EXPERIMENTAL AND NUMERICAL SIMULATION ON BURIED HOT FUEL OIL PIPELINES IN THREE MODES FLOW REGIME CONSIDERING TEMPERATURE LOSS DURING A SHUTDOWN

***Mohsen Dehdarinejad*[a], *Morteza Behbahani-Nejad*[a,b*], *Ebrahim Hajidavalloo*[a]**

[a]Department of Mechanical Engineering, Faculty of Engineering, Shahid Chamran University of Ahvaz, 61357-83151, Ahvaz, Iran

[b]Gas Networks Research Center, Shahid Chamran University of Ahvaz, Ahvaz, Iran

[*]Corresponding author; E-mail: bnmorteza@scu.ac.ir

Aiming to study the temperature distribution along buried pipelines containing hot fuel oil, a new large-scale laboratory is constructed from the perspective of the corresponding fluid thermophysical properties. Also, a modeling of the pipeline, and the soil around it, was performed along the pipeline for observation of all three modes of turbulent, laminarization, and laminar flow, which is validated by experimental results. Furthermore, the appropriate data are also gathered from the actual pipeline, 107 km of the 26" pipeline between Abadan Refinery and Mahshahr Port, and the results of the experiment and modeling are reconfirmed. The experiment shows that the viscosity and fluid density of fuel oil is strongly temperature-dependent. Many experiments are performed on the parameters affected by temperature according to their importance. The method chosen to simulate three flow modes along the pipeline shows less than 2% error in turbulent and laminar zones and reveals just a 3% error to experimental data in the laminar region. The maximum safe time during the stopping period of the pipeline (MSST) and holding fuel oil in it is calculated based on the pour point of fuel oil. This time is critical for the real pipeline in sudden shutdown and is calculated 41 hours.

Key words*: fuel oil, Pipeline, Laminarization, Experiment, Heat Transfer, Transform, MSST*

1. Introduction

Using a pipeline is an economical way to transfer heavy products of an oil refinery. Fuel oil is a heavy viscose product of the bottommost stage of a distillation tower in an oil refinery. It can be obtained from waste cooking oil in a batch reactor [1]. The fuel oil state is similar to gel at ambient temperature and cannot be transferred like other liquids. In order to make the flow movement possible in a pipeline, the fluid heating methods are applied at the beginning of the pipeline. Temperature constraints depend on many different parameters. From the highest and lowest temperature point of view, there are some limitations in practice. From another perspective, the temperature difference is around 45°C in 107 kilometers between Abadan Refinery's fuel oil and Mahshahr's Export Port. Because of this differentiation in temperature, the density changes by up to 6%. Given the pipeline's capability of around 200,000 barrels per day, this could lead to a computational error of 12,000 barrels per day.

Using numerical modeling is preferable to decrease costs in comparison with laboratory set-up, but for fluid species that are less prevalent in the industry, laboratory set-up is needed to adapt to the model. In the past, there were many models of temperature distribution in the cross-section of the pipe and peripheral soil, and some researches were performed on buried hot oil pipeline during normal operation and shutdown. As an early demonstration of exertion regarding this matter, an analytical method was applied to consider the covered hot oil pipeline [2]. In many cases, the analytical solution usually veers off enormously from the real instance because of significant improvements that are required. Numerical techniques can consider more factors with fewer suppositions. Danielewicz *et al.* investigate the difficulties of modeling thermal network energy losses and evaluate the parameters that affect them in a 3-dimensional manner [3]. Bo Yu *et al.* performed a study on an oil pipeline under normal operating conditions, using a series of assumptions [4]. They extracted the governing equations and then, by using the finite volume method and finite difference method, solved the obtained equations, so that the studied area was simulated with unstructured grids. In various months of the year, they investigated the numerical solution for the pipeline under normal operating conditions. C.J.Li *et al.* and Peysson *et al.* investigated the drop in temperature and the necessary restarted pressure at specific shutdown time [5, 6].

The purpose of this research is to investigate the position of the transition region and heat transfer of hot fuel oil going through the pipeline, thus allowing laboratory set-up to obtain the best laminarization and turbulence area equations. Given the creation of a 2-D heat transfer model in a buried pipeline using the appropriate coordinate suitable for a buried pipeline. Obtaining the maximum safe stop time (MSST) for the pipeline is one of the main and important results of this research.

2. Mathematical model of the buried hot fuel oil pipeline under the typical operation

The real pipeline containing hot fuel oil is buried about 2 meters under the ground and it is warmed by the heater at the beginning of the pipeline and then the fuel is transmitted and pumped into the pipe. Generally, the research of the buried hot fuel oil pipeline can be split into two sections, fuel oil heat transfer inside the pipeline and soil thermal conduction outside the pipeline. In a simple view, one-direction modeling in the pipeline and 2-direction simulation for conduction in the soil around the pipeline are considered and developed. Based on fuel oil conduction, it is reliable that density and viscosity should be regarded relative to temperature. This is due to the fact that according to the fluid inlet temperature, changes in the flow regime along the pipeline should be checked. Therefore, it is necessary to consider turbulent, laminarization, and laminar flow.

Because a large number of complex factors are included, the numerical modeling of heat transfer in a buried hot fuel oil pipeline needs sensible simplification and hypothesis to make the calculation computationally feasible. The main simplifications used in this research to get theory closed to reality are given as follows:

- It is presumed that the soil around the pipelines is homogeneous and isotropic. But blended soil and water are used for precise simulation in the calculation.

- In this research, radial temperature changes are ignored and the bulk temperature of any section is considered as a point temperature. Modeling is developed in one-dimensional through the pipeline and flow regime considered deeply and the effect of bulk temperature on the ground surrounding the pipeline is discussed.

- The layer of deposited wax on the pipeline wall is assumed to uniformly spread along the entire pipeline.
- The stagnation point is introduced as a critical temperature in shutdown time limitation. The concept of stagnation point introduced by Li indicates that fuel oil transforms into wax and it is named crystallization. In other words, fuel oil starts to be solid and occurs at the end of the pipeline [7].

Since Two-dimensional simulation of creating stagnation in oil pipeline has been investigated before, this study does not consider the radial changes and variations in the nature of fuel oil phase change, and only changes in the thermophysical properties of the fuel oil along the Longitudinal axis of pipeline and the regime flow changes throughout the pipeline are investigated. The stagnation point is usually higher than the gel point; for example, for the Puyang crude oil, the stagnation point is 7.4 ℃ greater than the gel point. Another Shengli crude oil sample indicates that the distinction between the stagnation point and the gel point is as great as 10.4 ℃. Experimental results in the various outlet of fuel oil samples from different distillation towers in Abadan Refinery show that the stagnation point differs from 11 to 28 ℃ [8].

Data measured in the field or theoretical calculation can determine the thermally impacted region of the pipeline. Previous studies by Xu Cheng et al. and Zhang Z.W *et al.* show that 10m is the reasonable depth of the hot fuel oil pipeline thermal influence region [9,10], which is adopted by our computation in this paper (Fig. 2, $X_d \leq 10, Y_d \leq 10$).

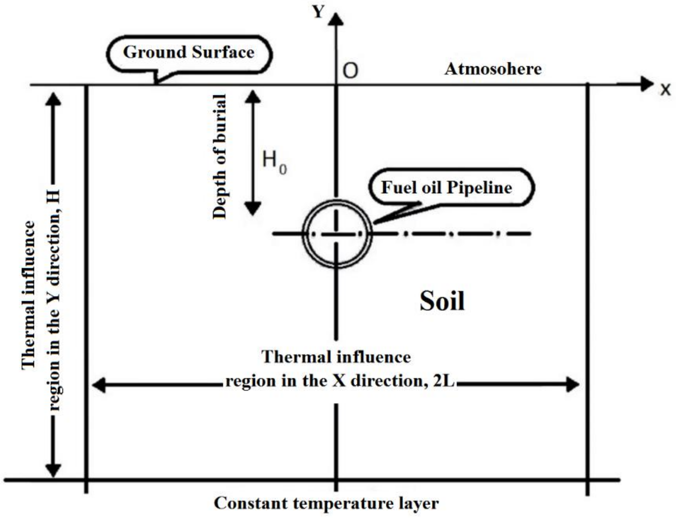

Fig. 1. The Sketch map of the impacted temperature region of the pipeline [3]

- Based on the actual pipeline, the pipeline coating only protects the pipe against corrosion and is highly conductive, and has no role as an insulation layer. Therefore, it is not appropriate to be regarded as an insulation coating in the calculation of heat.

A heat transfer mathematical model is established for a buried hot fuel oil pipeline, incorporating fuel oil, pipeline wall, corrosion-inhibiting coating, air, soil, and their interactions, with the hypothesis mentioned above and as shown in Fig. 1.

2.1. Heat conduction in soil

As stated above, due to environmental limitations, it is essential to consider exactly the impact of a fuel oil pipeline on soil and surface. Therefore, two-dimensional modeling is used to show transferring heat from the pipeline to the surface. The coordinate system used to explain heat transfer in the ground is an extension of Archer and O'Sullivan's methods [11]. Conduction factor of mixed soil and water is gotten from experiments in the research and development department of the Abadan refinery.

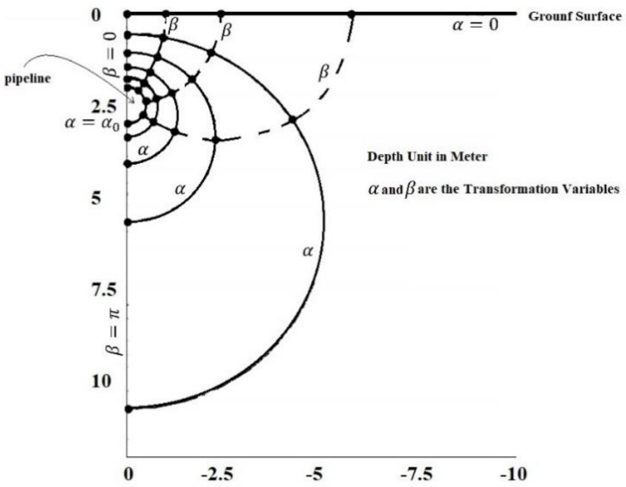

Fig. 2. The geometry of the nodes and domain in the transform system

The transformation of the variables used to define the new system of coordinates (Fig. 2) is:

$$x + iy = C \coth\left(\frac{\alpha + i\beta}{2}\right) \tag{1}$$

$$\alpha = \cosh^{-1}(\phi) \tag{2}$$

$$C = r_0 \sinh(\alpha_0) \tag{3}$$

$$\phi = \frac{Z}{r_0} \tag{4}$$

The range defines the half-domain (Symmetry applies to the other half):

$$0 \le \alpha \le \alpha_0 \quad , \quad 0 \le \beta \le \pi \tag{5}$$

$$x = C\left[\frac{\sinh\alpha}{\cosh\alpha - \cos\beta}\right] \tag{6}$$

$$y = C[\frac{\sin\beta}{\cosh\alpha - \cos\beta}] \tag{7}$$

The equation of heat conduction in the x-y plane is converted into the plane of α-β:

$$\frac{\rho C_p \partial T}{k\,\partial t} = \left(\frac{\cosh\alpha - \cos\beta}{C}\right)^2 \times (\frac{\partial^2 T}{\partial\alpha^2} + \frac{\partial^2 T}{\partial\beta^2}) \tag{8}$$

In this study, since the temperature distribution along the pipe is more important than the temperature changes in the radial axis to the ground surface, therefore, we consider the temperature of each section of pipe equal to the average pipe surface temperature. (In the longitudinal and radial calculations this temperature is used as the cross-section temperature).

The interaction effects of soil and pipelines in a steady-state and transient state by Perpar *et al.* have been calculated with accurate mathematical modeling [12].

2.2. Modeling of flow by considering different states

Given the nature of the fuel oil, the fluid flow inside the pipeline at an inlet temperature of 90°C would include all three states of turbulent, transition, and laminar along the pipeline. According to previous studies, as well as researches and experiments conducted by the National Iranian Oil Company at the Research Institute of Petroleum Industry and Laboratory Set-up for the purpose of this study, the best models of friction factor of turbulent and laminarization conditions are as follows.

That being the case, fluid faces all three turbulence, transition, and laminar conditions in the pipeline, modeling should be performed based on all three states. The Haaland equation [13] model was used for the turbulent state based on the results of the previous modeling, and the requirements for laminar flow are also known.

$$f = \begin{cases} {}^{64}/_{\mathrm{Re}} & \text{laminar} \\ \left[1.8\ln\left(\frac{{}^{\varepsilon}/_{D}}{3.7}\right)^{1.11} + \frac{6.9}{\mathrm{Re}}\right]^{-2} & \text{Turbulent} \end{cases} \tag{9}$$

Since the fuel oil has variable thermophysical properties, a particular model for determining the transition region's friction factor could not be predicted regardless of the experimental data. So, we have to use the current laboratory results and analyses for the transition range, and finally, the following model is achieved by combining them [14].

$$f = -5\times10^{-15}Re^{4} + 7\times10^{-11}Re^{3} - 3\times10^{-7}Re^{2} + 0.0006\mathrm{Re} - 0.345 \qquad Transition \tag{10}$$

Since the laboratory set-up pipe was new and the surface was smooth, the above formula error is approximately 10%.

2.3. Specification of fluid

In this research, Abadan oil refinery fuel oil is considered. As a general rule, there are three types of fuel oil 1100, 2000, and 12,000. The relationship between kinematic viscosity, conductivity heat transfer, and relative gravity in these three fuel oils are expressed in Tab. 1 as follows [14, 15, 16].

$$s = a_1 - a_2 \times T \qquad \text{relative density} \tag{11}$$

$$\nu = a_3/s \times e^{a_8/T+460} \qquad \text{kinematic viscosity} \tag{12}$$

$$k = a_4 + a_5 \times T \qquad \text{Conductivity heat transfer coefficient} \tag{13}$$

Table 1. Fixed coefficients related to thermophysical properties of three types of fuel oil in Abadan refinery

Fuel oil 12000	Fuel oil 2000	Fuel oil 1100
$a_1 = 1.0184$ $a_2 = 0.00035$	$a_1 = 0.994$ $a_2 = 0.0003$	$a_1 = 0.9885$ $a_2 = 0.000325$

$a_3 = 1.93733 \times 10^{-6}$ $a_4 = 0.0684508$ $a_5 = 2.034 \times 10^{-5}$ $a_8 = 11637$ $Z^* = 1.7 \times 10^{-6}\quad {}^{1}/_{K}$ $C_p = 1905\quad {}^{J}/_{Kg.K}$ $P_t = 311\quad K$	$a_3 = 5.586 \times 10^{-7}$ $a_4 = 0.0645$ $a_5 = 2.5 \times 10^{-5}$ $a_8 = 11515.7$ $Z^* = 1.7 \times 10^{-6}\quad {}^{1}/_{K}$ $C_p = 1796.4\quad {}^{J}/_{Kg.K}$ $P_t = 311\quad K$	$a_3 = 3.4999 \times 10^{-6}$ $a_4 = 0.06275$ $a_5 = 3.75 \times 10^{-5}$ $a_8 = 10127.9$ $Z^* = 1.7 \times 10^{-6}\quad {}^{1}/_{K}$ $C_p = 1796.4\quad {}^{J}/_{Kg.K}$ $P_t = 283.15\quad K$

In the above relations, Z^*, C_p and P_t are respectively the volumetric coefficient, specific heat capacity, and temperature of the pour point.

The equations and coefficients mentioned above are acquired from the petroleum fuel laboratory of the Iranian Petroleum Industry Research Institute.

3. Details of the experiment device

The modeling described in the preceding sections needs to be verified and, because the modeling for this fluid has not been solved with previously defined conditions, constructing a laboratory set-up seems essential. Therefore, according to the necessity of manufacturing, the same set-up was made to be attached to the main pipeline as described below in Fig. 5.

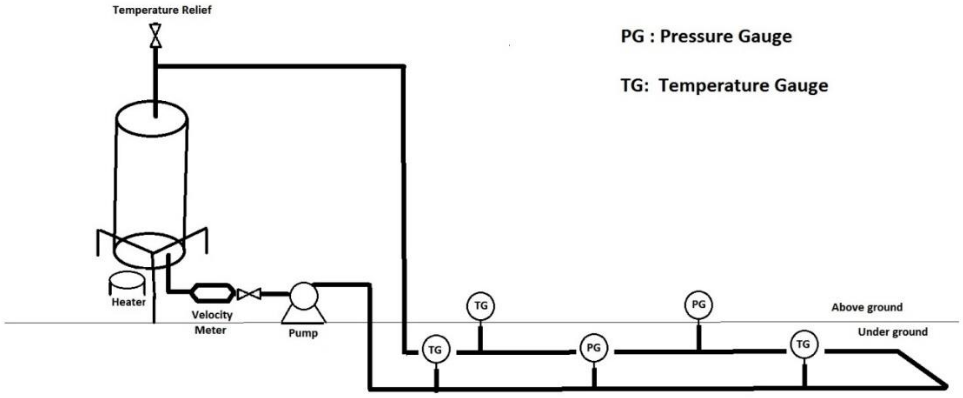

Fig. 3. Schematic of laboratory model

To verify the simulation, a closed fuel oil cycle was constructed. There are so many issues with obtaining data from the experiment. Laboratory set-up was built and installed in Ahvaz city. Due to the very high summer temperatures and groundwater as limits for testing, various methods used to experiment, are summarized.

Because of the short length of the pipe used in the test, the time of the shutdown and start-up scenarios is very short and the effects of the temperature are rapid and this is another problem. Considering the test conditions and the rigidity of creating these conditions, several people were simultaneously used to read the pressure and temperature numbers accurately.

Based on the average temperature chart for Ahwaz's lowest temperature, the pipe should be discharged from the fuel oil after each test because the fluid starts to become the gelation phase and creates new problems for the next test.

To obtain weather conditions like air temperature in different months of the year and wind speed during the year in the area, Information was obtained from the Meteorological Organization of Khuzestan Province [17] (Fig 4).

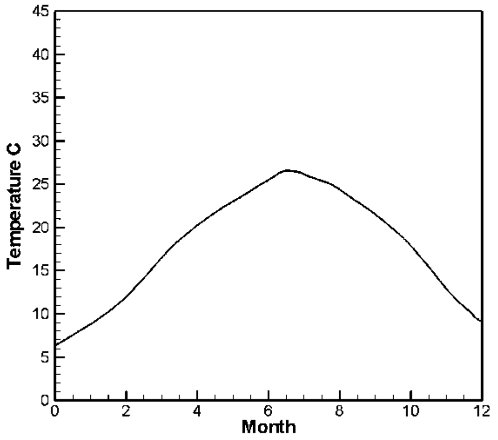

Fig. 4. The average monthly minimum temperature in Ahwaz

4. Experimental and simulation results and analysis

Using the experimental apparatus mentioned above, several tests were performed to find the conditions under which all three fluid flow regimes within a 200-meter pipe are seen. The transitional temperatures of the shutdown are also tested.

A method for cooling the soil around the pipe is used to achieve the acceptable temperature difference due to the low length and diameter of the pipe and the very high temperature of the air at the location of the laboratory set-up. In order to model the air and soil temperature in the winter, the foaming of the fire extinguisher in the pipe pit is used. Although the temperature of the soil is less than 10 °C, it is difficult to create conditions that all three flow regimes can be seen. First, at a temperature of about 100 °C, the fuel oil was injected into the pipe, which was tested at various speeds from 3 m/s to 10 m/s. With this incoming temperature, we encountered a temperature difference of 17 °C at the beginning and end at a speed of 3 m/s. But the entire fluid flow is laminar (Fig. 5). With a flow velocity of 10 m/s, a temperature difference of 6 °C was observed, but the fluid flow is turbulent throughout the pipe.

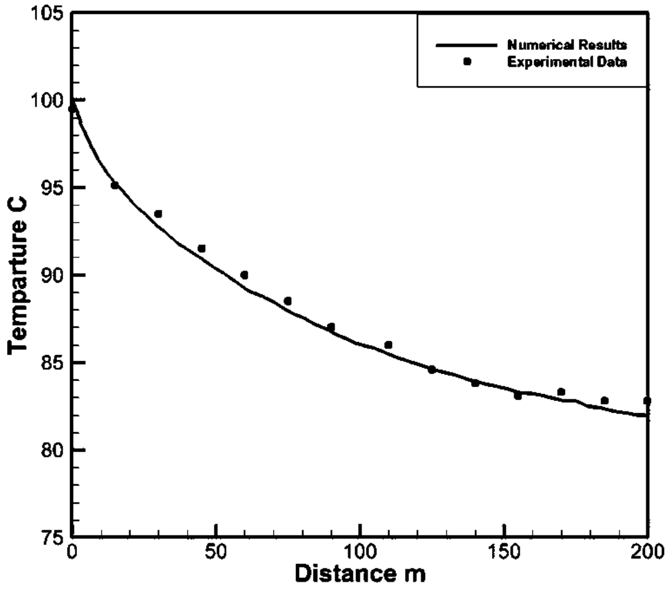

Fig. 5. Experimental and modeling data of temperature along the 200-meter pipe by 3 m/sec velocity

To reach the position of the three flow regimes, the inlet temperature is increased to 150 °C. According to the modeling calculations, and based on test measured data, at the beginning of the pipe as far as 140 meters the flow is turbulent. From this point to 180 meters the laminarization phase is observed (Reynolds about 2800 to 2200). At the end of the pipe, the flow is laminar. Due to the high-temperature risks of fuel oil at the entrance, it is not possible to raise the temperature, and the fluid speed increased to 10 m/s (Fig .6). By considering the experimental and calculated data, it is shown that the maximum deviation of about 3% occurs in the laminarization region, and the numerical modeling is carried out with excellent accuracy on the experimental results.

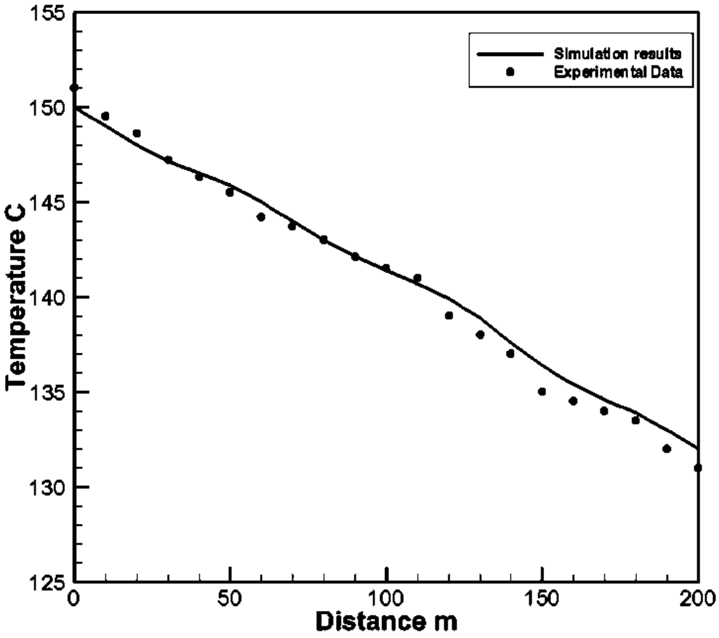

Fig. 6. Experimental and modeling data of temperature along the 200-meter pipe by 10 m/sec velocity and three flow regimes

When the fluid flow in the pipe is stopped, the fluid settles and the temperature distribution is transferred through the conduction heat to the surrounding soil. The initial conditions of the temperature distribution are known and equal to the last recorded temperatures, the uniform state of fluid flow. As expected, the temperature drop is greater in some parts with higher temperatures. By rising soil temperature around the pipe due to the discontinuity of the new injection of foam, the deviation increases in comparison with numerical modeling (Fig .7). This amount of deviation of 6 hours after stopping is quite evident. Over time, the graph slope is reduced due to a less temperature reduction in a region with lower temperatures.

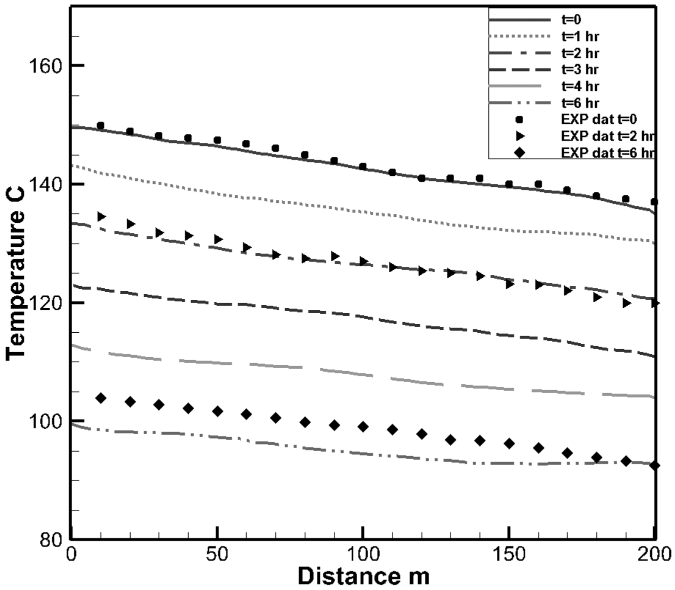

Fig. 7. Shutdown temperature distribution along the pipe, experimental data compared with numerical simulation results

Laboratory set-up is made, and numerical modeling is done for mutual verification. But in order to confirm the modeling, data is obtained from the actual pipeline between Abadan and Mahshahr city with a diameter of 26 inches and a length of 107 km and an average depth of 2 meters, with a flow rate of 180,000 barrels per day, and the results are shown in the following graph. The oil entry temperature into the pipeline is 90 C, which has a ceramic coating, an anti-corrosion heat-resistant layer. There is an even pit at a distance of about 10 km which is recorded by installing a barometer and thermometer, temperature, and pressure. When data is written down, the type of transported fuel oil is from the "2000" sample. The information is collected in the winter of 2018 and the evening, in coordination with the partnership with Iranian Oil Pipelines and Telecommunication Company. The temperatures are recorded in normal operation and they correspond to the time t = 0 in the graph below. In other words, if the pipeline is stopped at that time, the distribution of temperature along the pipeline becomes equal to the temperature recorded. Comparing the numerical modeling with the actual results of the pipeline shows that proper outcomes are achieved with very little error (Fig .8). The fluid flow at km 40 to 70 range is located in the area of transition and laminarization.

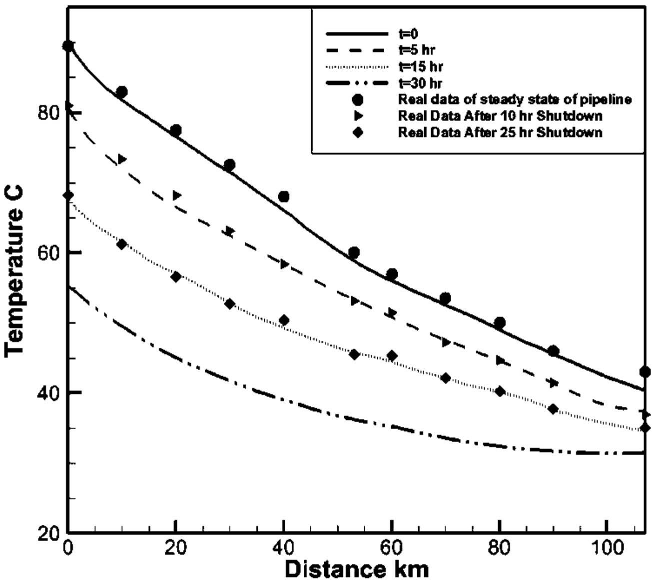

Fig. 8. Real temperature data from Abadan-Mahshar fuel oil pipeline and shutdown results of numerical modeling

Given the accuracy of the modeling, for the real pipeline and the operating conditions as mentioned above, the maximum safe stopping time (MSST) is greater than 41 hours. In this situation, about 5 km of fluids from the end of the pipeline is entered into the critical phase of becoming a gel, which can restart the pipeline with a 50 percent increase in the power needed to launch the pipeline. In such cases, it is very difficult to recharge the pipeline and often leads to serious damage to the pipeline system.

5. Conclusions

A large-scale laboratory set-up was constructed and numerical modeling for the normal operation mode for hot fuel oil has been established for all three modes of turbulent and flowing fluid flow. A1-dimensional and 2-dimensional finite-difference, combined and solved for both fluid flow in the pipeline and conducted heat throughout the soil around the pipeline. Simulations were carried out under different operating conditions and comparisons were made between the results of the calculation and the measured data. These comparisons provide several main parameters such as the inlet temperature, the velocity, and the range of soil temperature around the pipeline, and a proper compromise in the approach has confirmed our three-zone hydraulic and heat transfer simulation program. For such fluids that are strongly dependent on thermophysical parameters, the proposed solving method and the accurate modeling results compared to the test data are suggested in order to model Reynolds variations due to changes in viscosity, density, and flow regime. Using our numerical model, the analysis of various influential factors on the axial temperature drop under the buried hot fuel oil pipeline's working on a typical operation resulted in a lot of insightful conclusions. Also, considering all of the variables mentioned above, the heat transfer from the pipeline to the surrounding soil, and the combination of soil with water, as well as passing the pipeline through the lakes or rivers, the temperature distribution in stop mode and the finding of maximum safety stop time for the pipeline (MSST), are the achievements of this research.

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Nomenclature

C_p – specific heat at constant pressure, [$\text{kJkg}^{-1}\ \text{K}^{-1}$]
D – diameter of The pipeline, [m]
f – friction factor, [–]
g – gravity acceleration, [ms^{-2}]
h – specific enthalpy of the fuel oil, [Jkg^{-1}]
k – conduction Coefficient of soil, [$\text{Wm}^{-1}\text{K}^{-1}$]
k_f – conduction factor of water, [$\text{Wm}^{-1}\text{K}^{-1}$]
L – latent heat of vaporization, [kJkg^{-1}]
m_w – mass of water in a unit cubic meter of soil, [kg]
P_t – pour point Temperature, [K]
Re – Reynolds number ($=\rho VD/\mu$), [–]
S – elevation difference, [m]
s – relative density
t – time, [s]
T_f – fluid Temperature, [K]
T_g – fluid Temperature, [K]
u – specific energy of the fuel oil, [Jkg^{-1}]
Z^* – volumetric Coefficient, [K^{-1}]
ρ – density of soil, [kgm^{-3}]
α – thermal diffusivity of soil, [m^2s^{-1}]
ε – roughness height, [m]
v – kinematic viscosity, [L^2s^{-1}]

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