exchanger is chosen as the structure of heat exchanger in this system with a consideration of the convenience of cleaning, maintaining, setting and dismounting heat exchanger.

Rod baffle heat exchanger was developed by W. M. Small from Phillips Petroleum (USA) in 1970s for solving the problem of fluid induced vibration in large-sized shell-and-tube exchanger [5]. In the inner structure of this heat exchanger, the original segmental baffle plate was replaced by rod type support. Therefore the heat exchanger has the merits such as anti-vibration, high efficiency, low pressure drop, etc. Compared with traditional baffle shell-and-tube exchanger, rod baffle heat exchanger has great changes in inner structure. In shell-side of the heat exchanger, baffle grid consisting of baffle rod replacing baffle plate was adopted as support between tubes, which made the fluid in shell-side flows in parallel way rather than in lateral way. This not only largely reduced the dead area of heat transfer, but also greatly reduced shell-side pressure drop. Compared with current shell-and-tube exchanger, the overall heat transfer coefficient was improved more than 30% and the shell-side resistance was reduced more than 50%. Therefore, when dealing with the same heat load, the equipment required is lighter in weight. The design parameter comparison of two types of heat exchanger is shown in table 2.

Table 2: Design parameter comparison between rod and plate baffle heat exchanger

type of heat exchanger	rod baffle	plate baffle
Shell diameter (out) (mm)	159	273
Heat load (kW)	285	285
Overall heat transfer coefficient ($\text{W/m}^2 \cdot ^\circ\text{C}$)	332	185
Shell-side differential pressure (MPa)	0.027	0.081
Heat-transfer area (m^2)	27	52
overall weight (kg)	1200	2314

The crude oil flows on the shell side of the heat exchanger with an inlet temperature of $25\text{--}30^\circ\text{C}$ and an outlet of $50\text{--}55^\circ\text{C}$. The detailed technological parameter is shown in table 1. Hot water flows on the tube side of the heat exchanger with an inlet temperature of $70\text{--}80^\circ\text{C}$ and an outlet temperature of $50\text{--}60^\circ\text{C}$, which is provided by solar hot water system. The size of Shell is $\Phi 159 \times 6.5\text{mm}$ and the Heat exchanger tube is spiral grooved tube with a size of $\Phi 25 \times 2.5\text{mm}$. The overall heat transfer coefficient is about $332\text{W/m}^2 \cdot ^\circ\text{C}$, and the overall heat transferring area 24m^2 . The heat exchanger adopted is double-pipes tube bundle heat exchanger. The entire heat exchanger consists of six rod baffle heat exchangers units. As shown in Fig. 3.

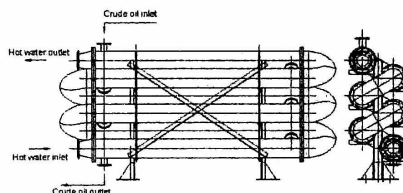


Figure 3: double-pipes heat exchanger with rod baffle tube bundle

3.5 Hot water storage tank

To make sure that the system could steadily operate and hot water inlet temperature of heat exchanger could not be directly affected by transient variation of solar radiation, the hot water from the solar collector should first enter the water storage tank, and then go into heat exchanger from the hot water tank. The system is installed with two hot water storage tank, one is a big size, the other one is a small size. The dimensions of the small one is 5m^3 , which is mainly used to ensure a fast starting of the system to make the hot water heated by solar collector arrive to the required operating temperature as soon as possible every morning. The dimensions of big one, which is 20m^3 , is mainly used to store up redundant solar energy in form of hot water in daytime. This stored energy can be used when no or less solar radiant energy.

3.6 Control system

The control system consists of the solar control part and the water jacket stove control part.

The functions of solar energy control part include heat supply, heat storage, the heat release of hot water in water tank, the switching function between solar heating system and water jacket stove heating system under different working conditions and automatically evacuating water in pipeline system at winter night.

The main functions of water jacket stove control part include steady temperature control in crude oil outlet, automatic control of heating of water jacket stove, automatic firing and heating according the crude oil temperature and controlling burning capacity of combustor.

4. THE PERFORMANCE OF THE SYSTEMS

The solar energy system for heating crude oil of transportation described in this paper has been applied in Liaohe oil field. The main performance indexes of the system are as follows:

(1) Under the regular radiant intensity of sunshine, the heat collecting system can provide heat for about 6–8 hours per day with the temperature of the water at the outlet reaching 75–80°C.

(2) The crude oil is heated up through the heat exchanger from 25–30°C to 50–55°C.

(3) If solar energy of this system is used to heat the crude oil, it is expected that 300m³ natural gas per day can be saved up for the whole oil field. And if the water temperature is higher than 80°C, the amount of natural gas saved will be increased.

(4) About 1×10⁵ m³ nature gas is consumed to heat the crude oil in this measurement station one day. By utilizing the solar energy, 30% of the total natural gas consume everyday will be save up. So about 1×10⁵ m³ natural gas has be saved

5. CONCLUSION

A new application field has been developed by utilizing the solar energy to heat the crude oil. The characteristics of this system are as follows:

(1) The evacuated tubular collectors with heat pipe improve the efficiency of the system, and meet the low ambient temperature environment.

(2) Indirect heating is adopted in this system and the construction of rod baffle double-pipe are adopted in the crude oil heat exchanger, which increases the

heat transfer efficiency and reduces the flow resistance of the system.

(3) The installation of two heat storage water tanks which are in small size and big size not only can accelerates the starting speed of the system but also can store up the superfluous heat quantity.

(4) The operation and the switching over between the functions of the system can all be self-controlled.

ACKNOWLEDGEMENTS

The present work was supported by the key project of Chinese Ministry of Education (NO. 105072).

REFERENCES

- [1] Badran, A A. Hamdan, M A. 1998. Utilization of solar energy for heating fuel oil Energy. *Energy Conversion and Management*. Vol 39. No (1-2). pp 105-111. UK.
- [2] Badran, A A, Jubran, B A. 2001. Fuel oil heating by a trickle solar collector. *Energy Conversion and Management*. Vol 42. No 7. pp 1637-1645. UK.
- [3] Anon. 1999. Solar-heating system studied for heavy-oil pipelines. *Oil and Gas Journal*. Vol 97. No 13. pp 44-46. USA.
- [4] He, Z N, Jiang F L, et al. 1994. Study on thermal performances of heat pipe evacuated tubular collectors. *Acta Energiae Solaris Sinica*. Vol 15. No 1. pp 73-82. China.
- [5] Gentry, C C. 1990. Rod-baffle heat exchanger technology. *Chemical Engineering Progress*. Vol 86. No 7. pp 48-56. USA.