Numerical Approach for Temperature Development of Horizontal Pipe Flow with Thermal Leakage to Ambient

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Abstract: *In this work, the effect of pipeline surface paint color on temperature development of horizontal pipe flow is investigated numerically. The classical pipe flow problem with constant wall heat flux is presented in which thermal leakage to the ambient from the outer surface of the pipe through convection and radiation is taken into account. The effects emissivity and absorptivity of pipe surface have been studied. The temperatures of fluid and pipe surface in the pipe flow problem are calculated numerically and experimentally. The results show that the bulk temperature tends to a limiting value (i.e. does not rise linearly as in the classical constant heat flux problem). It is found emissivity and absorptivity of outlet pipe surface are predominant parameters in temperature development in pipe flow that can increase or decrease pipe surface and fluid temperature for subjected objective. Furthermore, variations of friction factor in pipeline which that exposed to solar radiation and wind stream are investigated. The results show that friction factor and pressure loss are mainly affected by absorptivity and emissivity of exterior surface of pipe flow.*

Key words: *solar radiation, temperature development, pipe flow, emissivity and absorptivity, friction factor, pressure drop*

I. Introduction

The pipe flow is a classical heat transfer problem and has been studied in all heat transfer textbooks (e.g. Incropera and DeWitt (2002) & Kays and Crawford (1993)). Generally, two thermal boundary conditions are applied for the pipe surface: constant wall heat flux and constant wall temperature. In either case, analytical solutions have been derived both for determination of the convective coefficient of hydrodynamically and thermally fully developed laminar flow, as well as for the temperature distribution along the pipe axis. The constant heat flux condition can be produced by a heater element or radiation over the tube surface. For the latter case, thermal leakage to the surroundings cannot be neglected.

The influence of solar radiation on pipe flow is widely applied to solar devices designs and analyses, especially in cylindrical solar collector and much work has been carried out in this field. For instance, Kocifaj (2009) submitted analytical solution for daylight transmission via hollow light pipes with a transparent glazing; analytical solutions was introduced for both transparent component and lambertian diffuser enables rapid numerical simulations for systems composed of several types of light guides. Bourdoukan et al. (2008) proposed a model for solar heat pipe vacuum collectors in the desiccant cooling process. Chirarattananon et al. (2000) suggested a model for receiving solar radiation by light pipe in tropics for increasing air-conditioning load. Madani (2006) calculated temperature distribution of water inside the cylindrical tube with black cover by simple model of overall coefficient of heat losses. Yaghoubi et al. (2003) estimated temperature of oil inside cylindrical receiver for Shiraz solar power plant; they supposed unsteady state condition and neglected conduction variation along pipe and obtained nonlinear partial differential equation system and solved by numerical method. Saroja et al. (1996) carried out unsteady analysis of a cylindrical solar water heater. The physical parameters that govern the physical system were identified. The governing equations were solved using the fourth order Runge–Kutta method for different values of the parameters. Kim et al. (2007) 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. (2008) continued same work with three dimensional model and compared results with one dimensional model and showed that there are good agreement with each other. Recently, temperature development in the pipe flow which there is dissipation of the heat through the outer surface to the ambient was studied by Kowsary and Pourshaghaghy (2007). They considered a more realistic situation in which there is dissipation of the heat (generated by the heater element) through the outer surface by using the first law and available thermal modeling tools. They found that bulk temperature tends to a limiting value along pipe.

In light of the aforementioned discussion, the objective of this research is to survey numerically for effect of solar radiation on temperature development of incompressible flow inside an aboveground pipeline. The outer surface of the pipeline is exposed to solar radiation and wind stream. The radiation heat exchange with ambient is also taken into account. The impacts of exterior surface paint color which represented by emissivity and absorptivity have been studied. For simplifying the model, hourly steady state situation in pipe flow has been assumed. In most studies such as Suehrcke et al. (2008) & Sahin and Kalyon (2005) because of using thermal resistance of radiation to sky, pipe surface temperature is assumed constant; while at this paper pipe surface temperature variation along flow is taken into account.

II. Analysis

A pipe flow which is exposed to ambient may gain heat through solar radiation of short wavelength over outer surface of the pipe during the day. The wind also plays a major role in opposite direction by removing heat from outer surface

through convection heat transfer. There is also exchange of heat between outer surface and ambient through long wavelength radiation heat transfer. Although the circular cross-section has been chosen here as the most common geometry in practice, the same analysis could be applied for other cross-sectional geometries. The inlet temperature of the fluid is T_{fi} and the outlet temperature is T_{fo}. Other parameters were shown as Fig. 1. It's considered that problem is three-dimensional at pipe and fluid flow.
Radiation heat flux can be expressed by considering the solar radiation of short wavelength and the ambient radiation of long wavelength and also radiation from ground as,

$$q_r = \alpha I_{solar} + \varepsilon\sigma(T_{sky}^4 - T_s^4) + I_{ground} \quad (1)$$

Where α and ε is the absorptivity and the emissivity of the surface paint color for radiation, while σ is the Stephan-Boltzmann constant and T_{sky} is the effective sky temperature that is given by Sharma and Mullick (1991) as,

$$T_{sky} = 0.0552\, T_{\infty}^{1.5} \quad (2)$$

The solar radiation is the primary phenomena which effects 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 (Zekai (2008)). In all of these models, the weather condition and location are important factors. Iranian researchers have examined various models including Angstrom, Bristow & Campbell, Hargreaves and Reddy for Iran's cities and compared them with measured values (Kamali and Moradi (2005)). These models have been also modified by taking into account some other relevant meteorological variables and some suggesting coefficients for the difference regions. Kamali and Moradi (2005) 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 following equation as (Zekai (2008)),

$$\frac{I}{I_o} = a + b\frac{s}{s_o} \quad (3)$$

Where for Kharg Island, a=0.37 and b=0.35 in spring & summer, and a=0.37 and b=0.38 in autumn & winter (Kamali and Moradi (2005)).

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 (1969):

$$\delta = 23.45\sin[\frac{360}{365}(284+n)] \quad (4)$$

$$\omega_s = Arc\cos(-\tan\phi.\tan\delta) \quad (5)$$

$$s_o = \frac{2}{15}\omega_s \quad (6)$$

The cloudless hourly global irradiation received can be calculated using the following equation as (Duffie and Beckman (1991)),

$$I_o = \frac{12\times 3600}{\pi} I_{sc}(1+0.033\cos\frac{360n}{365})[\cos\phi\cos\delta(\sin\omega_2 - \sin\omega_1) + \frac{2\pi(\omega_2-\omega_1)}{360}\sin\phi\sin\delta] \quad (7)$$

In this equation I_{sc} has adopted a value of 1367 W/m^2 according to the world radiation center and ω is solar hour as given by following equation that recommended by Duffie and Beckman (1991) as,

$$\omega = 15(t-12) \quad (8)$$

Solar energy can be varied by geographical situation. The Kharg Island condition is determined for numerical study, the pipe in the presented study is assumed to be located at Kharg island situation (Latitude: 29° and Longitude 51°). The model was solved for the climatic conditions of the Kharg Island, representing the southern Iran for the typical days (5th August 2008) of summer.

For calculation solar radiation on pipe surface following steps is taken into account. The total radiation on pipe surface consists of three components: beam solar radiation, sky diffuse radiation and ground reflected radiation. The total radiation calculated by:

$$I_T = I_b R_b + \frac{I_d}{2} + \rho_g \frac{I}{2} \quad (9)$$

While Reflectance of ground is considered as $\rho_g = 0.2$. The equations are presented in ASHRAE (1993), Handbook of Fundamentals. At above equation R_b is calculated as,

$$R_b = \frac{\left[1-(\cos\phi\sin\delta - \sin\phi\cos\delta\cos\omega)^2\right]^{1/2}}{\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta} \quad (10)$$

The total hourly horizontal solar radiation, I, can be obtained from Eq. (3). However, data on beam solar radiation, I_b, and diffuse solar radiation, I_d, are not available. Therefore, a correlation between horizontal diffuse, I_d, and total horizontal solar radiation, I, is required. A correlation between horizontal diffuse and horizontal total solar radiation recommended by Boes (1979) is employed as follow:

$$\frac{I_d}{I} = 1 - 0.09K_T \qquad \text{For} \quad K_T \le 0.22 \quad (11)$$

$$\frac{I_d}{I} = 0.9511 - 0.1604K_T + 4.388K_T^2 - 16.638K_T^3 + 12.336K_T^4 \qquad \text{For} \quad 0.22 < K_T \le 0.8 \quad (12)$$

$$\frac{I_d}{I} = 0.165 \qquad \text{For} \quad K_T > 0.8 \quad (13)$$

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. The heat transfer coefficient from the pipe to the surrounding can be calculated by a correlation against wind speed as from Duffie and Beckman (1991):

$$h_o = 5.7 + 3.8V_w \quad (14)$$

The following assumptions for utilized model are considered:

1. The physical properties of all components of the pipe flow don't change with temperature.
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.
6. The topper surface of pipeline is considered for numeric and experiment study.
5. Although emissivity and absorptivity are related to each other; but its effect is infinitesimal and so ignored.

Eqs. (15–19) are derived based on the above assumptions to examine the steady state behavior of pipe flow under investigation:

Continuity equation:

$$\frac{1}{r}\frac{\partial}{\partial r}(\rho r v_r) + \frac{1}{r}\frac{\partial}{\partial \theta}(\rho v_\theta) + \frac{\partial}{\partial z}(\rho v_z) = 0 \quad (15)$$

Momentum equation:

— r component:

$$\rho(v_r\frac{\partial v_r}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_r}{\partial \theta} + v_z\frac{\partial v_r}{\partial z} - \frac{v_\theta^2}{r}) = \mu[\frac{\partial}{\partial r}(\frac{1}{r}\frac{\partial}{\partial r}(r v_r)) + \frac{1}{r^2}\frac{\partial^2 v_r}{\partial \theta^2} - \frac{2}{r^2}\frac{\partial v_\theta}{\partial \theta} + \frac{\partial^2 v_r}{\partial z^2}] - \frac{\partial p}{\partial r} + \rho g_r \quad (16)$$

— θ component:

$$\rho(v_r\frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta} + v_z\frac{\partial v_\theta}{\partial z} - \frac{v_r v_\theta}{r}) = \mu[\frac{\partial}{\partial r}(\frac{1}{r}\frac{\partial}{\partial r}(r v_\theta)) + \frac{1}{r^2}\frac{\partial^2 v_\theta}{\partial \theta^2} + \frac{2}{r^2}\frac{\partial v_r}{\partial \theta} + \frac{\partial^2 v_\theta}{\partial z^2}] - \frac{1}{r}\frac{\partial p}{\partial \theta} + \rho g_\theta \quad (17)$$

— z component:

$$\rho(v_r\frac{\partial v_z}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_z}{\partial \theta} + v_z\frac{\partial v_z}{\partial z}) = \mu[\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial v_z}{\partial r}) + \frac{1}{r^2}\frac{\partial^2 v_z}{\partial \theta^2} + \frac{\partial^2 v_z}{\partial z^2}] - \frac{\partial p}{\partial z} + \rho g_z \quad (18)$$

Energy equation:

$$\rho(v_r\frac{\partial h}{\partial r} + \frac{v_\theta}{r}\frac{\partial h}{\partial \theta} + v_z\frac{\partial h}{\partial z}) = \alpha[\frac{1}{r}\frac{\partial(r\partial T/\partial r)}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2}] \quad (19)$$

To solve these rather complex equations, commercial computational fluid dynamics (CFD) package Fluent 6.0.12 (Ansys Inc.) based on the finite volume approach has been employed. Convection terms are approximated using upstream differences whereas a fully implicit scheme is introduced to handle transient terms. Also, pressure and velocity fields are linked together by the SIMPLE algorithm. Solutions are obtained for the system when it is assumed to have achieved a steady state operation with the lapse of time.

Due to obtain the pipe surface temperature profile and fluid inside, a numerical analysis has been employed. Fig. 2 shows a partial view of the three-dimensional grid system used in the present analysis. The system consists of 266,000 elements where non-uniform ones are employed in domains of high fluid motion and heat transfer. The generated mesh distribution was designed to give an optimal accuracy: small elements (2.4 mm) were used in the pipe, air and fluid, while larger elements (20 mm) were used for the terrain below the pipe flow. It is constructed according to the physical dimensions and properties of the pipe flow under investigation. In all cases considered in the present analysis, temperatures were initially assumed at 20 °C.

III. Results and discussion

In order to illustrate for the influence of absorptivity and emissivity variation and discuss the relevant parameters, a base case is selected for which the thermophysical parameters and pipeline dimensions are given in Table 1. The working fluid is chosen to be light oil. The thermal properties of oil at 15.5 °C are also brought in Table 1. The flow is assumed to be fully developed and laminar. For the base case the Reynolds number is calculated to be,

$$Re = \frac{\rho V D_i}{\mu} = \frac{858.4 \times 0.01 \times 0.0214}{0.0145} = 12.66$$

This ensures that the flow is laminar. The heat transfer coefficient on the inner surface of the pipe is then calculated to be,

$$h_i = \frac{k_{oil} Nu}{D_i} = \frac{0.1483 \times 4.364}{0.0214} = 30.24$$

The profile of the fluid temperature is affected by the selection of the outer convective and radiative heat transfer coefficients. Therefore, for the case study selected the radiation heat transfer is considered to be significant. (When studying absorptivity effect, ε set to 0.8 and for surveying the effect of emissivity coefficient, α set to 0.8). The paint color material thickness is very low in compare with pipe thickness such that when thermal resistance of color over the pipe is considered to be neglected.

The pipe flow system was evaluated for a day period on an hourly basis. The major output of the numerical analysis was the temperature profile for both the fluid and the pipe surface for the pipe flow. As an example, the steady state pipe temperature in the pipe flow as well as the ground temperature distribution which is located below the pipeline is shown in Figs. 4 during at 12:00 and 13:00o'clock in 5th august 2008. At noon, solar radiation directly hit the upper surface of pipe and so no solar radiation will arrive to ground elements which are located below the pipe, hence the temperature of these elements will be lower than other elements. This matter is obvious in fig. 3 which can verify the numerical results anyhow.

Fig. 4 shows the variation bulk fluid temperature for the base case (ε=0.8). As the inlet temperature of fluid entering the pipe is lower than the surrounding, the fluid bulk temperature along the pipe is expected to increase. It could be found that increasing absorptivity coefficient also growing bulk temperature along pipe. In addition, the bulk temperature inclined to a limiting value after some distance from the beginning of the pipe. Considering ambient temperature, it may be realized for high absorptivity coefficients (0.9, 0.7 …), the bulk flow limiting temperature is much higher than ambient temperature. As for liquids, viscosity (and so pressure drop along the pipe) decreases as temperature increases, one way to reduce pumping work required for moving crude oil along long distance pipelines is to paint exterior surface with dark color.

Fig. 5 shows effect of absorptivity coefficients on variation of pipe surface temperature along flow for base case (ε=0.8). As it is known, high absorptivity coefficient causes higher amount of solar radiation to be absorbed by pipe surface, therefore steady state pipe temperature at end of flow for α=0.9 is higher than pipe temperature with lower absorptivity coefficients. Considering ambient temperature, it could be realized for low absorptivity coefficient (0.1), the pipe surface temperature is lower than ambient temperature for whole pipe length. The main reason for this behavior is due to exchange of heat (long wavelength radiation) between the pipe surface and sky which is at much lower than ambient temperature. This effect could be especially observed in clear sky (and night) in actual conditions.

Figs. 6 and 7 indicate effect of emissivity coefficients on variation of the bulk fluid and surface temperature for the base case (α=0.8) respectively. As shown the effects of emissivity on temperature variation of fluid and pipe surface has inversely influence rather than absorptivity. Emissivity coefficient causes reflection of heat from pipe surface to sky, therefore as it increases, heat rejection from pipe surface to sky increases and so pipe surface and fluid temperature decreases. It could be found that lower emissivity coefficient is caused higher pipe surface temperature. Due to convey better insight for the problem under investigation, influences of regular paint color in industry on temperature development in the pipe flow are represented in Fig. 8. The corresponding absorptivity and emissivity for each color are listed in table 2. As expected, using black paint as envelop color of pipeline leads to intensify fluid flow temperature through pipeline.

In accordance with above figures, whatever proceed along the pipeline, it can be seen that the slope of fluid and pipe surface temperature is tended to straight line and at the end of pipe is converged to limited value. In fact, when there is heat dissipation through the radiation and convection to the ambient, the bulk temperature changes similar to exponentially, reaching a limiting value for large x (fig. 8-b). Moreover, both the fluid temperature and the tube surface temperature tend to an identical value far from the tube entrance. This is unlike the classical constant wall heat flux case in which temperature rises unboundedly in a linear manner (fig. 8-a). To check validity of the numerical results, a comparison has been made between the numerical results and measured values of outer pipeline surface temperature. The experimental temperatures have been measured using infrared thermometer from upper surface of pipeline on 5th august 2008 at 12:00 o'clock. The pipeline is considered to have off-white paint color accompanied by absorptivity and emissivity equals to 0.34 and 0.9 respectively. At that particular day, light crude oil flows through pipeline while the outlet surface temperature of pipe has been measured along axial distance on the pipeline. The outlet surface temperature has been measured from pipeline entrance while its length is about 300 m. Comparison between the numerical and experimental results are depicted in Fig. 9. In this work, it is found that the results of the developed numerical model are in good agreement with the measured values.

The current section will try to discuss the effects of the pipe surface absorptivity and emissivity coefficients on transferring fluid through pipe in laminar flow 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. Flow is always accompanied by friction. This friction results in a loss of energy available for work. A general equation for estimate pressure drop due to friction is the familiar Darcy equation as,

$$\Delta p = \frac{0.5\rho f_m L V^2}{D_i} \qquad (20)$$

That friction factor is obtained for laminar flow as below,

$$f_m = \frac{64}{\mathrm{Re}} \qquad (21)$$

Fluid temperature is an important parameter on variation of fluid viscosity and in consequence friction factor. The viscosity is decreased due to increasing temperature and so loss work could be diminished. Hence fluid flow pressure drop will be declined along pipe. Here, the effects of exterior surface emissivity and absorptivity upon fluid temperature are taken into account. As discussed previously, the fluid temperature tends to an identical value far from the tube entrance in pipe. Which this is depended on emissivity and absorptivity coefficients of surface paint color. Variation of viscosity and destiny versus temperature for the light oil is gained by following equations. The variation of properties by temperature is based on experimental analysis of the Iranian light crude oil.

$$\rho = -0.732T + 869.3 \qquad (22)$$

$$\mu = 10^{-8}T^4 - 10^{-6}T^3 + 7\times10^{-5}T^2 - 0.002T + 0.033 \qquad (23)$$

In current study, the temperature is assumed to be reached to its final value so viscosity and density could be assumed constant for each case. By knowing, viscosity and density, the friction factor, f_m, could be calculated by Eq. (21). Once the friction factor is calculated, the pressure drop for the studied pipeline could be easily obtained by Eq. (20).
The influence of different absorptivity and emissivity coefficients of pipe exterior surface on the developed temperature, friction factor and eventually pressure drop are indicated in the table 3. It is seen that the pipe surface with higher absorptivity and lower emissivity bring about fluid temperature to increase; subsequently oil viscosity and loss work to decrease and therefore pressure loss will be decreased.

Considering the effects of absorptivity and emissivity of exterior surface which represents surface paint color on fluid bulk temperature development, it could be concluded that surface paint color should be selected based on the desired application. If the intention is to reduce fluid temperature, lighter color should be applied. For Kharg Island pipeline, any temperature rise of crude oil will have a negative impact on accuracy of flow measurement. So paint color with lowest absorptivity and highest emissivity is proposed. Like discussed, for oil pipeline the dark color should be applied to reduce pressure drop along the pipelines.

IV. Conclusions

In the present study, a numerical analysis for predicting temperature development for classical problem of fluid flow inside a pipe with constant wall heat flux by solar radiation in which there is leakage of the heat flux to the ambient has been established. The outer surface of the pipeline is exposed to solar radiation and wind stream. The radiation heat exchange with ambient is also taken into account. The effects of exterior surface paint color which represented by emissivity and absorptivity has been studied. The model has been developed to study crude oil flow temperature development along flow direction in an aboveground pipeline. The results of the numerical solution are in good agreement with those of the experimental model of the kharg oil pipeline with off white as envelope color.

The results obtained by the model show that the bulk temperature of the fluid and pipe surface along pipe varies exponentially in the direction of tube length. In the limit $x\to\infty$, the bulk temperature and surface temperature of the pipe do not increase unboundedly; rather, they tend to an asymptotic value. Based on the results which indicated significantly of exterior surface paint color, one should choose the paint color by considering its effects on temperature development. For increasing fluid temperature, the paint color that has high absorptivity and low emissivity should be used and for lower growing or constant temperature objective the paint color that has low absorptivity and high emissivity could be proposed.

Nomenclature

D_i	inner diameter of pipe (m)
D_o	outer diameter of pipe (m)
g	acceleration due to gravity (m/s^2)
f_m	Friction factor (dimensionless)
h	enthalpy (J/kg)
h_i	convection coefficient of inside pipe (W/m^2 K)
h_o	convection coefficient of air around pipe (W/m^2 K)
I	hourly solar radiation on horizontal surface (W/m^2)
I_b	beam solar radiation (W/m^2)
I_d	diffuse solar radiation (W/m^2)
I_o	extraterrestrial radiation (W/m^2)
I_{sc}	solar constant (W/m^2)
I_T	hourly solar radiation on pipe surface (W/m^2)
K_T	Daily average clearness index (dimensionless)
k_w	conductivity of pipe (W/m.K)
L	Length of pipeline (m)
Nu	Nusselt number (= hD/k)
n	number of day of the year, starting from the first of January
q_r	Radiative heat flux (W/m^2)
r, θ, z	Cylindrical coordinates
Re	Reynolds number, (=VD/ ν)
S	Daily average daily measured sunshine duration (h)
S_o	Daily average maximum possible sunshine duration (h)
T_f	Fluid temperature (°C)
T_s	Pipe surface temperature (°C)
V	Velocity (m/s)
V_w	Wind velocity (m/s)
P	Pressure (Pa)
ΔP	Pressure drop (Pa)

Greek symbols

ρ	density (Kg/m^3)
ε	emissivity (dimensionless)
σ	Stefan–Boltzmann constant (5.67×10^{-8} W/m^2 K^4)
α	absorptivity (dimensionless)
ø	latitude of site (◦)
ω	solar angle (◦)
δ	solar declination angle (◦)
μ	dynamic viscosity, kg/m.s
ζ	z dimensionless axial distance (z/L)

Subscripts

r	radial
θ	angular
z	lengthwise

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Table 1. Parameters used in numerical study.

Parameter	Value
L(m)	10
D_o(m)	0.0254
D_i(m)	0.0214
k_w(W/m.K)	30
T_∞(°C)	36
I(W/m^2)	700

V_w(m/s)	4.3
Duration in day (h)	12–13
ρ_{oil} (Kg/m^3)	858.408
Cp_{oil} (KJ/kg°C)	1.887
K_{oil}(W/m.K)	0.1483
μ_{oil} (pa.s)	0.0145

Table 2. Sample for various envelope color.

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

Table 3. Main results for the effect of absorptivity and emissivity on pressure drop and other related parameters.

	absorptivity (α)				emissivity(ε)			
	0.1	0.4	0.7	0.9	0.1	0.4	0.7	0.9
Final temperature (◦C)	35.6146	39.599	43.5835	46.2398	48.5584	46.8263	45.3544	44.4901
Friction factor	2.1731	1.8266	1.5133	1.3199	1.16	1.2787	1.3831	1.446
Pressure drop (pa)	44.3695	37.423	31.1118	27.2	23.9538	26.3648	28.48	29.7522

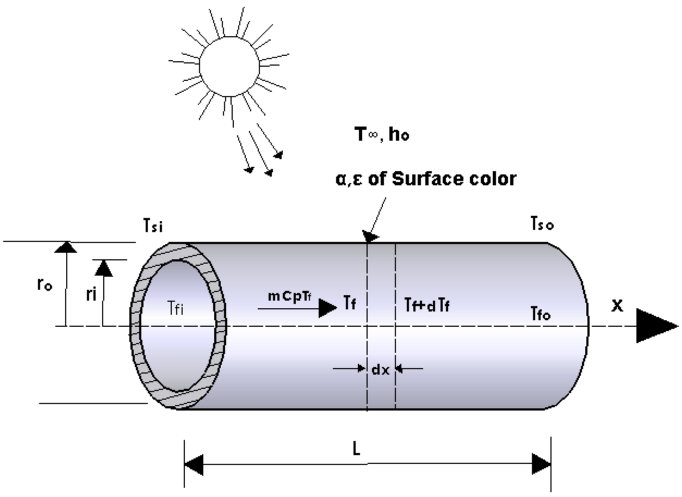

Fig. 1. A schematic diagram of pipe flow under investigation.

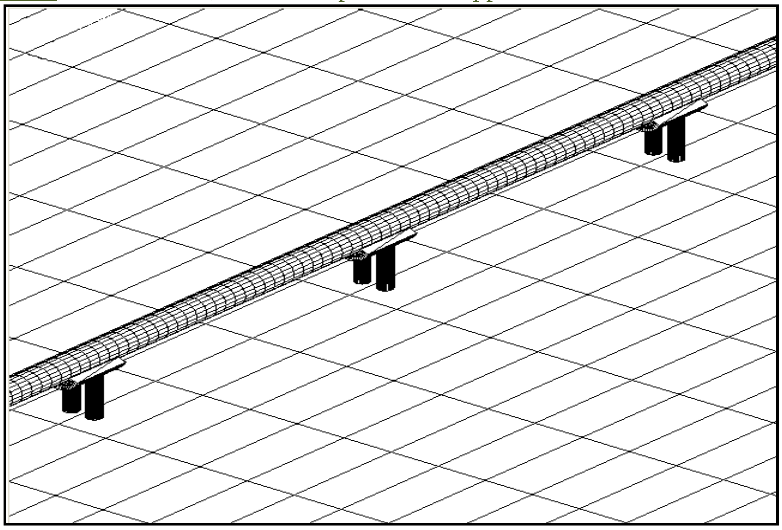

Fig. 2. A section of mesh system for aboveground pipe flow.

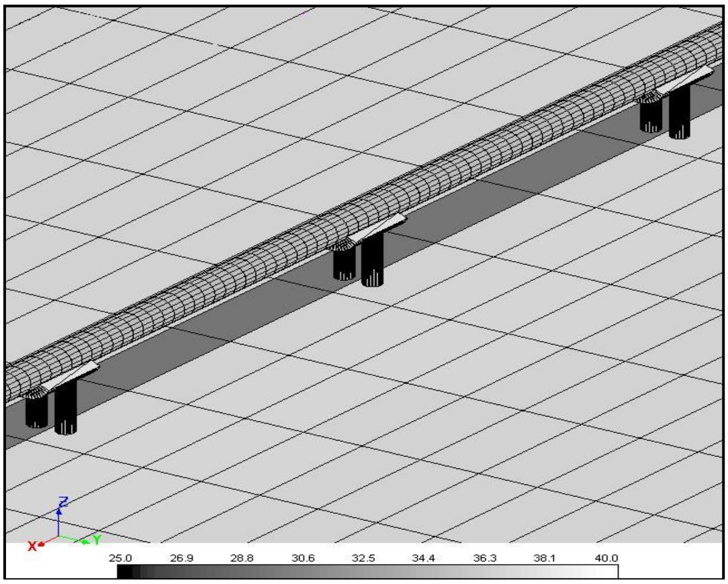

Fig. 3. Temperature distribution in the pipe surface and ground during at 12:00 and 13:00 o'clock in 5th august 2008.

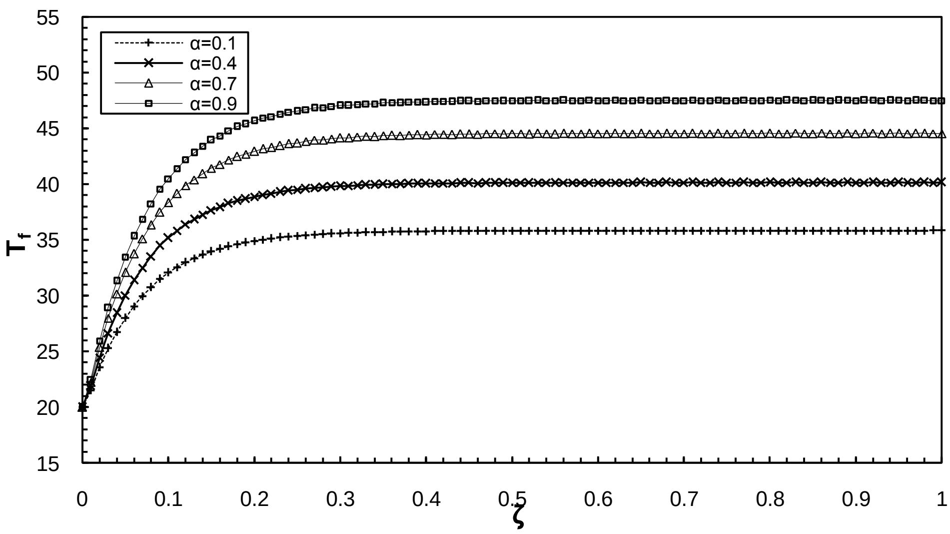

Fig. 4. Effect of absorptivity coefficient on temperature variation of bulk fluid along the pipeline.

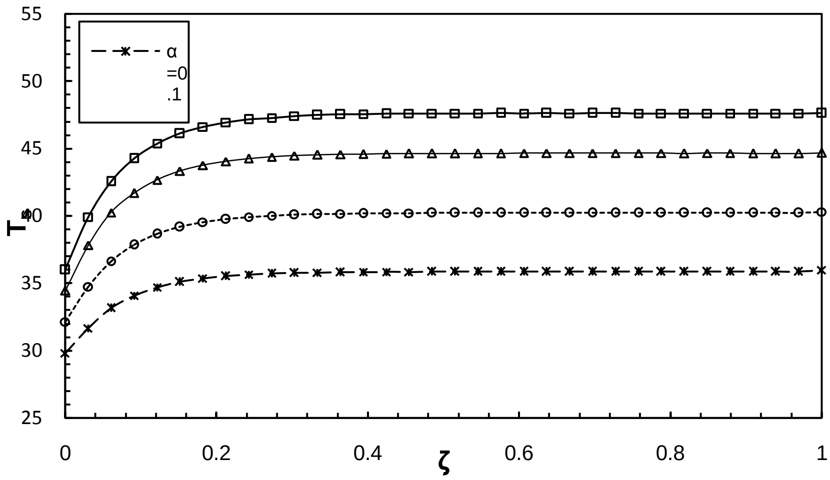

Fig. 5. Effect of absorptivity coefficient on temperature variation of pipe surface along the pipeline.

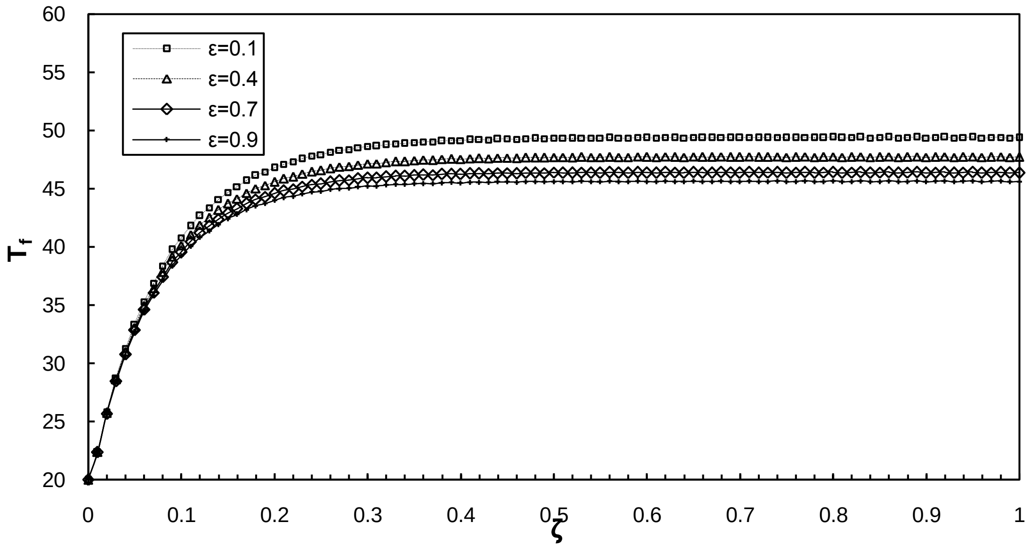

Fig. 6. Effect of emissivity coefficient on temperature variation of bulk fluid along the pipeline.

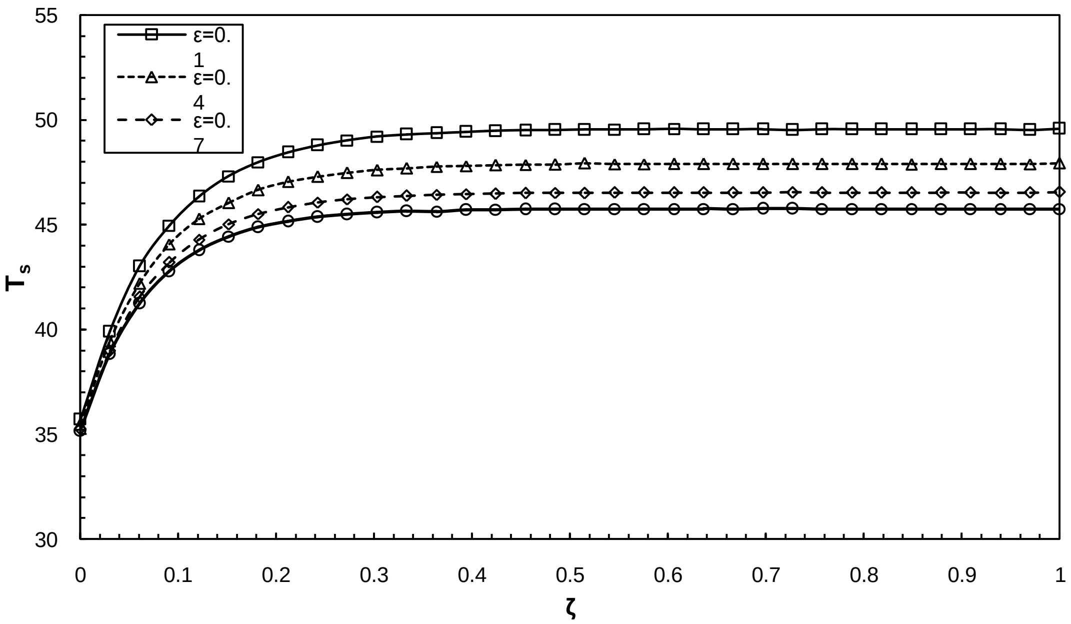

Fig. 7. Effect emissivity coefficient on temperature variation of pipe surface along the pipeline.

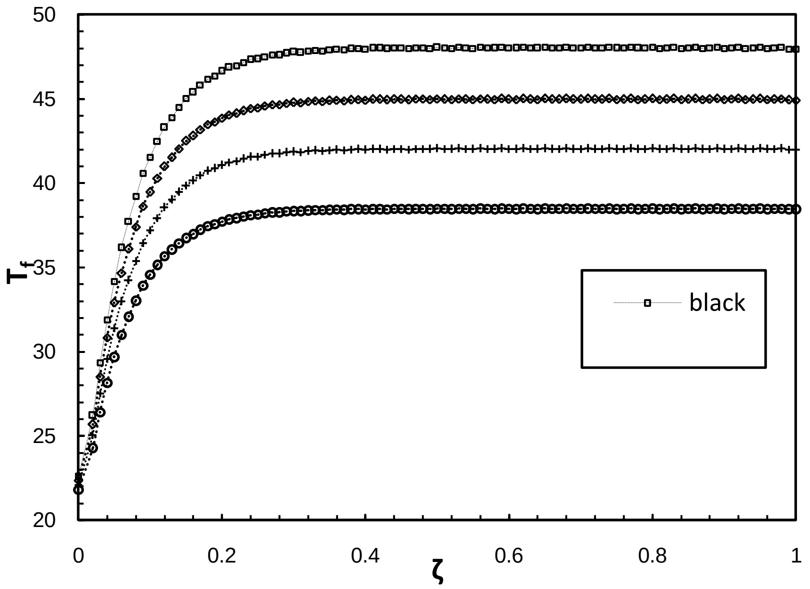

Fig. 8. Effect of pipe surface color on temperature variation of bulk fluid along the pipeline.

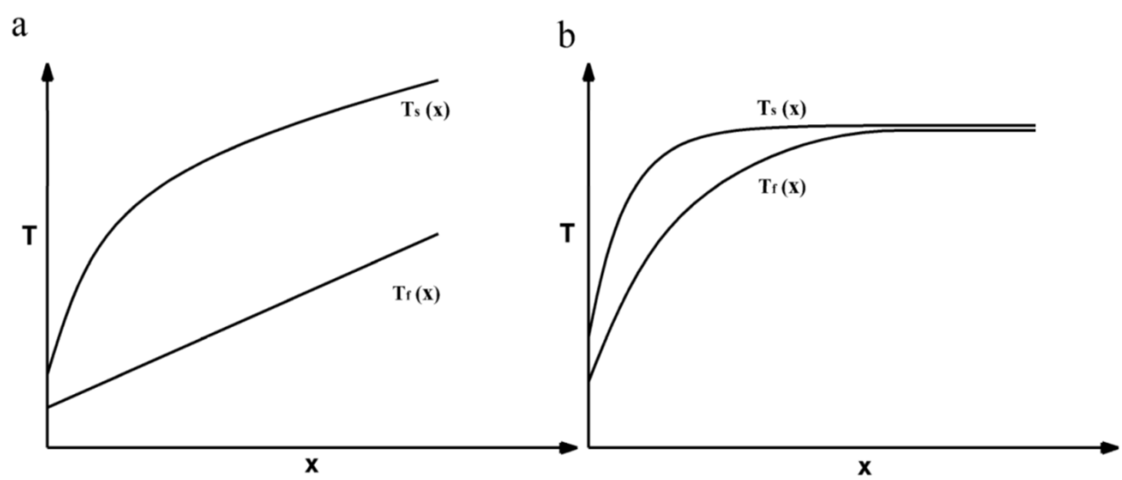

Fig. 9. temperature Variation of pipe surface and fluid along the pipe with constant wall heat flux, a) no heat dissipation (classical pipe flow problem), b) heat dissipation to ambient

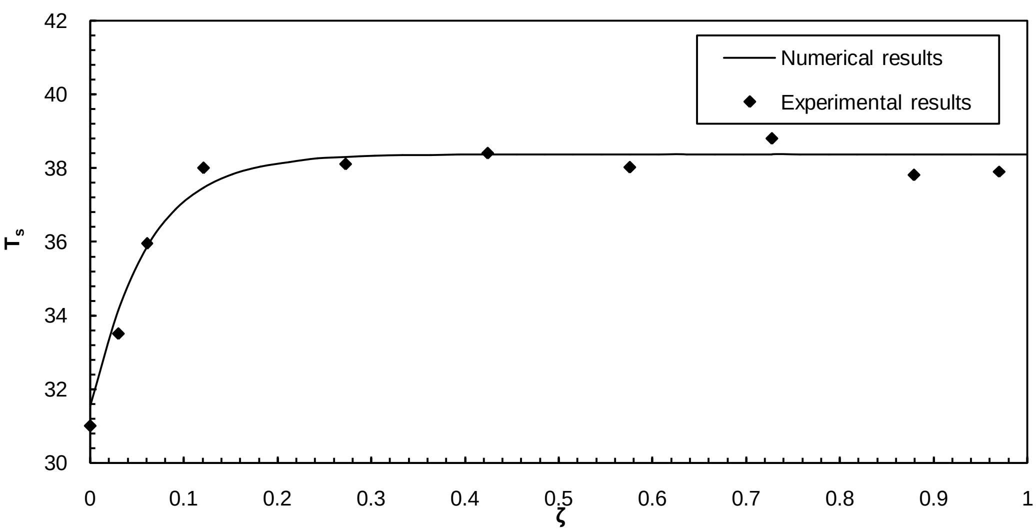

Fig. 10. Comparisons of the calculated and measured temperatures on the surface of the kharg oil pipeline in august 2008.