LOWERING UNCERTAINTY IN CRUDE-OIL MEASUREMENT BY SELECTING OPTIMIZED ENVELOPE COLOR OF A PIPE-LINE

by

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Lowering uncertainty in crude-oil volume measurement has been widely considered as one of main purposes in an oil export terminal. It is found that crude-oil temperature at metering station has big effects on measured volume and may cause big uncertainty at the metering point. As crude-oil flows through an above-ground pipe-line, pick up the solar radiation and heats up. This causes the oil temperature at the metering point to rise and higher uncertainty to be created. The amount of temperature rise is depended on exterior surface paint color. In the Kharg Island, there is about 3 km distance between the oil storage tanks and the metering point. The oil flows through the pipe-line due to gravity effects as storage tanks are located 60 m higher than the metering point. In this study, an analytical model has been conducted for predicting oil temperature at the pipe-line exit (the metering point) based on climate and geographical conditions of the Kharg Island. The temperature at the metering point has been calculated and the effects of envelope color have been investigated. Further, the uncertainty in the measurement system due to temperature rise has been studied.

Key words: *aboveground pipe-line, envelope color, oil volume measurement, solar energy, uncertainty*

Introduction

Accurate measurement of crude-oil in an oil export terminal is primary objective. Any type of measurement error can result in a financial loss, whether it is to the buyer or the seller. Such errors are due inaccuracies that occur during the custody transfer process and results in the buyer receiving more or less product than contracted. Three primary sources of error in crude-oil measurement include (a) volume measurement, (b) sediment and water, and (c) temperature rise. Accurate temperature compensation of gross measured volume is critical to overall volume measurement accuracy.

Today paint color is commonly utilized in control of absorbed solar radiation by surfaces and much work has been carried out in this field (*e. g.* [1-5]). In thermal manner, each color has specific absorptivity and emissivity coefficient. While sun radiate to surface, absorbed and

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reflected energy will change with absorptivity and emissivity coefficient of surface paint color. For surveying effect of surface radiative parameters, Esfahani *et al.* [6] studied the effect of radiative parameters such as, surface reflectivity and absorptivity on thermal degradation of polyethylene. Here, by considering the Kharg Island climate conditions, solar radiation has predominantly effect on crude-oil temperature rise inside pipe-line. As the Kharg Island is main Iran oil export terminal, the accuracy of measurement is very important issue. Considering the fact that, the pipe-line exterior surface paint color has effect on crude-oil temperature rise; their effects on accuracy of the measurement system have been investigated.

At the fields of effect solar radiation on temperature variation in pipe flow, there have been previous studies such as Kowsary *et al.* [7]. They have considered a more realistic situation in which dissipation of the heat through the outer surface to the ambient has been considered. They computed temperature development in pipe flow with considering thermal leakage by heater element that was shown bulk temperature tends to a limiting value along pipe. Yaghoubi *et al.* [8] estimated temperature of oil inside cylindrical receiver for the Shiraz solar power plant; they supposed unsteady state condition and neglected conduction variation along pipe and obtained non-linear partial differential equation system then solved by numerical method. Madani [9] calculated temperature distribution of water inside the cylindrical tube with black cover by simple model of overall coefficient of heat losses. At this work, we suppose hourly steady-state situation in pipe flow that temperature of oil and pipe vary in the direction of flow. Kim *et al.* [10] obtained thermal performance of a solar system composed of parallel, all-glass (double skin) vacuum tubes by using a one-dimensional analytical model; they supposed constant heat flux around tube under unsteady-state condition; Han *et al.* [11] continued same work with three-dimensional model and compared results with one-dimensional model and showed that there are good agreement with each other. Luminosu *et al.* [12] studied analytically the process of preheating bitumen using solar energy to optimize connection between several solar collectors.

In the present research, a practical analytical model for incompressible flow inside an above-ground pipe-line has been constructed and presented. The outer surface of the pipe-line is exposed to solar radiation and wind stream. The radiation heat exchange with ambient is also taken into account. Further, the effects of exterior surface paint color which represented by emissivity and absorptivity have been studied. It is assumed that each paint color has its specific absorptivity and emissivity and these indices have been considered compatible with common paints in industry. The model has been developed to study temperature development of crude-oil flow within a specific pipe-line. For simplifying the model, hourly steady-state situation in pipe flow has been assumed. In most studies because of using thermal resistance of radiation to sky, pipe surface temperature is assumed constant [13, 14]; while at this paper pipe surface temperature variation along flow is taken into account. The model has been applied to a specific crude-oil pipe-line. The pipe-line is located in the Kharg Island, main Iran export terminal and delivers the crude-oil from storage tanks to the exporting ship. The effects of pipe-line paint color in various volume flow rate are investigated theoretically and experimentally under the relative weather conditions of Kharg Island. The effects of paint color have been represented by absorptivity and emissivity of the exterior surface. By considering the fact that absorptivity and emissivity of the exterior surface has the primary effects and knowing the properties of available paints in industry, one could select the best pipe-line surface coating in accord with its emissivity and absorptivity.

Initially amount of absorbed solar energy by pipe-line surface has been estimated for the Kharg Island climate condition. Then by computing convection heat transfer coefficient the outlet oil temperature was calculated by employing energy balance along the pipe line for a day (5th August, 2007). Finally by catching relationship between temperature and error, the uncertainty in crude-oil volume measurement has been calculated. It is found that pipe paint color is important parameter on alteration of oil temperature and caused big uncertainty in oil measurement.

Problem description

The problem under investigation is heat transfer from horizontal pipe with incompressible fluid flow inside. Figure 1 shows the geometry and the configuration of the problem which is based on the actual condition of the Kharg Island oil terminal. Crude-oil flows from the storage tank (located 60 m higher than the pipe-line) into the pipe-line which its length is about 3 km as shown in fig. 1. At pipe-line exit, oil reached to the metering station for measuring and the custody transfer process. It is obvious that oil temperature was affected by solar radiation as oil travels through the pipe-line. The main objective of this paper is to determine outlet oil temperature. By knowing the outlet temperature, it is possible to construct a relationship between temperature and uncertainty then estimate error in crude-oil volume metering.

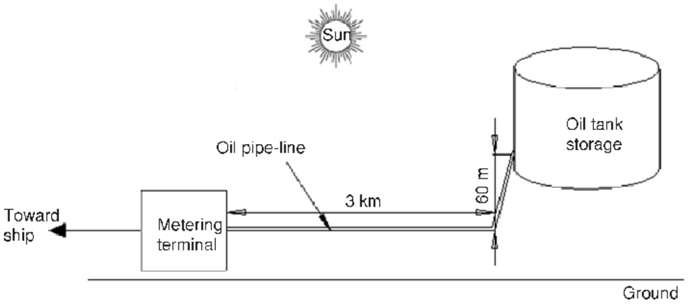

Figure 1. Schematic diagram of oil pipe-line system with storage tank in Kharg Island

Solar radiation over pipe-line increase the heat load during the day, but wind on the other side has an effective role to remove heat load from the pipe. The inlet temperature of the fluid, T_{fi}, is assumed to be equal to oil storage tank temperature and the outlet temperature is T_{fo}. As pipe-line length is much higher than its diameter, the problem is assumed to be one-dimensional so temperature variation along the pipe (x-direction) is only considered. The parameters which are kept constant during the investigation are the pipe's diameter *D* and pipe-line length *L*. A picture of the pipe-line and a schematic diagram of adopted thermal model are shown in fig. 2.

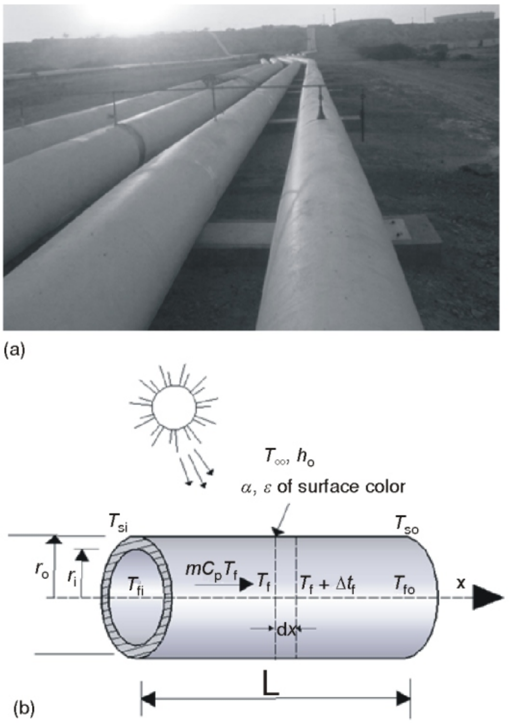

Figure 2. (a) The Kharg oil pipe-line, (b) a schematic diagram of considered problem under inves-

Mathematical modeling

The solar radiation is the primary phenomena which affects temperature variation of surfaces. To be able to estimate pipe and fluid temperature, solar radiation should be calculated in first step. For estimating solar radiation many engineering models have been developed and proposed. In all of these models, the weather condition and location are important factors. Kamali *et al.* [15] suggested that Angstrom model is more suitable for the Kharg Island. Therefore, the Angstrom model has been employed in this study to calculate solar radiation. Based on Angstrom model, solar radiation can be estimated using the equation [16]:

$$\frac{I}{I_\mathrm{o}} \quad a \quad b\frac{s}{s_\mathrm{o}} \tag{1}$$

where for the Kharg Island, $a = 0.37$ and $b = 0.35$ in spring and summer, and $a = 0.37$ and $b = 0.38$ in autumn and winter [15].

The solar declination (δ), the main sunshine hour angle (ω_s) and the maximum possible sunshine duration day length (s_o) was calculated from Cooper [17]:

$$\delta \quad 23.45\sin\frac{360}{365}(284 \quad n) \tag{2}$$

$$w_\mathrm{s} = \arccos(-\tan\phi\tan\delta) \tag{3}$$

$$s_\mathrm{o} \quad \frac{2}{15}\omega_\mathrm{s} \tag{4}$$

The cloudless hourly extraterrestrial radiation on horizontal surface can be calculated using the equation [18]:

$$I_\mathrm{o} \quad \frac{12 \;\; 3600}{\pi}I_\mathrm{sc} \;\; 1 \quad 0.033\cos\frac{360n}{365} \quad [\cos\phi\cos\delta(\sin\omega_2 \quad \sin\omega_1) \quad \frac{2\pi(\omega_2 \quad \omega_1)}{360}\sin\phi\sin\delta] \tag{5}$$

In this equation I_sc has adopted a value of 1367 W/m^2 according to the world radiation center and ω is the solar hour as given by equation [18]:

$$\omega = 15(t - 12) \tag{6}$$

The pipe-line in the presented study is located at the Kharg island (latitude 29° and longitude 51°). As solar energy can be varied by geographical situation, the model was solved for the climatic conditions of the Kharg, representing the southern Iran for the typical days (August 5th, 2007) of summer. Figure 3 shows amount of solar radiation on horizontal surface and ambient temperature on August 5th, 2007. Solar radiation is manifested between sunrise

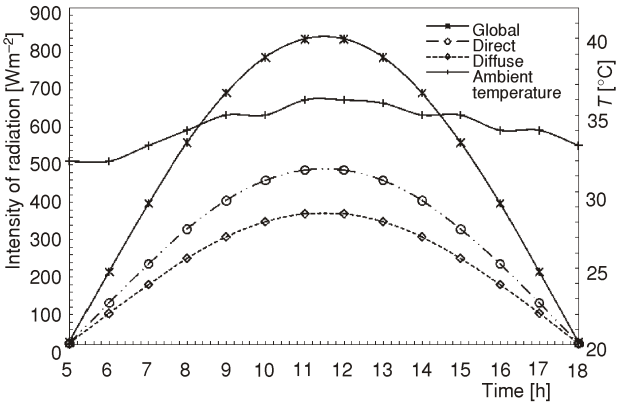

Figure 3. Solar intensity on horizontal surface at the Kharg Island on August 5th, 2007

and sunset. It could be realized that the radiation is highest at about 11:30 A. M. and is negligible outside of the considered time interval for the considered day.

We estimated solar radiation in horizontal surface already; for calculation solar radiation on pipe surface, following steps is taken into account. Figure 4 gives a graphical representation of the amount of solar radiation striking the pipe surface. As shown, the intensity of solar radiation varies depending on the angle of incidence (γ), which changes according to the daily movement of the Sun. Sunlight, however, always hits half of the pipe-line area because of its circular shape. The following equations are obtained by integrating the normal component of solar radiation along the circumference of a semi-circle, which yields the total solar energy absorbed by the pipe-line:

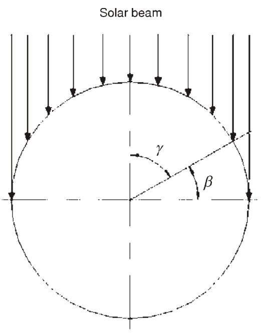

Figure 4. Amount of solar radiation striking the pipe-line surface

$$I_{\mathrm{p}} = I\cos\gamma \tag{7}$$

$$I_{\mathrm{p}} \quad \frac{2\,{}_{0}^{\pi/2} I\cos\ \frac{\pi}{2}\quad \beta\ \ \frac{D_{\mathrm{o}}}{2}L\mathrm{d}\beta}{\pi D_{\mathrm{o}}L} \quad \frac{2I}{\pi}\,{}_{0}^{\pi/2}\sin\beta\,\mathrm{d}\beta \tag{8}$$

Here I_{p} [Wm^{-2}] could be interpreted as the solar energy absorbed per unit area of pipe surface:

$$I_{\mathrm{p}} \quad \frac{2I}{\pi} \tag{9}$$

The total radiation on pipe-line surface consists of beam radiation and ground-reflected radiation. The total radiation could be calculated by:

$$I_{\mathrm{T}} \quad \frac{2I}{\pi} \quad \rho_{\mathrm{g}}\,\frac{I}{2} \tag{10}$$

while reflectance of ground is considered as $\rho_{\mathrm{g}} = 0.2$ [19]. In order to estimate the convective heat transfer in outside pipe, the concept of mixed convection should be employed. The directions of air motion due to natural and forced convection are approximately perpendicular. For combined free and forced convection from horizontal tube several correlations for various flow regions and flow Reynolds number are proposed. Such correlations can be found in [20]. The most widely used correlation to estimate convection coefficient over of a horizontal pipe in cross flow is:

$$\mathrm{Nu} \quad C\,\mathrm{Re}^{m}\,\mathrm{Pr}^{n}\ \frac{\mathrm{Pr}}{\mathrm{Pr}_{s}}{}^{0.25} \qquad 0.7 \quad \mathrm{Pr} \quad 500 \text{ and } 1 \quad \mathrm{Re} \quad 10^{6} \tag{11}$$

where all properties are evaluated at T_∞, except Pr_{s}, which is evaluated at T_{s}, cylinder surface temperature. Values of C and m are given in [20]. If $\mathrm{Pr} = 10$, $n = 0.37$; if $\mathrm{Pr} > 10$, $n = 0.36$.

Figure 5 shows variations of convection heat transfer coefficient outside of the Kharg oil pipe-line (h_{o}) on August 5th, 2007. Geometrical characteristics of the Kharg Island oil pipe-line are brought in tab. 1. Convection coefficient can be obtained from eq. (11) and with considering wind velocity at the Kharg Island on studied day.

The schematic diagram of pipe flow under investigation was shown in fig. 1. As dimensions in radial direction are much smaller than the x (along flow direction), one-dimensional flow is considered. The paint color pipe surface reflects and absorbs normal solar radiation flux. Absorbed solar radiation flux increases the surface temperature and it is transferred by conduction to the inside of the pipe then temperature of fluid is increased. In order to obtain the temperature profile of fluid inside, a differential energy balance was carried out. The following assumptions for energy balance equations are considered:

(1) temperature gradient across the thickness of the pipe is insignificant,
(2) steady-state situation assumed and heat transfer coefficients are considered to be constant at the selected time interval (hourly here),
(3) the surface color is opaque with constant absorptivity and emissivity,
(4) the variations in the absorptivity and emissivity of the color surfaces with the variation in angle of the incoming radiation are neglected,
(5) fluid properties are independent of temperature and mean amount is considered, and
(6) heat conduction variation along fluid flow is neglected.

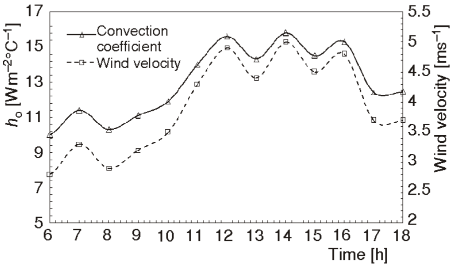

Figure 5. Convection coefficient for Kharg oil pipe-line in August 5th, 2007

The energy balance equations for pipe, control volume 1, and fluid, control volume 2, as shown in fig. 6 could be written and presented as:

– for volume control (1):

$$Q_{\text{conduction\_x}} + Q_{\text{radiation}} = Q_{\text{sky}} + \text{Q}_{\text{conduction\_x+dx}} + Q_{\text{convection\_ambient}} + Q_{\text{convection\_fluid}} \tag{12}$$

In the above equation, $Q_{\text{radiation}}$ indicates the incoming energy in consequence with solar radiation and reflectance of ground into pipe surface which is obtained from eq. (10). With substitution other related equations:

$$kA\frac{\mathrm{d}T_\mathrm{s}}{\mathrm{d}x} \quad \alpha I_\mathrm{T}(\pi D_\mathrm{o}) \quad \varepsilon\sigma(\pi D_\mathrm{o})(T_\mathrm{s}^4 \quad T_\mathrm{sky}^4) \qquad kA\frac{\mathrm{d}T_\mathrm{s}}{\mathrm{d}x} \quad kA\frac{\mathrm{d}^2T_\mathrm{s}}{\mathrm{d}x^2}$$

$$h_\mathrm{o}(\pi D_\mathrm{o})(T_\mathrm{s} \quad T_\infty) \quad h_\mathrm{i}(\pi D_\mathrm{i})(T_\mathrm{s} \quad T_\mathrm{f}) \tag{13}$$

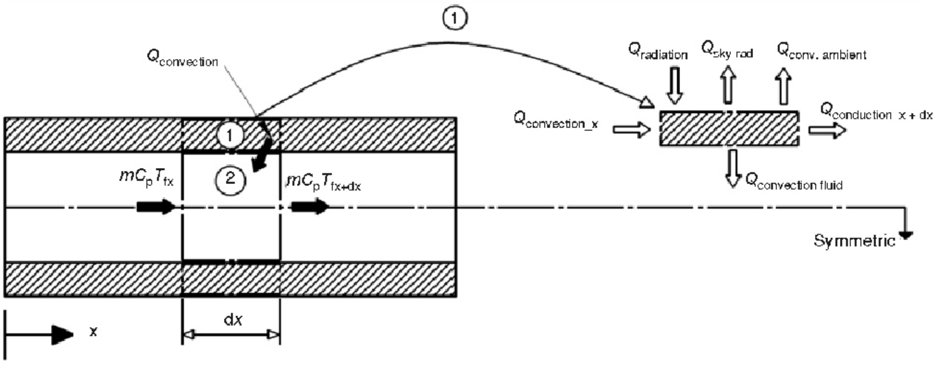

Figure 6. Pipe and fluid control volumes for analytical study

that $A \quad [\pi(D_o^2 \quad D_i^2)]/4$, where the sky temperature is given by Sharma *et al.* [21] as:

$$T_{sky} \quad 0.0552 T_\infty^{1.5} \tag{14}$$

After simplification we have:

$$\frac{k}{4} \quad D_o \quad \frac{D_i^2}{D_o} \quad \frac{d^2 T_s}{dx^2} \quad h_o \quad h_i \frac{D_i}{D_o} \quad T_s \quad h_i \frac{D_i}{D_o} T_f \quad \varepsilon\sigma T_s^4$$

$$\alpha I_T \quad h_o T_\infty \quad \varepsilon\sigma T_{sky}^4 \tag{15}$$

The pipe surface temperature differences within the flow are assumed to be sufficiently small so that T_s^4 may be expressed as a linear function of temperature. This is done by expanding T_s^4 in a Taylor series about the free-stream temperature T_∞ and neglecting higher-order terms to yield:

$$T_s^4 \quad 4T_\infty^3 T_s \quad 3T_\infty^4 \tag{16}$$

Substitution eq. (16) into eq. (15) we have:

$$\frac{k}{4} \quad D_o \quad \frac{D_i^2}{D_o} \quad \frac{d^2 T_s}{dx^2} \quad h_o \quad h_i \frac{D_i}{D_o} \quad T_s \quad h_i \frac{D_i}{D_o} T_f$$

$$\varepsilon\sigma(4T_\infty^3 T_s \quad 3T_\infty^4) \quad \alpha I_T \quad h_o T_\infty \quad \varepsilon\sigma T_{sky}^4 \tag{17}$$

After simplification, eq. (17) can be written as:

$$\frac{k}{4} \quad D_o \quad \frac{D_i^2}{D_o} \quad \frac{d^2 T_s}{dx^2} \quad h_o \quad h_i \frac{D_i}{D_o} \quad 4\varepsilon\sigma T_\infty^3 \quad T_s \quad h_i \frac{D_i}{D_o} T_f$$

$$\alpha I_T \quad h_o T_\infty \quad \varepsilon\sigma T_{sky}^4 \quad 3\varepsilon\sigma T_\infty^4 \tag{18}$$

– For volume control (2):

$$\rho Q C_p \frac{dT_f}{dx} \quad h_i \pi D_i (T_s \quad T_f) \tag{19}$$

where T_s can be written as:

$$T_s = \frac{\rho Q C_p}{h_i \pi D_i} \frac{dT_f}{dx} \quad T_f \tag{20}$$

With substitution eq. (20) into eq. (18) then eq. (18) can be written as:

$$a_1 \frac{d^3 T_f}{dx^3} \quad a_2 \frac{d^2 T_f}{dx^2} \quad a_3 \frac{dT_f}{dx} \quad a_4 T_f \quad d \tag{21}$$

in which

$$a_1 \quad \frac{\rho Q C_p \quad D_o \quad \frac{D_i^2}{D_o} \quad k}{4\pi D_i h_i}, \quad a_2 \quad \frac{k \quad D_o \quad \frac{D_i^2}{D_o}}{4}, \quad a_3 \quad \frac{-\rho Q C_p}{\pi D_i h_i} \quad h_o \quad h_i \frac{D_i}{D_o} \quad 4\varepsilon\sigma T_\infty^3 \ ,$$

$$a_4 \quad (h_o \quad 4\varepsilon\sigma T_\infty^3), \text{ and } d \quad \alpha I_T \quad h_o T_\infty \quad \varepsilon\sigma T_{sky}^4 \quad 3\varepsilon\sigma T_\infty^4$$

Equation (21) is non-homogeneous ordinary differential equation from third order; boundary conditions for this differential equation are:
(1) inlet fluid temperature is defined: $T_f(0)$ = defined,
(2) inlet pipe surface temperature is defined then from eq. (19):

$$\frac{dT_f}{dx}_{x\quad 0} \quad \frac{h_i \pi D_i}{\rho Q C_p}[T_s(0) \quad T_f(0)]$$

(3) fluid temperature at infinite condition is finite: $T_f(\infty)$ = finite.
The total solution of eq. (21) is given as:

$$T_f \quad c_1 \exp(\lambda_1 x) \quad c_2 \exp(\lambda_2 x) \quad c_3 \exp(\lambda_3 x) \quad \frac{d}{a_4} \tag{22}$$

c_1, c_2, and c_3 can be gained by upper boundary conditions, λ_i coefficients can be computed by following equation:

$$a_1\lambda^3 + a_2\lambda^2 + a_3\lambda + a_4 = 0 \tag{23}$$

Pipe surface temperature can be gained by eq. (24):

$$T_s \quad \frac{\rho Q C_p}{h_i \pi D_i}[c_1\lambda_1 \exp(\lambda_1 x) \quad c_2\lambda_2 \exp(\lambda_2 x) \quad c_3\lambda_3 \exp(\lambda_3 x)]$$
$$c_1 \exp(\lambda_1 x) \quad c_2 \exp(\lambda_2 x) \quad c_3 \exp(\lambda_3 x) \quad \frac{d}{a_4} \tag{24}$$

Table 1. Parameters used in case study

Parameter	Value
L [m]	3000
D_o [m]	1.0668
D_i [m]	1.04774
K [Wm^{-1}K^{-1}]	30
T_{fi} [°C]	25
T_{si} [°C]	25

Table 2. Thermal properties of crude-oil at 15.5 °C

Fluid	P [kgm^{-3}]	C_p [kJkg^{-1}°C^{-1}]	k [Wm^{-1}K^{-1}]	μ [Pa·s]
Light oil	858.408	1.887	0.1483	0.0145

Equations (22) and (24) are the governing equations for variations of the hourly bulk temperature and pipe surface temperature along the flow, respectively, the profile is in an exponential form, however, for most practical cases, it is very close to a linear function. Hourly outlet oil temperature from pipe-line is dominant parameter that we need. For catching this, we solved eq. (22) at each hour of day that Sun radiate on pipe-line. Relative parameters for the case study are shown in tab. 1.

The working fluid is chosen to be light crude-oil. Oil carries the maximum heat from the pipe due to its thermal and physical properties. Table 2 gives the thermal and physical properties of the selected fluids. The flow is assumed to be fully developed and turbulent.

Table 3. Sample for various envelope color

Color	Black	Green	Brown	Off-white	White
Absorptivity	0.96	0.8	0.58	0.34	0.28
Emissivity	0.91	0.85	0.8	0.9	0.91

The following section discuss the effects of the surface paint color on transferring crude-oil through the Kharg pipe-line using the previous described model. This may help engineers in their design to determine and select the optimum envelop color. The selection may be the prime interest of many engineering applications. There are five different envelop color in this analysis as shown in tab. 3. The corresponding absorptivity and emissivity for each color are also listed in this table.

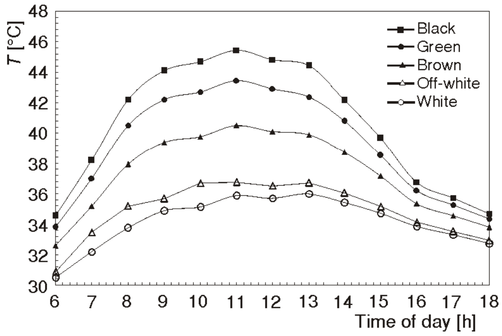

Figure 7. Outlet oil temperature from the pipeline at 1000 barrel per hour on August 5th, 2007

Figures 7, 8, and 9 show variations outlet oil temperature from pipe-line for various volume flaw rates during day-time. As expected, the black painted envelope caused higher temperatures than the other painted one during the day-time. Higher absorptivity of the exterior surface may result in a significant amount of absorbed solar radiation and, therefore, its inward transmission into the oil inside space; eventually result high heat load. By comparing figures, it could be realized at lower volume flow rate (*e. g.* 1000 barrel per hour), outlet oil temperature is higher than the other (larger) volume flow rate. So increasing volume flow rate is one simple and practical way for lowering outlet oil temperature.

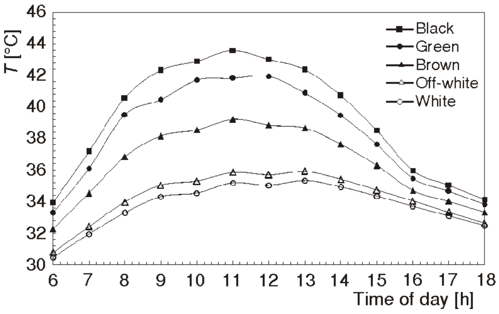

Figure 8. Outlet oil temperature from the pipeline at 2000 barrel/hr on August 5th, 2007

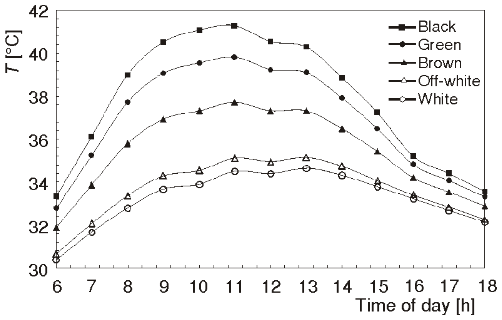

Figure 9. Outlet oil temperature from the pipeline at 3000 barrel/hr on August 5th, 2007

To verify validity of the mathematical model and numerical results, a comparison has been made between the numerical results and measured values of pipe-line surface temperature. The experimental temperatures have been measured using infrared thermometer from pipe-line surface on August 5th, 2007. The pipe-line, shown in fig. 2, is considered to have off-white paint color. At that particular day, light crude-oil flows through pipe-line with volume flow rate at 1000 barrel per hour. The outlet surface temperature has been measured hourly during the day at distance of 300 m and 750 m from pipe-line entrance. The numerical results are obtained by solving eq. (24) at each hour during of same day at corresponding distances then compared with measured values. Comparison between the theoretical and experimental results is depicted in fig. 10(a) and (b). In this work, it is found that the results of the developed mathematical model are in good agreement with the measured values.

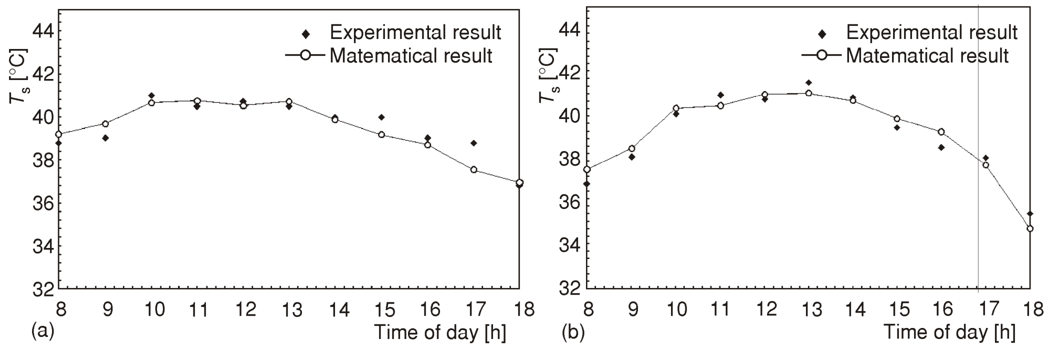

Figure 10. Temperature of the Kharg oil pipe-line on August 5th, 2007 in distance of (a) 750 m (b) 300 m from pipe entrance

Temperature effect on uncertainty of the metering system

There are standard methods to quantify errors associated with any type of measurements such as the proposed method of Moffat [22]. The maximum possible errors in various measured parameters were estimated from the minimum values of output and the accuracy of the instruments. This method is based on careful specification of the uncertainties in the various experimental measurements. In current study such method is not applicable as the aim is to quantify errors associated with temperature rise. For this purpose, it is assumed that there is no uncertainty in temperature measurement or other measured parameters.

To quantify errors associated with temperature rise, two worldwide acceptable methods for correcting the measured volume to the volume at the standard condition are utilized and compared. The difference between the values reported by each method is assumed to be uncertainty.

Turbine flow meter is used at metering station of the Kharg Island for measuring volume of transferred oil. As it is known, base of buying oil in international market is transferred volume at standard condition (1 atm and 15.5 °C). For convert the measurement volume to standard condition, *CTL* (temperature coefficient liquid) and *CPL* (pressure coefficient liquid) are used. Also is clear the amounts of these coefficients at standard condition are equal one. Two worldwide acceptable methods to calculate the amount of *CTL* are (a) calculated from API tables [23] and (b) from the equation:

$$CTL' = \mathrm{e}^{-\beta \Delta T(1 + 0.8\beta \Delta T)} \tag{25}$$

where $\Delta T \quad \textit{Observed temperature} \quad 60 \quad \mathrm{F}(15.5 \quad \mathrm{C}), \quad \beta \quad \dfrac{613.9723}{(\rho_{\text{standard condition}})^2}$

CPL is constant *vs*. temperature alterations; therefore *CTL* is only reason making error of metering. The *CTL* coefficients *vs*. temperature for light crude-oil are shown in tab 4. It could be concluded that the difference between *CTL* values calculated from the two utilized methods increase as temperature rise.

Here eq. (26) is utilized to quantify uncertainty in oil volume measurement:

$$Uuncertainty = error_{\mathrm{CTL}} \cdot CPL \cdot V \tag{26}$$

Uncertainty in volume measurement is computed by eq. (26) according to pipe-line outlet oil temperature toward metering station and *CTL* values in tab 4. Daily uncertainty has been estimated by adding hourly uncertainty during a day. The uncertainty percent is calculated based on the relation:

$$Uncertainty\% \quad \frac{Daily\ volume\ error}{Daily\ transported\ volume}100 \tag{27}$$

Table 4. Variation of CTL uncertainty with temperature for light oil

T [°C]	CTL_{API}	CTL'	$\lvert CTL_{\mathrm{API}} \quad CTL \rvert$	T [°C]	CTL_{API}	CTL'	$\lvert CTL_{\mathrm{API}} \quad CTL \rvert$
5	1.0087	1.0088	0.0001	30	0.9881	0.9879	0.0002
7.5	1.0066	1.00667	0.0001	32.2	0.9860	0.9858	0.0002
9.5	1.0050	1.0051	0.0001	33.8	0.9849	0.9846	0.0003
12.5	1.0027	1.0028	0.0001	35	0.9839	0.9836	0.0003
15.5	1	1	0	37.5	0.9819	0.9816	0.0003
17.7	0.9982	0.9981	0.0001	40	0.9798	0.9795	0.0003
20.5	0.9959	0.9958	0.0001	42.5	0.9777	0.9774	0.0003
22.5	0.9943	0.9942	0.0001	45	0.9756	0.9752	0.0004
25	0.9922	0.9921	0.0001	47.5	0.9736	0.9732	0.0004
27.5	0.9902	0.9900	0.0002	50	0.9715	0.9710	0.0005

Figure 11 shows daily uncertainty percent in metering system at the Kharg oil terminal on August 5th, 2007. These data were obtained from eq. (27) and results in figs. 7, 8, and 9. It could be realized that black color makes higher uncertainty than other colors. This is due to higher pipe-line outlet temperature (see figs. 7, 8, and 9) and the values of *CTL* in tab 4. As difference between standard oil temperature (15.5 °C) and observed (here computed) temperature increases, uncertainty in metering will increase too. As black paint makes highest outlet oil temperature then uncertainty is biggest for this color envelop. So using lighter color (white color)

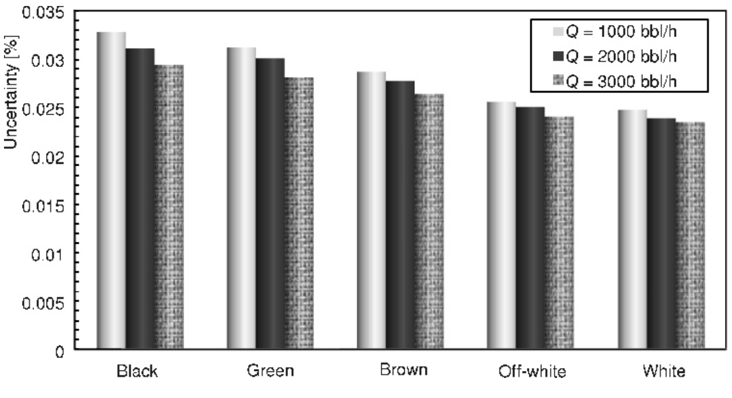

Figure 11. Effects of exterior surface paint color and volume flow rate on daily error uncertainty

for painting exterior surface is one practical way to reduce uncertainty. The other result which could be concluded from fig. 11 is positive effect of volume flow rate on uncertainty reduction. So by increasing volume flow rate, the other simple way for reducing uncertainty percent could be utilized.

Ostensibly, it may be released from fig. 11 that uncertainty is not significantly different for different conditions and therefore it will be negligible. Since the volume of exported oil reach to several million barrels per year, this infinitesimal difference could be induced very big uncertainty in oil volume measurement.

Conclusions

At this work a mathematical model for temperature development in an above-ground crude-oil pipe-line which exposed to solar radiation and wind stream was presented. Based on climate and geographical conditions of the Kharg Island and utilizing the mathematical model, the temperature at pipe-line outlet (the metering point) has been calculated and the effects of main pipe line flow rate and exterior surface paint color on temperature rise have been investigated. Two worldwide acceptable methods for correcting the measured volume to the volume at the standard condition are utilized and the difference between the values reported by each method is assumed to be uncertainty. By considering relation between temperature and uncertainty and the other results obtained in this work, the following points may be concluded.

The results of the proposed mathematical model are in good agreement with the field measured values in the Kharg oil pipe-line with off-white as envelope color.

Outlet oil temperature from the pipe-line increase either by lowering volume flow rate or using darker painting (higher absorptivity and lower emissivity) for pipe-line exterior surface.

Uncertainty in measurement could be reduced by painting exterior surface with lightest color (lower absorptivity and higher emissivity; white here) which seems a practical way.

One simple and feasible way of reducing uncertainty is to transport crude-oil with maximum allowable volume flow rate through the pipe-line.

However, by a glance at uncertainty variations in different conditions, it may be concluded the uncertainty remains constant in different situations; but due to the fact that oil is generally exported in very high values and afterwards brings about almost big uncertainly in oil volume measurement provided that can't be neglected. Finally, utilizing paint color with lower absorptivity and higher emissivity (white here) has been recommend as pipe-line surface color which can reduce uncertainty in oil volume measurement.

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Nomenclature

C_p – specific heat of crude-oil, [Jkg^{-1}K^{-1}]
D – pipe diameter, [m]
h – convection coefficient, [Wm^{-2}K^{-1}]I
I – solar radiation, [Wm^{-2}]
K – conductivity of pipe, [Wm^{-1}K^{-1}]
k – thermal conductiity of oil, [Wm^{-1}K^{-1}]
n – number of day of the year, [–]
Nu – Nusselt number (= hD/k), [–]

Pr – Prandtel number (=kν/α), [–]
Q – volume flow rate, [kgS^{-1}]
Re – Reynolds number (= $\rho uD/\mu$), [–]
S – daily measured sunshine duration, [h]
T – temperature [°C]
t – time of day, [h]
V – oil volume, [barrel]
x – axial distance, [m]

Greek letters

α – absorptivity, [–]
β, γ – angle, [°]
ε – emissivity, [–]
μ – dynamic viscosity, [Pa·s]
σ – Stefan-Boltzmann constant, [Wm^{-2}K^{-4}]
ρ – density, [kgm^{-3}]
$ø$ – latitude, [°]

Subscripts

T – total
p – pipe
f – fluid
i – inner
o – outer
s – surface
∞ – ambient value

References

[1] Takebayashi, H., Moriyama, M., Surface Heat Budget on Green Roof and High Reflection Roof for Mitigation of Urban Heat Island, *Building and Environment, 42* (2008), 2, pp. 2971-2979
[2] Wang, X., *et al*., Dynamic Thermal Simulation of a Retail Shed with Solar Reflective Coatings, *Applied Thermal Engineering, 28* (2007), 8-9, pp. 1066-1073
[3] Smith, G. B., *et al*., Coloured Paints Based on Iron Oxide and Silicon Oxide Coated Flakes of Aluminium as the Pigment, for Energy Efficient Paint: Optical and Thermal Experiments, *Solar Energy Materials & Solar Cells, 79* (2003), 2, pp. 179-197
[4] Baneshi, M., *et al*., A New Approach to Optimizing Pigmented Coatings Considering Both Thermal and Aesthetic Effects, *Journal of Quantitative Spectroscopy & Radiative Transfer, 110* (2009), 3, pp. 192-204
[5] Berger, O., Inns, D., Aberle, A., Commercial White Paint as Back Surface Reflector for Thin-Film Solar Cells, *Solar Energy Materials & Solar Cells, 91* (2007), 13, pp. 1215-1221
[6] Esfahani, J. A., Abdolabadi, A. G., Effect of Char Layer on Transient Thermal Oxidative Degradation of Polyethylene, *Thermal Science, 11* (2007), 2, pp. 23-36
[7] Kowsary, F., Pourshaghaghy, A., Temperature Development in Pipe Flow with Uniform Surface Heat Flux Condition Considering Thermal Leakage to the Ambient, *Energy Conversion and Management, 48* (2007), 8, pp. 2382-2385
[8] Yaghoubi, M., Azizian, K., Kenary, A., Simulation of Shiraz Solar Power Plant for Optimal Assessment, *Renewable Energy, 28* (2003), 12, pp. 1985-1998
[9] Madani, H., The Performance of a Cylindrical Solar Water Heater, *Renewable Energy, 31* (2006), 3, pp. 1751-1763
[10] Kim, J. T., *et al*., The Performance Simulation of All-Glass Vacuum Tubes with Coaxial Fluid Conduit, *International Communications in Heat and Mass Transfer, 34* (2007), 5, pp. 587-597
[11] Han, H., *et al*., A Three-Dimensional Performance Analysis of All-Glass Vacuum Tubes with Coaxial Fluid Conduit, *International Communications in Heat and Mass Transfer, 35* (2007), 5, pp. 589-596
[12] Luminosu, I., De Sabata, C., But, A., Solar Equipment for Preheating Bitumen, *Thermal Science, 11* (2007), 1, pp. 127-136
[13] Suehrcke, H., Peterson, E., Selby, N., Effect of Roof Solar Reflectance on the Building Heat Gain in a Hot Climate, *Energy and Buildings, 40* (2008), 12, pp. 2224-2235
[14] Sahin, A. Z., Kalyon, M., Maintaining Uniform Surface Temperature along Pipes by Insulation, *Energy, 30* (2005), 5, pp. 637-647
[15] Kamali, G. A., Moradi, E., Solar Radiation Fundamentals and Application in Farms and New Energy, Ferdowsi University press, Tehran, 2005
[16] Zekai, S., Solar Energy Fundamentals and Modeling Techniques, Springer, London, 2007
[17] Cooper, P. I., The Absorption of Solar Radiation in Solar Stills, *Solar Energy, 12* (1969), 3, pp. 333-345
[18] Duffie, J. A., Beckman, W. A., Solar Engineering of Thermal Processes, John Wiley and Sons, New York, USA, 1991
[19] ***, 2009 ASHRAE Handbook: Fundamentals, American Society of Heating, Refrigeration and Air Conditioning Engineers Inc., Atlanta, Geo., USA, 2009

[20] Incropera, F. P., Dewitt, D. P., Introduction to Heat Transfer, John Wiley and Sons, New York, USA, 1990
[21] Sharma, V. B., Mullick, S. C., Estimation of Heat Transfer Coefficients, the Upward Heat Flow, and Evaporation in a Solar Still, *ASME Journal of Solar Engineering, 113* (1991), 1, pp. 36-41
[22] Moffat, R. J., Using Uncertainty Analysis in the Planning of an Experiment, *ASME Journal of Fluids Engineering, 107* (1985), 2, pp. 173-178
[23] Ferry, R., Volume Correction Factor for the Manual of Petroleum Measurement Standards, American Petroleum Institute., Washington, D. C., 1995

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