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Experimental study of implementing nano thermal insulation coating on the steam injection tubes in enhanced oil recovery operation for reducing heat loss

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ABSTRACT

Thermal recovery in oil fields is an effective conventional method for extracting heavy oil. Steam injection is one of the main techniques in thermal recovery. Temperature reduction of the injected steam due to heat transfer from tubes to the reservoir environment is one of the essential problems in this method. Increasing the steam temperature or injection rate to overcome this energy loss and to provide the required temperature at the tube outlet considerably enhances the steam generation costs. Furthermore, increasing the injection temperature enhances the thermal stress to injection tubes that in turn brings irreparable damages to production units like casing breakage. In this study, an experimental setup used to simulate steam injection operation in order to decrease the heat transfer coefficient and reduce heat loss to conserve the injected steam temperature. This aim ascertained by using nano coatings as thermal insulator. Two types of thermal insulators including nano silica-based and nano ceramic-based insulators used in this study. Temperature, pressure, and injection rate of steam, and type and thickness of nano thermal insulators were the operating variables. Results show that increasing the injection temperature from 119 °C to 145 °C improves the heat transfer coefficient about twofold that in turn, causes rapid reduction of temperature in injection process. It was also shown that increasing the injection rate from 2.1 g/l to 6.3 g/l inside the bare tube improves the heat transfer coefficient up to 2.5-folds. Therefore, increasing the temperature or injection rate of steam could not be the suitable solution for compensating steam heat loss. The experimental results showed that using ceramic-based and silica-based nano insulation with 5 mm thickness reduces the heat loss up to 45% and 33% for injected steam at 145 °C, respectively.

1. Introduction

Heavy oil is a fluid that does not flow easily. It named “heavy” since its density is higher than that of light oil. Usually, heavy oil has an API less than 20 so that its viscosity is between 50 and 10000 cP (Go et al., 2015; He et al., 2017). High viscosity, high density, and having heavier molecular composition are the main physical properties that distinguish this type of oil from light oil. Heavy oil is one of the important sources of oil storage that plays an important role in the world energy economics.

Thermal energy processes are one of the advanced techniques in enhanced oil recovery that used to extract large volume of oils per day. In 1993, world oil production using these methods was 700,000 barrels per day (Green and Willhite, 1998). These methods are based on the fact that the oil viscosity reduces with increasing temperature. Heat injection into the reservoir in addition to viscosity drainage has some other advantages like oil expansion, oil distillation at high temperature that separates light components of the oil, and also reservoir pressure enhancement that accelerates the oil movement towards the oil production wells.

Steam injection is one of the thermal methods for enhanced oil recovery. Chunsheng et al. (2017) stated that steam injection is one of the simple and usually successful methods in thermal enhanced oil recovery. In this method, thermal energy transferred into the reservoir using hot steam injection, and as a result, the heavy oil temperature increases. Steam injection operation may extend about one month (Thomas, 2008). When the oil viscosity reduces, the pressure of the oil layers

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improves for easy production (Go et al., 2015; Chunsheng et al., 2017). Gu et al. (2014) revealed that the effect of steam injection in thermal recovery is more noticeable than hot water injection since steam could transfer more enthalpy per unit mass. Steam injection is limited to the depth of 1000 m since heat loss is great in more depths (Green and Willhite, 1998).

Satter (1965) showed that pressure, temperature, injection rate, time, and well depth are the main parameters influence on the heat loss in steam injection wells. Fidan (2011) developed a model for the determination of heat loss in offshore and onshore platforms. This study showed that using thermal insulation could considerably reduce the heat loss in steam injection tubes.

One of the suggested solutions for compensating the heat loss in steam injection operation is using higher temperature steam to overcome the temperature decay along the oil wells so that it receives to the reservoir at the prescribed temperature. This method causes more costs and depreciation, and also entails damage to well and tubes. Injected steam temperature is one of the important parameters the affects oil to steam ratio (O/S), and also greatly changes the steam generation costs. O/S is the ratio of producing oil using steam injection to the amount of injected steam. Thomas (2008) said that this ratio is initially 1 or 2 or less, and increases with the steam injection cycles. Farouq Ali (2003) stated that more than 3000 bbls/d water should be used for the production of 15 MW steam. Its cost was evaluated as 5000 US$/d in 2002. Therefore, as the low temperature injection steam is used, the efficiency of viscosity drainage and other effective mechanisms of oil movement with the steam reduced. On the other hand, if higher temperature injection applied, more heat loss is expected, and the probability of casing breakage and other damages increases. Furthermore, steam injection at higher temperature causes the oil component to be vaporized, and this is disadvantageous form economical point of view. So, it is very important to work at the optimized temperature.

Li (2008) demonstrated that thermal stress has the most impact on the casing breakage in enhanced oil recovery operation that is due to heat transfer to the casing. It shows that number of heavy oil wells in which casing breakage happened due to thermal stress in enhanced oil recovery operation is more than 20,000 wells. This value shows a remarkable economic loss to oil industries (Zhong-hong and Li-Yang, 2009). Tao (2015) used a casing in the laboratory with 34% higher resistance to breakage at high temperatures. Wu et al. (Wu and Knauss, 2006) recommended high-grade casing (e.g. P-110) to reduce the risk of breakage. Although these solutions are suitable to prevent casing breakage but they are not suitable in the case of heat loss.

In the previous years, several investigations performed on the application of thermal insulators for heat transfer reduction in tubes. Theses insulators could reduce the heat transfer to some extent but they suffer from some problems such as low stick ability to the surface, hard to work with them, and low thermal resistance. Wei et al. (2015) stated that heat loss could be reduced up to 25% using the conventional insulators.

In the recent years, application of nanomaterials broadly extended. For example, nanosilica was added to base materials of cement to improve its solidity. Nanotubes and nanofibers were used to enhance the flexural and tensile strength of the concrete. Nano titanium dioxide was implemented as enamel for its sterilization and anti-fouling properties (Bozsaky, 2015). So, nanotechnology is currently applied effectively in nanomaterials synthesis and also coating processes. Analysis on the nano coatings showed that their properties are notability enhanced in some aspects comparing with the conventional coatings. Nano coatings have higher thermal expansion, hardness, toughness, and more resistance to corrosion, erosion, and abrasion (Wang et al., 2007). Nano insulators could suitably entrap the air in their structure due to its greater porosity, and as a result, their insulation efficiency is noticeable even at lower thickness. Besides these properties, their cost is reasonable and their coating method is easy. Nano insulator paints are used in industrial applications as thin film thermal insulation. These insulators have low thermal conductivity and high stick ability, and could simultaneously prevent corrosion and heat transfer.

In this study, nano insulators, according to their properties mentioned before, used to reduce the heat transfer coefficient in steam injection tubes. If the heat transfer coefficient reduces, heat loss along the injection tubes decreases, and consequently, it will be possible to deliver the steam to the reservoir at the temperature close to the injection temperature. One of the methods that usually applied to fight with the steam temperature reduction is increasing the steam injection rate or steam temperature. These methods increase the operating costs for steam generation and increases thermal stress to equipment that may eventually result in casing breakage. Casing breakage in oil wells could bring serious damages to oil industries. It may even lead to losing the injection well. All the above-mentioned points besides the environmental effects of using more fossil fuels for steam generation highlight the importance of nano thermal insulators. Therefore, an experimental apparatus used in this research to simulate the steam injection operation in tubes with and without thermal insulation. The experiments performed at different operating conditions including temperature, pressure, and injection rate of steam, and type and thickness of nano insulators.

2. Materials and methods

2.1. Materials

In order to reduce heat transfer along the injection tube, two commercial types of nano thermal insulation coatings were used in this study. The first one is nano ceramic-based insulator supplied from Nano Axon Co., and the second one is nano silica-based insulator provided from Nano Isola Co.

Nano ceramic thermal insulators were introduced to the thermal insulation market in previous decay. These nano insulators are like paint and constructed from small microsphere ceramic cells. These hollow spheres have been made from molten ceramics at high temperature. Some references reported their thermal conductivity in the range of 0.001–0.003 W/m°C, and some others reported the higher values as 0.01–0.14 W/m°C (Bozsaky, 2015). Nano silica-based insulation also used as thermal insulator. Its thermal conductivity is about 0.02 W/m°C (Gao et al., 2014). Certainly, the nanoparticle size affects its thermal conductivity (Chari et al., 2013).

Steam was used in this experiment as injection fluid. The temperature and pressure of the steam selected so that the steam is in superheated condition according to thermodynamics tables (Smith and Van Ness, 1959). Then, the experiments performed at three different temperatures and pressures according to Table 1.

2.2. Experimental setup

For simulating the steam injection operation, an experimental setup was fabricated. Fig. 1 schematically represents the experimental apparatus.

It is important to consider this point in the design of the experimental setup that the experimental results should be generalized enough to utilize in industrial applications. The scale down criterion conducted using Reynolds number as a basis. It was aimed to have similar Reynolds number in the experimental setup and in reality. In the crude oil production unit, Reynolds number varies from 3000 to 10,000 according to

Table 1
Temperatures and pressures of the steam used in this study.

#	(kPa) P	(°C) T
1	200	119
2	300	134
3	400	145

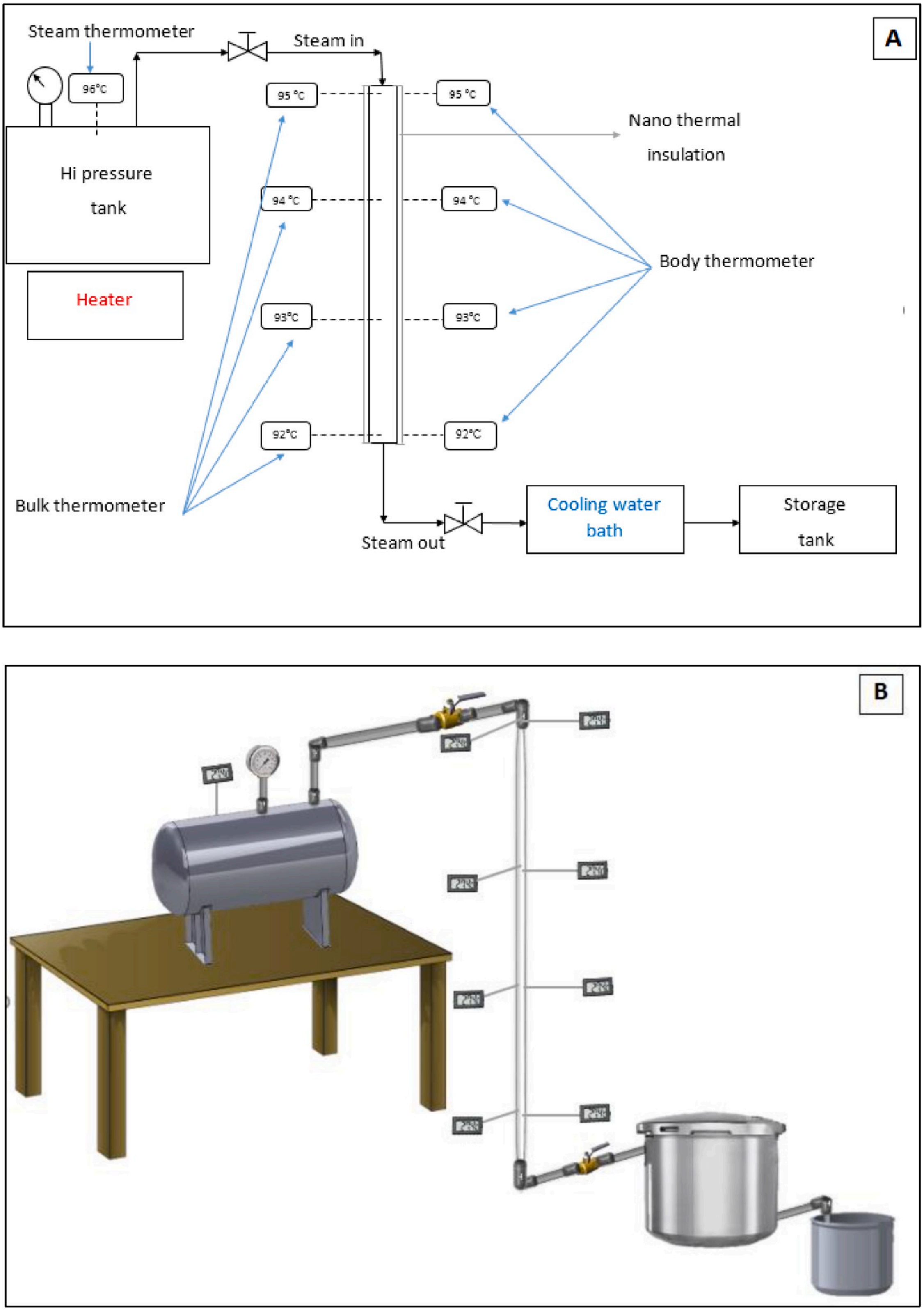

Fig. 1. Schematics of the experimental setup (A) 2D (B) 3D.

operating conditions (Morgan and Carlson, 1960). Reading the density and viscosity of the steam from thermodynamic tables at the conditions presented in Table 1, the dimensions of the tube selected so that the experimental Reynolds number was in this range. The experimental tube with the diameter of 0.022 m and length of 2 m was selected. The steam velocity tuned at the range of 7–10 m/s so that Reynolds number adjusted at the range of 7800–9700 in all the experiments.

First, steam at different temperatures and pressures was generated in the heated vessel. The heater purchased from OLYMPIA Co. with 1500 W power. This vessel equipped with a pressure gage and a thermocouple. Pressure gage provided by PENTAX Co. with the precision of 0.2 bar, and thermocouple purchased from BTMCO Co. with the precision of 0.1 °C. A tube with the mentioned dimensions used for steam injection inside it. This tube has the thermal conductivity of 0.02 kW/m°C similar to the tubes used in the real operation. After reaching the temperature and pressure of the steam to the prescribed values, the valve opened and the steam flows into the tube downward. The temperature data including steam bulk temperature and tube wall temperature recorded at five different cross sections of the tube. Two thermocouples mounted at the beginning and two others at the end of the tube. In addition, the temperature data from three other cross-sections of the tube gathered to observe the temperature gradient along the tube. So, the thermocouples installed 0.5 m apart from each other. For the measurement of steam injection rate, the tube effluent conducted to a cold-water bath to condense the steam completely. Steam injection rate calculated according to the mass of condensed water and the corresponding time. Fig. 2 shows the actual view of the experimental setup.

For the coating of nano thermal insulation on the external surface of the tube, the tube was first sand blasted and prepared for insulation. Then, the insulators coated on the tube surface according to vendor's instruction. This instruction includes environmental condition, drying time of each layer, thickness of each layer, coating apparatus, and so on. Both nano thermal insulators were coated on the tube surface at two thicknesses of 3 and 5 mm. It should be mentioned that these two thicknesses are more than critical thickness of insulation for both insulators. So, it is expected that applying these insulations enhances thermal resistance.

In these experiments, the following assumptions were considered:

- Heat transfer along the tube length is steady state.
- In steam injection, temperature, pressure, and injection rate are constant.
- Experimental conditions (temperature and pressure) around the tube are independent of geological conditions existed in the actual operation.

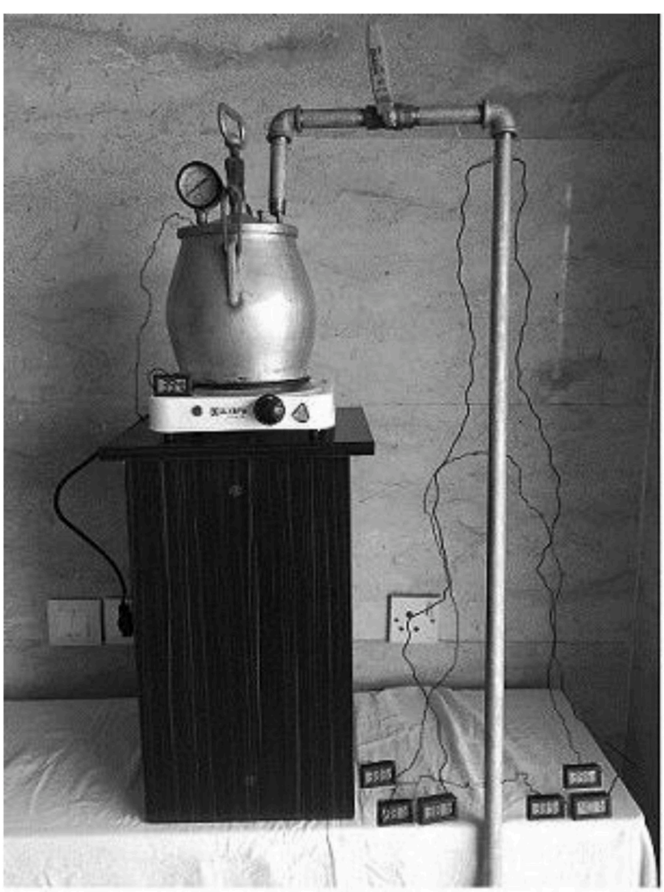

Fig. 2. Experimental setup used in this study.

2.3. Calculation

In this research, for the validity of the experimental apparatus, theoretical and experimental heat transfer coefficients were compared. The injected steam starts condensing just after entrance to the tube, and a condensate film appeared on the internal surface of the tube. It means that condensation is the governing mechanism of heat transfer. Therefore, heat transfer, q, can be calculated as follows:

$$q = \dot{m}\, h_{fg} \tag{1}$$

where m is injection rate (kg/s), h_{fg} is vaporization enthalpy (kJ/kg).

On the other hand, heat transfer can be calculated using Newton's cooling law for convection heat transfer (Holman, 1989):

$$q = h.A.(T_b - T_w) \tag{2}$$

where A is heat transfer surface (m^2), h is local convective heat transfer coefficient, and T_w and Tb are the wall and the bulk temperatures.

Combining Eqs. (1) and (2), the experimental local convective heat transfer coefficient obtained:

$$h_{local,\text{exp.}} = \frac{\dot{m}\,.h_{fg}}{A.(T_b - T_w)} \tag{3}$$

The average value of heat transfer coefficient can be calculated by integration from Eq. (3) along tube length (Zhong-hong and Li-Yang, 2009):

$$\bar{h}_{\text{exp.}} = \frac{\int h_{local,\text{exp.}} dx}{\int_0^l dx} = \frac{1}{l}\int_0^l h_{local,\text{exp.}} dx \tag{4}$$

For calculating the theoretical heat transfer coefficient, Rohsenow (Rohsenow et al., 1998) suggested a relation for condensation inside vertical tubes. He stated that condensation inside the vertical tubes depends on the vapor flow direction. For downward flow, at low flow velocity, the condensate flow is dominated by gravity, and therefore, the relation for vertical plates could be used. On the other hand, for high flow velocity and turbulent flow regime, Eq. (5) proposed for the calculation of heat transfer coefficient:

$$\frac{\bar{h}_{theo.}}{k_l}\left(\frac{\mu_l^2}{\rho_l(\rho_l - \rho_v)g}\right)^{1/3} = 1.33\mathrm{Re}_l^{-1/3 + 9.56\times10^{-6}\mathrm{Re}_l^{0.89}\mathrm{Pr}_l^{0.94} + 8.22\times10^{-2}} \tag{5}$$

where k_l is liquid film thermal conductivity, ρ_l is liquid film density, μ_l is liquid film viscosity, ρ_v is injected steam density, g is acceleration of gravity, Re_l is Reynolds number, and Pr_l is liquid film Prandtle number.

Now, it is possible to calculate the experimental and theoretical Nusselt number using Eqs. (4) and (5):

$$Nu = \frac{h.D}{k} \tag{6}$$

where D is tube diameter (m), and k is thermal conductivity of the steam (W/m°C).

Another result that will be discussed in this study is the heat loss along the tube length. When the steam injected downward, some of its energy dissipated from tube to the atmosphere. This heat dissipation could reduce the steam quality and enthalpy. Therefore, it is important to calculate the heat loss as a design parameter in steam injection operation. Heat loss in oil zones was estimated under steady state condition (Chunsheng et al., 2017).

Special efforts performed to reduce the heat loss by applying thermal insulation. Reducing heat loss along the tube maintains the initial temperature of the steam. An insulator would be more suitable if lower heat loss observed.

Assuming the heat transfer inside and outside of the tube performed under steady state condition, the heat loss can be calculated as follows (Fidan, 2011):

$$\dot{Q} = \frac{T_b - T_A}{\sum R} \tag{7}$$

where T_b is fluid bulk temperature, and T_A is external surface temperature of the tube.

Fig. 3 demonstrates the tube and its insulation. ΣR is total thermal resistance which can be calculated according to Fig. 3 as follows:

$$\sum R = R_{conv1} + R_{cond1} + R_{cond2} + R_{conv2} \tag{8}$$

where the first term at right hand side related to tube interior thermal resistance, the second term for tube material thermal resistance, the third term for insulation thermal resistance, and the fourth term for exterior fluid (atmosphere air) thermal resistance. Eq. (8) could be rearranged in the extended form as Eq. (9):

$$\sum R = \frac{1}{h_1 A_1} + \frac{1}{2\pi K_1 l}\ln\frac{r_2}{r_1} + \frac{1}{2\pi K_2 l}\ln\frac{r_3}{r_2} + \frac{1}{h_2 A_2} \tag{9}$$

where r_1, r_2, and r_3 are internal and external radii of the tube, and external radius of the insulator, respectively. h_1 and h_2 are the heat transfer coefficient inside and outside the tube, respectively. k_1 and k_2 are thermal conductivity of tube material and insulation, l is tube length, A_1 and A_2 are internal and external surfaces of the tube, respectively.

Certainly, total thermal resistance for the case of no insulation is calculated as follows:

$$\sum R = \frac{1}{h_1 A} + \frac{1}{2\pi K_1 l}\ln\frac{r_2}{r_1} + \frac{1}{h_2 A} \tag{10}$$

3. Results and discussion

3.1. Verification

For the sake of validation of experimental setup, a comparison performed between the experimental and theoretical average heat transfer coefficients before applying nano thermal insulators. Fig. 4 shows this comparison at three different steam inlet temperatures. Eq. (5) was used as the theoretical relation for the prediction of condensation heat transfer coefficient inside vertical tubes. The experimental heat transfer coefficients were obtained from Eq. (4).

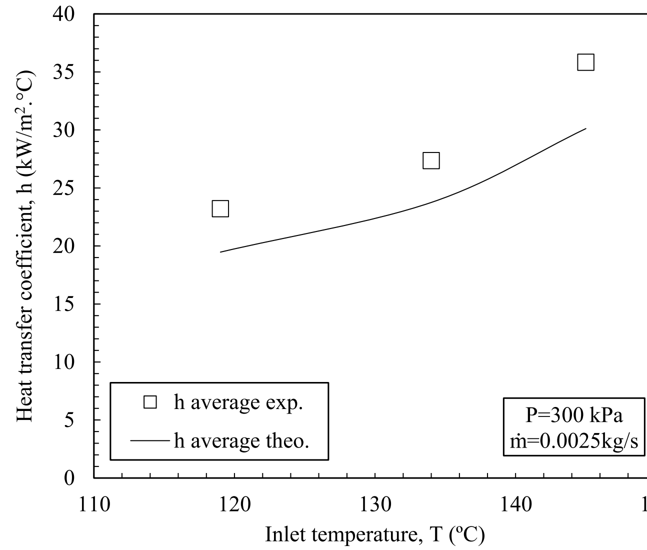

Fig. 4. Comparison between the theoretical and experimental heat transfer coefficients.

Results show that the experimental data have maximum deviation of less than %10. This comparison, although not shown here, performed at the other injection rates. Totally, maximum deviation did not exceed % 10. So, the accuracy of the experimental system proved to be acceptable.

3.2. Local heat transfer coefficient

Installing five pairs of thermocouples along the injection tube (each 0.5 m, a pair of thermocouples installed), the fluid bulk temperature and the tube wall temperature were measured, and then, the local heat transfer coefficient at different positions were calculated using Eq. (3). Fig. 5 demonstrates the effect of steam injection temperature (119, 134, and 145 °C) on the local convective heat transfer coefficient. It is obvious that the local heat transfer coefficient improves with increasing steam injection temperature. Increasing the temperature from 119 to 145 °C enhances the heat transfer coefficient almost 2 times at the beginning of the tube, and about 1.5 times at the end of the tube.

On the other hand, it is clear in Fig. 5 that the heat transfer

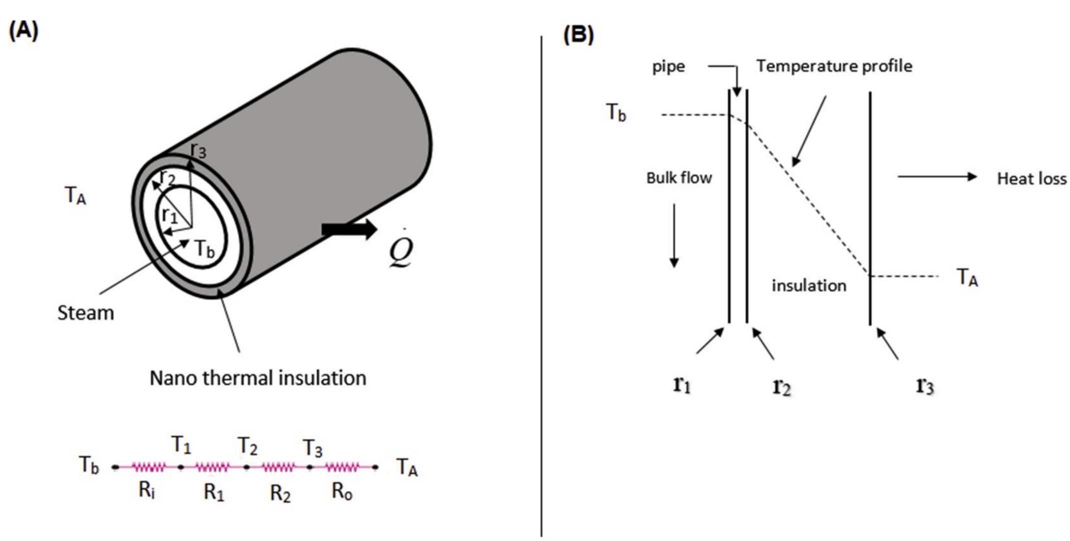

Fig. 3. Schematics of experimental tube and nano thermal insulation on it.

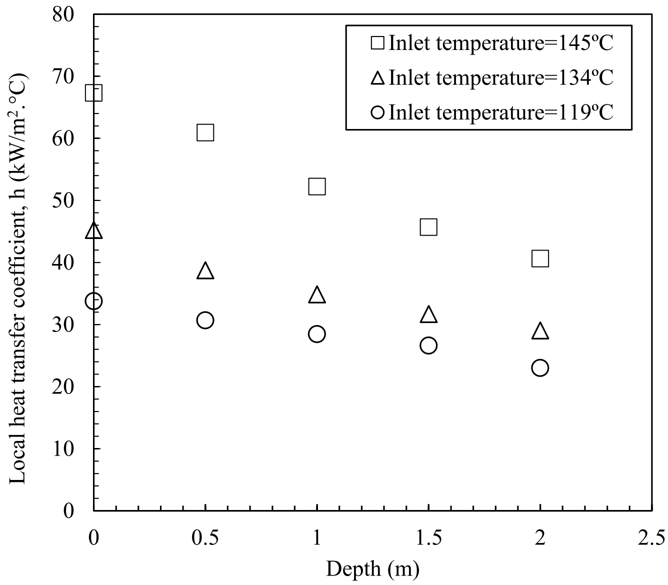

Fig. 5. Variation of heat transfer coefficient with steam inlet temperature and tube depth.

coefficient decreases when the steam goes downward the tube. It is due to the heat loss that causes the steam temperature reduces and to be inclined to the ambient temperature. Therefore, the heat transfer coefficient decreases since it is dependent on the temperature difference. Indeed, it is acceptable theory that at the entrance region (developing flow region) of the tube where the boundary layer thickness is smaller, greater heat transfer coefficient would be expected.

In industrial steam injection operation for compensating heat loss, steam is injected at higher temperature and pressure. Fig. 5 shows that this action although can deliver the steam at the higher temperature, could in turn enhance the heat transfer coefficient and heat loss considerably. It means that if an appropriate insulation could be implemented, there is no need to increase the steam temperature at the injection point to overcome the heat loss. This issue will be discussed in the next section.

Fig. 6 demonstrates the variation of local heat transfer coefficient of the steam inside the tube without insulation and with two different thicknesses of nano thermal insulation. It is shown that applying 3 mm of nano silica and nano ceramic thermal insulations, the heat transfer coefficient reduces 28% and 43% compare with the bare tube, respectively. Increasing the insulators thickness to 5 mm reduces the heat transfer coefficient to 46% and 50% for nano silica and nano ceramic thermal insulations, respectively.

It is also clear in Fig. 6 that slope of the line of the heat transfer coefficient in bare tube is slightly higher than that of the insulated tubes. It means that not only the heat transfer coefficient in insulated tubes is lower than the bare tube; the heat transfer coefficient reduction along the tube length of the insulated tube is also lower than the bare tube. Overally speaking, both effects cause the heat loss to reduce by using thermal insulators.

3.3. Average heat transfer coefficient

The average heat transfer coefficient is an appropriate viewpoint for analyzing the heat transfer condition in steam injection operation. Fig. 7 shows the variation of average heat transfer coefficient as a function of injection temperature in bare tube and nano thermal insulated tubes with different thicknesses. In this experiment, steam pressure and injection rate were constant, and only the effect of injection temperature was considered. Fig. 7 shows that the heat transfer coefficient increases with increasing the steam temperature. Overheating the steam enhances the heat loss. It is also shown that the average heat transfer coefficient for bare tube at the lowest injection temperature (119 °C) is similar to that for nano ceramic-based insulated tube with 5 mm thickness at the highest injection temperature (145 °C). It means that using maximum injection temperature accompanied with nano thermal insulation has the same heat transfer coefficient or heat loss in comparison with the bare tube at the lowest injection temperature. Certainly, at low injection temperature, the heat transfer coefficient decreases to one-half using ceramic-based nano thermal insulator with 5 mm thickness. This maintains the steam temperature and eliminates the need for overheating the steam. Another point which should be explained in Fig. 7 is the slopes of the lines. It is clear that the slope of the line of the bare tube is more than those of insulated tubes. It means that increasing the steam temperature enhances the heat transfer coefficient of bare tube more than that for insulated tubes. Therefore, it is expected that at higher steam injection temperature the effect of implementation of nano coatings would be more considerable. It is also demonstrated in Fig. 7

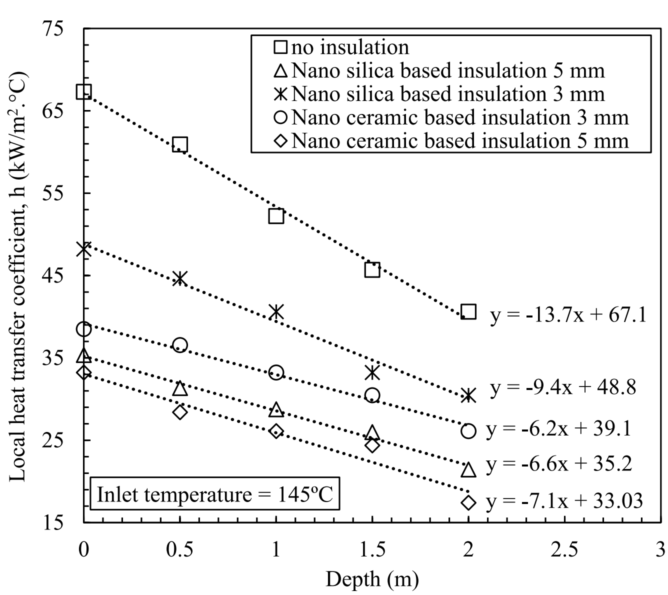

Fig. 6. Local convective heat transfer coefficient inside the nano thermal insulated tube.

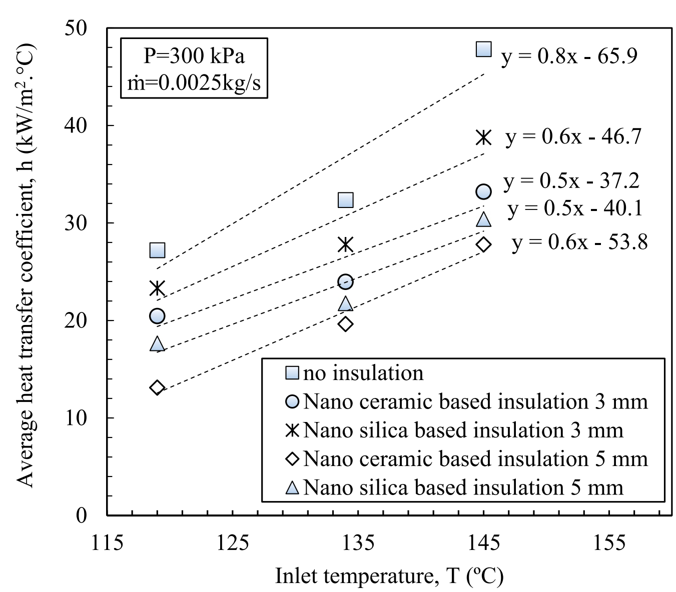

Fig. 7. Effect of insulation on the average heat transfer coefficient at different steam injection temperatures.

that the insulation efficiency of nano ceramic thermal insulator is better than that of nano silica at similar thickness.

Fig. 8 depicts the variation of average heat transfer coefficient at different steam injection rates. The temperature and pressure of the steam kept constant in these results, and the injection rate varied from 2.1 to 6.3 g/s. It is obvious that the average heat transfer coefficient enhances with increasing steam injection rate. Increasing the steam injection rate improves the turbulence in the tube, and consequently, enhances the heat transfer coefficient. Therefore, enhancement of steam injection rate is not always a suitable solution for increasing the hydrocarbon fluid temperature since it accompanied with more heat loss from the tube. The heat transfer coefficient at the highest injection rate by using 5 mm nano ceramic insulator is only slightly more than that of the bare tube at the lowest injection rate. As can be seen, nano thermal insulation reduced the average heat transfer coefficient from 30% (3 mm nano silica insulator) to 50% (5 mm nano ceramic insulator). In addition, the slope of the line of heat transfer coefficient versus injection rate for the bare tube is more than that for the insulated tubes.

3.4. Heat loss

Fig. 9(A) and (B), and (C) shows the effect of insulation on the percentage of heat loss at different depths of tube for three states of steam including 119 °C and 200 kPa, 134 °C and 300 kPa, and also 145 °C and 400 kPa, respectively. Fig. 9 (A) demonstrates that the heat loss at the end of tube reached to 63%. After applying 3 mm of nano silica-based insulator, the heat loss reduced to 35%. Furthermore, nano ceramic insulator at this condition reduced the heat loss to 25% which is remarkable reduction. Indeed, when the insulator thickness enhanced to 5 mm, the heat loss reduced to 31% for nano silica and 18% for nano ceramic insulators. It is also clear from Fig. 9 that enhancement of heat loss with the tube depth shows an asymptotic behavior. So, it is probably expected that (although not at the range of this study) maximum heat loss obtained after some distance from the beginning, and after that point the amount of heat loss would be inappreciable. This conclusion is in accordance with the results of Fig. 6 which showed that the local heat transfer coefficient reduces from the tube beginning to the end.

Comparing Fig. 9(A) and (B), and (C) reveals that the amount of heat loss increases with increasing the steam injection temperature and pressure. For example, in Fig. 9 (B), the heat loss in bare tube reached to 70% and in Fig. 9 (C) reached to 73% while at the best condition of insulation, these two numbers reduced to 22% and 25%, respectively.

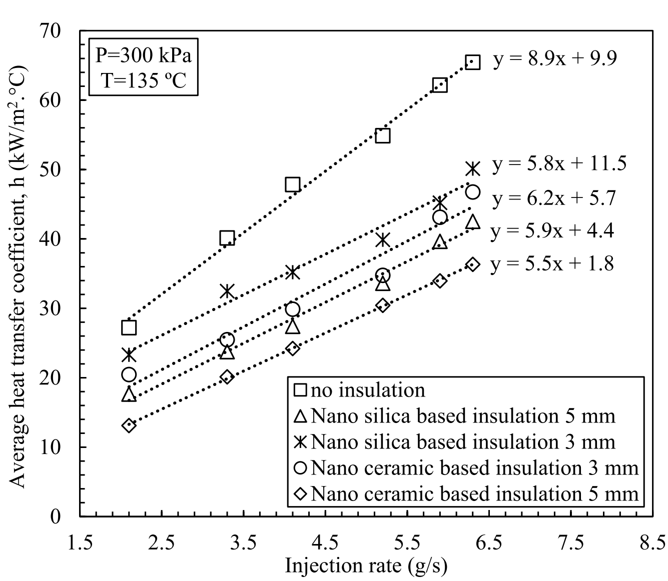

Fig. 8. Effect of insulation on the average heat transfer coefficient at different steam injection rates.

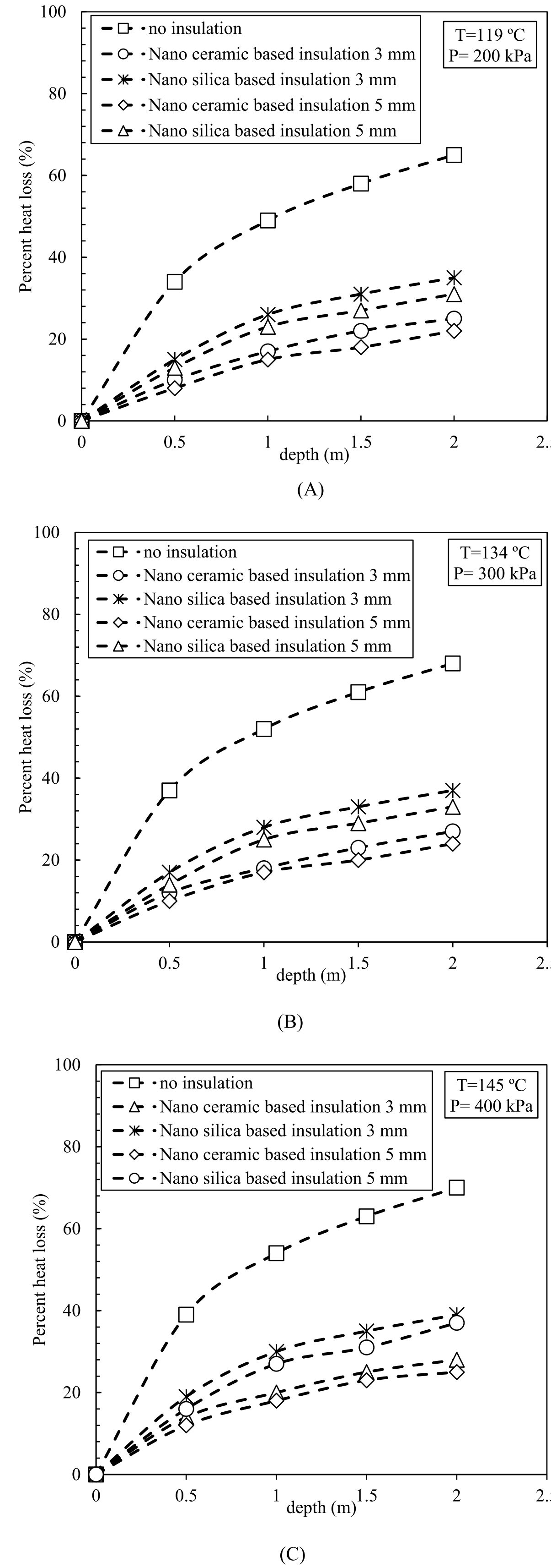

Fig. 9. Variation of heat loss with depth at the injection temperature of (A) 119 °C, (B) 134 °C, (C) 145 °C.

Enhancement of injection pressure and temperature leads to greater temperature difference between the steam and the ambient. This could enhance the heat transfer to the ambient.

It can eventually be concluded that application of nano ceramic thermal insulations with 5 mm thickness reduced the heat loss up to 43%. So, this is better strategy for compensating heat loss to deliver the steam at higher temperature to the reservoir fluid rather than increasing the steam injection temperature or pressure or rate. The latter not only increases the heat loss itself, enhances the steam generation cost and increases the repair and maintenance expenses.

It should be mentioned that steam temperature in the industrial thermal recovery methods reaches up to 300 °C or even more. However, working with the saturated steam at 300 °C or higher needs to operate at very high pressure. For example, increasing the steam temperature from 100 to 300 °C, enhances the steam pressure about 86 folds. So, preparing the required safety for the experiments would be very expensive and to some extent impossible. On the other hand, as previously demonstrated in Fig. 9(A) and (B), and (C), heat loss increased with increasing steam temperature. It is clear that implementing nano thermal insulator could reduce the heat loss up to %45 at steam temperature of 145 °C. Results showed that implementing the nano thermal insulator is more effective at higher steam temperatures (at the range of our study, 119, 134, and 145 °C). Therefore, it may be expected that at the industrial temperature of about 300 °C, this trend would be continued. It is expected that nano thermal insulator reduces the heat loss even at higher temperatures than those tested in this study.

4. Conclusion

In this paper, an experimental apparatus used to simulate the steam injection operation in enhanced oil recovery. Two types of nano thermal insulators (ceramic-based and silica-based) implemented to reduce the convective heat transfer coefficient, reduce the heat loss, and maintain the steam temperature for injection to the reservoir. Temperature, pressure, injection rate, depth, insulator type and thickness were considered as the operating variables. Several experiments conducted to obtain the heat transfer coefficient (local and average) and heat loss along the tube. The main conclusion presented here:

- To compensate the heat loss during steam injection operation, it is not suitable to increase the steam temperature or pressure since it enhances the temperature gradient and heat transfer coefficient, and leads to greater heat loss. For example, increasing the steam temperature and pressure from 139 °C to 200 kPa to 145 °C and 400 kPa enhances the heat loss from 63% to 73%.
- The heat loss reduced up to 43% using nano thermal insulators. So, there is no need to enhance the steam temperature or injection rate since they terribly affect the energy consumption.
- Nano ceramic thermal insulator showed about 10% better performance than nano silica insulator in reducing the heat loss along the steam injection tube.
- Increasing the steam injection rate from 2.1 to 6.3 g/s improved the average heat transfer coefficient up to 2.5 times.
- In addition to the fact that lower heat loss leads to non-destructive effect on the environment, it causes less thermal stress on the casing and reduces the risk of breakage of this tubes. Casing breakage may terminate to well losing. Therefore, using nano thermal insulators reduces the steam generation cost and decreases the depreciation of the apparatus.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Mohammad Afra: Writing - original draft, Data curation. **S.M. Peyghambarzadeh:** Supervision, Writing - review & editing, Methodology. **Khalil Shahbazi:** Resources, Conceptualization. **Narges Tahmassebi:** Resources.

Nomenclature

A	area, m^2
D	diameter, m
g	gravitational force, m/s^2
h	heat transfer coefficient, $kW/m^{2\circ}C$
$\bar{h}$	average heat transfer coefficient, $kW/m^{2\circ}C$
h_{fg}	enthalpy of saturated steam, kJ/kg
$\dot{m}$	mass injection rate, kg/s
k	thermal conductivity, $kW/m^\circ C$
L	length, m
Nu	Nusselt number
q	heat flux, kW
Pr	Prandtel number
Q	heat loss, kJ
R	thermal resistance, °C/kW
r	radius, m
Re	Reynolds number
T	temperature, °C

Subscripts

A	ambient
b	bulk
cond	conduction
conv	convection
exp.	experimental
l	liquid

theo theoretical
v vapor
w wall

Greek symbols
ρ density, kg/m^3
μ viscosity, kg/m.s

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.petrol.2020.107012.

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