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Investigation of Pipeline Enhancement to improve its Capacity for Heavy oil Transmission

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ABSTRACT

In this study, minor modifications are studied to enhance the exploitation of an existing underground pipeline which represents a capital intensive infrastructure. This study includes thermal improvements of pipeline constructed for transporting light oils to its capacity to transport heavy oils which correspond to higher pressure drop which may exceed the constraints of pressure and temperature and that may lead to overcoming the reduction in pipeline transportation capacity that results due to the increasing in friction loss accompanied by heavier oils due to high viscosity. The study involving an existing pipeline of length 100 km that used to transport the light oil named as ***Oil (1)*** *, the gradual conversion from transporting a light oil to heavier oil such* ***[Oil (2), Oil (3), Oil (4) and MAZUT]*** *by thermal improvements for future applications of this pipeline to transport these heavier oils. This improvement includes more additional heat at some selected points along the pipeline. This strategy depended on pre-heating the oil by using single and multiple intermediate heating stations as stated in several cases. The requirements of heat added for each case are determined. The reduction in pipeline transmission capacity after these thermal management technologies can significantly decrease, and that leads to observed remarkable savings in capital operating costs. This approach significantly advantageous over other alternatives because of the low-cost of the presented heating technique.*

Key Words: Heavy Oil, maximize pipeline transmission capacity, thermal improvement in the pipeline transportation system.

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Nomenclature

Parameters

A_c Cross section area of pipeline m^2
A_O Outside surface area of pipe, m^2
C_c Specific heat capacity of the heavy oil, J/kg. K
C_P Specific heat capacity , J /kg. K
D Outer diameter of the pipeline, m
f Total friction factor inside the pipeline
h_{cd} Heat transfer coefficient by conduction, W/m^2. K
h_{cv} Heat transfer coefficient by convection, W/m^2. K
h_i Convection heat transfer coefficient for the inside surfaces of piping system , W/m^2. K
h_o Convection heat transfer coefficient for the outside surfaces of piping system , W/m^2.
K Thermal conductivity of oil, W/m. K
K_i Thermal conductivity of pipe material, W/m. K
K_{ins} Insulation thermal conductivity, W/m. K
K_s Thermal conductivity of the soil, W/m. K
L Length of pipe, Km

$L_{\Delta PMAX}$ Length at maximum pressure drop, Km
m Max maximum capacity production before improvement at the case of light oil transported, Mtpa
$m^{\bullet}_{n}$ The capacity of the pipeline when transported light oil before improvement, Mtpa
$m^{\bullet}_{R}$ The capacity heavy oil transported after thermal modification, Mtpa
$\% \ m^{\bullet}_{RED}$ Percentage of reduction in heavy oil transported after thermal modification, %
ΔP Total pressure drop along the pipeline, Pa
ΔP_{MAOP} The value of pressure drop which constrained by maximum allowable operating pressure, Mpa
q Amount of heat adding (Heat duty), MW
q_{tot} Amount of heat transfer by conduction per unit length , W/m
U_{EX} The total heat transfer coefficient between pipe and soil, W/m. K
Re Reynolds number
$r_{ins,o}$ Outer radius of the insulation layer , m
R_{ins} Insulation material resistance, K/W
R_{p} Pipe material resistance, K/W
$R_{p,i}$ Inner radius of pipe wall, m
$R_{p,ins}$ Total thermal resistance of insulated pipeline, K/W
R_{soil} Soil resistance, K/W
t_{ins} Insulation thickness, m
T_{f} The local temperature of the oil transported through the pipeline, °C
T_{F} Average temperature of the oil, °C
T_{in} Inlet temperature of the oil to the pipeline, K
$T_{ins}(x)$ The local insulation temperature along the pipeline distance, ºC
T_{P} The outside surface temperature of pipeline, K
$T_{s,a}$ The mean temperature between the soil and outside air, °C
T_{s} The soil temperature, K
T(x) The local temperature of the oil ay any location inside the pipeline**,** K
V_{in} linear velocity inside pipeline, m/sec
x Position on the pipeline in longitudinal direction, m
X Insulation thickness, m

Greek Letter

ρ Total density of heavy oil through the pipeline (x=L) , kg/m^3
ρ (x) The local oil density, kg/m^3
μ Dynamic viscosity**,** Pa.s
ν Fluid kinematic viscosity, cSt, [cSt $=10^{-6}\ m^2/s$]
δ_d The distance from the center of pipeline to the ground surface, m

Indices

°API American Petroleum Institute for oil gravity
S.G Specific gravity
LOSS losses through the inner surface of pipeline
OU Outlet
P Pipe side
o Outer pipe surface
W Wall of pipeline
MAX Maximum
MAOP Maximum allowable operating pressure, Mpa
MeABP Mean average boiling point, °C
Mtpa Million tonnes per year
en Environment
EPS Expanded Polystyrene
fr Friction
P_{r} Prandtl number

GR Ground surrounding the pipe
H.Sta.0 Inlet heating station
i Inner
in Inlet
ins Insulation side

I. INTRODUCTION

Heavy crude oil pipelines are the main source of our energy supply. Every day, all countries use millions of gallons of crude oil to support their daily lives. The pipelines are the safest method, most efficient and economical ways for transportation this natural resource. Heavy oil or petroleum product transmitted by pipeline reaches its destination safely more than 99.999% of the time. In addition, most incidents do not impact the public or the environment, with 71% of incidents in 2015 occurring and contained wholly within an operator's facility, **Zhang al et, 2010**.

Once instill the pipeline system, it's difficult to improve the pipeline and wasn't capable of development or change in the type of fluid required to be transported. So during the building design stage of the infrastructure, the requirements of the future must be taken into account at the same time if there are many possible scenarios for the pipeline system usage in the future such as any change in a capacity required or transported oil . More than over construction model must be confirmed to optimize the capital signatures of operating to cover any potential modification, **Chakkalakal , 2014** .

Some further pumping stations must be installed, for the requirement of the change in the pipeline system. Continuous heating techniques, such as the pipeline model , where the skin-effect electrical heating system used the also need significant infrastructures as the auxiliary gas pipeline, power generation stations, and the special construction of the pipeline, **Chakkalakal , 2014** .

Obviously, there are many probabilities for initial thermal improvement and gradual readjustment, and the best procedure can only be found with a detailed techno-economic analysis depended on the probability of change in oil quality and to what span will become heavier. Some general noticing can be obtained, the main restriction of heating techniques that focused on fired Heaters or heat exchangers. These technologies need additional instrumentation for new heating stations and infrastructure as piping, steam generators, pumps, and power stations, greatly modifications in the existing pipeline structure which can lead to more pressure drops and friction due to the increase in viscosity which resulting from changing the transported oil to the heaviest or increasing the capacity required , **Dunia , 2012** .

The development of the single and the multi-point heating procedure can be performed by the addition of heat adding that would offer a potential alternative to the techniques of the cold reduction in drag or the installation of new pumping or heating stations. These achievements can be obtained by the heating techniques that need to feature low impact on existing infrastructure and be easy to instilled, dismantling, and improve. These requirements also can be performed by a unit's construction and installation, with flexible heat addition and minimal capital cost. The ability to use a variety of fuels at high efficiency, to give perfect performance over a wide heating range, and be simple to control are additional demanded features, **Kulikov, 2014**.

Porsin, 2015 , observed the direct surface heating of the pipeline by using flameless catalytic heating that fit the demands in retrofit the pipeline system to cope with transporting of heavier oils, because of its ability to be wrapped around' existing pipelines and low costs of installation and ease of maintenance. There are constructed for easy gradual addition or removal of heat and high operating efficiency. The evolution of such a technique would give a good thermal procedure for improving the pipelines for transporting heavier oils.

Literature review for thermal improvements of the pipeline system to cope with transporting heavier oil

Dunia et al, 2011 , performed a study for developing the pressure and temperature profiles for transport heavy oil via pipelines with a simulation under a variety of external boundary conditions they used Method of Lines with Control Volumes ***MOLCV*** to transform a system of partial differential formulas into a system of ordinary first-order differential formulas in cylindrical coordinates and because of the variation in physical and thermal property, the momentum and energy equations applied for the flow of the heavy oil. Their result showed the pressure drop profile due to the boundary conditions, and the weather forecast during the process of heavy oil transportation through the pipeline.

Sheng et al, 2010 and **Zhang et al, 2010** presented models to study the heating losses from underground pipelines to the environment. Nevertheless, those were mathematically costly and more suitable when the main subject of the study was the effect of a hot pipeline on the surroundings as presented in [**Wang et al ,2008** , **Zhang et al ,2010)**] .

A mathematical model was performed by **Zhang et al, 2010** to study the heat transfer and oil flow of a buried hot oil pipeline under normal operation. With certain acceptable assumptions and some derivative governing equations for the thermal analyses. Numerical analyses are performed in a wide range of operating conditions, which covered 5 months with flowrates ranged from 15,007 to 27,451 tons/day and the temperatures at outlet were varied from 40.6 to 64.8 $^{\circ}$C. The in site measured data were provided for comparison with the calculated results. This model proposed to perform a numerical analysis to simulate the heat transfer and oil flow of buried hot crude oil pipelines, and to analyze a number of effective factors as *the inlet temperature, the hydraulic loss between every two heating stations and the temperature of the soil field around the pipeline* on the temperature distribution of oil along the pipeline.

The most economical method to transport large amounts of oil through long distances was the pipelines systems that depended on the pressure drop ΔP due to friction, and the elevation of the ground was the main term must consider entire the hydraulic design of the pipelines, the main important variables in the design include transmission capacity, operating temperature, environmental conditions, and the future expected for the oil physical properties, **Arnold, 2000**.

The changing of viscosity due to the oil temperature variation was the main variable for design procedure, to calculate the diameter of the pipeline, the number of pumping stations and their location. The requirements of pumping power for the system and also the capital and operating costs, when the oil temperature decreased. The pressure drop due to raise in friction due to the increase in viscosity, and reduction in capacity, unless the case of very lower transmission capacity [flowrate] for high viscous oils, **Guevara, 1998** . The pipeline transmission capacity, Viscosity, the temperature of transported oil, and the heat losses along the pipeline are the main variables that can specify the maximum distance between pumping stations. The pipelines located in a cold region, are seasonally or permanently exposed to an extremer cold environment. Under those conditions, viscosity rises because of imperceptible cooling along the pipeline, and usage of drag reduction methods may be required for high viscosity oils, **IEA, 2013** .

Martínez, 2011 and **Saniere, 2004** observed the main technologies for the reduction in drag to minimize the oil viscosity. Other methods used for viscosity reduction represented in heating, dilution, core annular flow, and water emulsion. Emulsion and dilution are obtained adding more than 30 percent of water volume or other diluents to minimize the viscosity of the oil, which minimize oil capacity and need more auxiliary facilities. Other methods, such as core annular flow, internal coatings, and reduction in drag, represent more efficient techniques for transporting cold flow but are still expensive and may raise stability issues or field application difficulty depending on the contents of the oil.

On the other side, heating or thermal techniques are most effective and permit fully using the pipeline capacity to transport oil, but need continuous heat added. The Procedure of heating depended on preserving the high temperature at which oil is produced and inserted into the pipeline by using insulation (passive strategy, as insulation layers) and, in most cases, reheating in another point is needed as existing heated pipelines in Alaska , **Saniere, 2004** and Chad-Cameroon pipeline [**Dehkissia,2004** and **Dunia, 2012**] both systems have heating at pumping stations but in Mangala pipeline in India which have continuous heating along the pipeline length, **Chakkalakal, 2014** .

Sheng, 2010 , presented a case of a cost and long un-heated pipeline via remote sites seasonally exposed to high cold conditions and constructed to transport light oil. The main task concentrated to develope pipeline system that can transport the same high capacity for heavier oils. There is a difficulty in the prediction of the changes in oil quality during the lifetime of a pipeline that is typically designed. So, if using more viscous oils, expected problem in the existing pipelines that originally designed light oil, and occur a blockage during the transporting process. In this study, a possible procedure was performed to convert the transmission process through the pipeline from light oil to heavier quality. The main challenge in this improvement process is the prediction of the reduction in capacity arising and determine if drag reduction technology needs to be improved. These result in instilling a new system to the existing pipeline with more additions into the capital cost, which that an unavoidable to perform the thermal improvement.

The design and improvement processes of the pipeline infrastructures was performed by modeling analysis by **Guevara, 1998** was also enabled in the control of the heating systems to guarantee the flowability and prevent blockage problems . Also presented a synchronized solution of momentum and energy balance equations for evaluating the variation of temperature and pressure drop along the pipeline length, **Vianna, 2013**.

For exact prediction of these variations, it is important to consider the changes in the oil properties to determine heat losses, according to the boundary condition associated with pipeline system (underground, subsea, over-ground), **Dunia, 2011**. The constraints of temperature to be considered during the heating systems construction, **Arnold, 2000**. These constraints represented in limitation of top temperature that determined by vapor pressure consideration (to avoid partial vaporization at hot spots and avoid the flashpoint of the transmission oil) or by the maximum allowable temperature of the pipe wall material and minimum temperature limit that determined by maximum viscosity of transported oil or by the wax appearance temperature if the oil also has the problems of formation the deposits of wax, **Aiyejina, 2011**.

Mathematical analysis

In this study, a thermo-hydraulic analysis of an underground, insulated pipeline uses to study a realistic pipeline section. The effect of oil quality included, and further thermal improvement options that include inlet heating, intermediate single and multiple heating are analyzed. The trade-off between the reduction in capacity and the needed heating is quantified, and optimum locations of the heating stations are also obtained.

In summary, this optimization problem can be described as follows …

i. As shown in table 1&2 , the given factors include:

1- Pipeline geometry and operating conditions
2- Heavy oils properties at 40 $^{\circ}$C according to the experimental date presented in ASME (D445).
3- Inlet and outlet condition of the oils in the pipeline where inlet temperature can determine by optimization analysis for the heating process constrained by flash point and pour point of the oil and guarantee the oil fluidity during the transportation process through the pipeline. The inlet and outlet pressure of the oil which constrained by the maximum operating pressure of the pipeline.
4- Thermal conductivity of pipeline, insulating material, and the outlet temperature.

ii. Factors to be determined include:

1- The physical properties of the heavy oils to be transported through the pipeline, and the pipeline needs for thermal improvement to perform this transportation process. The outlet temperature was determined by using Sukhov formula in **eq. 28** at x=L.
2- For each heavy oil: maximum transported length with and without heating at the inlet and the reduction in transportation capacity without overcoming the constraints of maximum pressure drop, which is determined by the maximum allowable operating pressure of the pipeline *MAOP* .
3- The variation of temperature, viscosity, and pressure drop of oils in each case of thermal retrofits, *as shown in Fig.6* are calculated.
4- The variation of the percentage of reduction in transmission capacity with the increase in temperature ΔT due to heating stations in each case of thermal retrofits, *as shown in Fig.6* are obtained.

iii. The solution of the model effectively ,the following assumptions and given parameters are illustrated in Table 1 , 2 & 3 :

1- The ambient condition is taken according to the climate in Egypt.
2- The inlet temperature range is to be confined between the flashpoint and pour point of the oil to reduce the viscosity in the operating range, which guarantees the oil keeps on its fluidity case and avoid it is freezing inside the pipeline.
3- The flow of incompressible Newtonian fluid in a round pipe has been assumed (Mazut for this case), three different regimes for the oil flow through the horizontal pipeline were identified, Regime I (laminar flow, where Re<2000), Regime II (transient flow, where 2000<Re<4000), and Regime III (turbulent flow, where Re>4000). According to the value of the Reynolds number and type of regime, the friction factor is determined.
4- The pipeline under study has a diameter of 200 mm, used currently for the transport of light oil at a flow of $\dot{m}_{Max}$ = 8.502 Mtpa to keep the pressure under the maximum allowable operating pressure MAOP.

Mathematical model

In this section, a mathematical model presented for this problem is an fminsearch model, Appling by a Matlab solver to obtain the solution. The minimization of the reduction in heavy oil transmission capacity and maintaining the original pipeline transmission capacity is the main objective of the thermal modification for pipeline improvement.

1. Objective functions

$$\min_{x}[\%m^{\bullet}_{RED.}(x,\rho(x))] = \sum\left(\frac{m^{\bullet}_{n}-m^{\bullet}_{R}}{m^{\bullet}_{n}}\right) \quad (1)$$

The objective functions of **eq. 1** aids to minimize the total percentage of capacity reduction in the pipeline when transport light oil [oil (1)] by adding heating stations in some sites along the pipeline length to improve it to equivalent with the transporting of heavier oils, that's because the number of heating station predicted according to the value of total percentage of capacity reduction $\%m^{\bullet}_{RED.}$.

Where R indicated to the pipeline after thermal improvement , these are used to predict the reduction in capacity percentage after the thermal improvement $\%m^{\bullet}_{RED.}$ from this minimization process in % which taking into consideration the variation of density **ρ** along the pipeline and local position inside the pipeline **x** .

2. General Formulas

a- The mass flow rate **m•** can predicted as following:

$$m^{\bullet} = \pi R^{2}_{w,i}\,\rho\, V \qquad (2)$$

By assuming the heavy oil flow was turbulent, the physical properties of the oil can be determined by using API relationships as function of the parameters of the oil characteristic as [°API , kinematic viscosity at 20 ºC] according to the experimental data illustrated in ASME code, local bulk temperature and mean average boiling point MeABP , **M.R. Riazi, 2005** .

b- The energy balance and local heat flux through the pipe wall are recognized as:

$$q_{w}(x,r) = \left(-K_{i}\frac{\partial T_{w}(x,r)}{\partial r}\right) \quad ,\forall x \in (0,L)\,, r \in (R_{w,i}, R_{w,o}) \qquad (3)$$

Then, we conclude:

$$q_{tot} = \frac{\Delta T}{\sum R} = \frac{\left((T_{ins}(x)|_{r=r_{ins,o}} - T_{s}\right)}{\sum R_{tot}} = \frac{(T_f - T_p)}{R_p} = \frac{(T_p - T_{ins})}{R_{ins}} \quad ,\forall x \in (0,L)\,, r \in (R_{w,i}, R_{w,o}) \quad (4)$$

Where

$$R_{tot} = R_{soil} + R_{ins} + R_{p} \qquad (5)$$

$$R_{soil} = \frac{\ln\left(\frac{\delta_d}{r_1}\right)}{2\pi L K_s} \quad ,R_{ins} = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi L K_{ins}} \quad , \quad R_p = \frac{\ln\left(\frac{r_1}{r_0}\right)}{2\pi L k_i} \qquad (6)$$

c- The outside surface temperature of pipeline T_p can be obtained as following:

The heat transfer to the surroundings by three major modes of conduction, convection and radiation , **Rohsenow et al, 1998_** and at steady-state conditions the internal and external heat flows are identical, from that the outside surface temperature of pipeline T_P can be calculated from the fourth-order equation as following: **Gorman et al , 2013**

$$(\epsilon\sigma F_v)T_P{}^{4} + (C_D + h_{cv})\,T_P = C_D T_f + (h_{cv} + \epsilon\sigma F_v)T_a \qquad (7)$$

Where F_v is the gray body view factor [F_v = 0.59] which indicated to the type of outside pipeline surface cladding , **ϵ** is the emissivity, [ϵ = 0.066] for polished steel and **σ** represented the Stefan-Boltzmann Constant in $W/m^2.K^4$, [$\sigma = 5.6703*10^{-8}$ $W/m^2.K^4$] ,and C_D is a constant can calculated as following :

$$C_D = \frac{r_0\; h_{cv}\, h_{cd}}{r_1\, h_{cd} + r_0\; h_{cv}} + \; h_{cd} \qquad (8)$$

Where

$$h_{cv} = 0.023\,\mathrm{Re}^{0.8}\,p_r^{\,0.4}\,\frac{k_i}{2\,r_o} \quad , \quad h_{cd} = \frac{k_i}{r_1 \ln(\frac{r_1}{r_0})} \quad (9)$$

d- The outside surface temperature of insulation, T_{ins} **Rathore, 2005**

The outside surface temperature of insulation can be obtained as following:

$$\mathrm{T_{ins}} = \mathrm{T_p} - \frac{R_{ins}(\mathrm{T_f} - \mathrm{T_p})}{R_p} \quad (10)$$

e- Average heat transfer coefficient along the pipeline

The inside and outside heat transfer coefficient along the pipeline can calculated as following:

From Ditttus- Boelter equation, the convection heat transfer coefficients for the inside surfaces of piping system h_i can be obtained by Rathore, 2005

$$h_i = 0.023\,Re^{0.8}\,p_r^{\,0.4}\,\frac{k_i}{2\,r_o} \quad (11)$$

$$P_r = C_p\,\frac{\mu}{K} \quad (12)$$

The convection heat transfer coefficients from the outside surfaces of piping system h_o as given by Rathore, 2005 can be written as :

$$h_o = 11.59(\frac{1}{d_{ins}})^{0.2}(\frac{2}{T_{s,a} + T_{ins}})^{0181}(T_{s,a} - T_{ins})^{0.266}(1 + 2.86V_{air})^{0.5} \quad (13)$$

Where $\mathbf{d_{ins}}$ is the outer diameter of the insulation material in m , $\mathbf{d_{ins}=2*r_2}$, T_{ins} is the outside surface temperature of pipeline in °k , $T_{s,a}$ is the daily mean temperature between the soil and outside air in K as mentioned in **Frank ,2018** and V_{air} is the outside air Velocity .

a- The overall heat transfer coefficient, U_{EX}

Can be predicted as follow,

$$U_{EX} = (\frac{1}{R_{p,ins} + (x/k_{ins})}) \quad (14)$$

$$R_{p,ins} = \frac{1}{h_i A_i} + \frac{\ln(\frac{r_1}{r_o})}{2\pi L K_i} + \frac{\ln(\frac{r_2}{r_1})}{2\pi L K_{ins}} + \frac{1}{h_{o,ins} A'_o} \quad (15)$$

3. Model constraints

These model consist of four spatial domains

1- Pipe-side domain where the temperature and pressure are fixed at the inlet at x = 0

$$T|_{x=0} = T_{ins} \quad (16)$$

$$P|_{x=0} = P_{ins} \quad (17)$$

$$q_w|_{r=R_{w,i}} = q_{loss} \quad (18)$$

2- The temperature between the wall-insulation domains which assumed to continuity in the radial coordinate

$$T_w|_{r=R_{w,o}} = T_{ins}|_{R_{ins,i}} \quad (19)$$

3- For the heat flux through pipe wall and insulation

$$q_w|_{r=R_{w,o}} = q_{ins}|_{r=R_{ins,i}} \quad (20)$$

4- For the heat flux through insulation and transferred to environment domains.

$$q_{en} = q_{ins}|_{r=R_{ins,o}} \quad (21)$$

5- Numerous- sections of pipeline

Pipeline divisions connected in series to indicate intermediate operation, such as pumping, heating, or flow divisions.

This study, discussed only the increasing in temperature by intermediate heating stations. The pipeline section connections ***J-1*** and ***J*** is predicted as the following:

$$T_{ou\,J-1} + \Delta T_{J-1} = T_{ins\,J} \quad (22)$$

$$P_{ou\,J-1} = P_{ins\,J} \quad (23)$$

$$m^{\cdot}_{J-1} = m^{\cdot}_{J} \quad (24)$$

Where **j** is the number of pipeline section, ΔT_{J-1} is the inlet oil temperature due to intermediate heating raise between pipe sections ***J-1*** and ***J***, **ou** subscription indicated to outlet of pipe conditions.

4. Viscosity-Temperature formula , Wai-Lin, 2004 , Riazi, 2005

The Walther equation used to predict the numerical values of dynamic viscosity at specific Temperature.

$$\mathbf{lin}[\nu(x) + C)] = e^{[A + B\,\mathrm{lin}\,(T(x))]} \qquad (25)$$

Where ***A, B, C*** are constants depending on the oil nature, ***ν (x)*** is the local oil kinematic viscosity in cSt, ***T(x)*** is the local oil temperature in K and C=0.6 for viscosities above 1.5 cSt and varies slightly with smaller viscosities.

This equation depends on the experimental data for the kinematic viscosity between two-reference temperature 40℃ and 100℃ are given in ASTM (D445, D396, and D2270-93). The values of kinematic viscosities ***ν*** for the heavy oil at temperatures 40°C and 100 °C, are used to find constants ***A*** and ***B*** from eq. 25.

5. API Gravity formula , Liu al et , 2018

° API gravity is an expression of the oil density that indicated to the density of the oil at *20 ºC* which predicted from specific gravity, where specific gravity is the ratio between densities of heavy oil at *20 ºC* and water density and *20 ºC* represented the reference temperature that used to predict **eq. 26** according to ASME code.

The °API gravity and specific gravity relationship is as the following:

$$°API = (141.5/S.G)-131.5 \qquad (26)$$

$$S.G = \frac{\rho_{20}}{\rho_W} \qquad (27)$$

Where ρ_{20} is the density of oil at *20 ºC* in kg/m^3 which used in **Eq. 31** to predict the density of the oil at any temperature, and ρ_w is a water density in kg/m^3.

6. Temperature drop formula , Guoyu al et ,2010

The heating stations concept for heating heavy oil to guaranty its fluidity during transmission via pipeline. The Sukhov formula **eq.28** from **Guoyu al et ,2010** is used to calculate temperature distribution along the length of pipeline, the local oil temperature T(x) can be predicted as following:

$$T(x) = (T_s + b) + (T_{in} - (T_s + b))e^{-\alpha x} \quad ,\forall x \in (0, L) \qquad (28)$$

$$\alpha = \frac{U_{Ex}\pi D}{m^{\bullet} C_C} \quad , \quad b = \frac{gI}{\alpha C_C} \quad , I = \frac{H_{loss}}{x} \qquad (29)$$

Head loss is express by Darcy-Weisbach equation as following: Manning, 1991

$$H_{loss} = \int_0^l \frac{f(x) * V(x)^2}{2gD}\, dx \qquad (30)$$

Where **I** is a hydraulic gradient of oil which is means [the rate of change of oil pressure along the pipeline], **L** is a pipe length in m, **x** is a position on the pipeline at longitudinal direction in m, H_{loss} represent the total head loss along the pipeline in m, ***V*** is mean velocity of the oil flowing through the pipeline in m/sec, and **g** is acceleration of gravity in m/sec^2.

7. Density - temperature formula , Darko, 2006

The model used in this study considers the oil density at **20 °C** as a reference density to obtain the density at any temperature **T** as following:

$$\rho\,(x) = \rho_{20} - (1.825 - 0.001315\,\rho_{20})\,(T(x) - 20) \qquad (31)$$

8. Pressure drop formula, Henryk, 2012

For turbulent can be predicted as follow:

$$\Delta P(x) = \rho(x)\, g\, H_{fr}(x) \quad ,\forall x \in (0, L) \qquad (32)$$

$$\Delta p = \frac{0.8\, m^{\bullet\,2}}{g\, D^5} \int_0^L \frac{f(x)}{\rho(x)}\, dx \qquad (33)$$

Where $\Delta P(x)$ represent the pressure drop distribution along the length of pipeline in pa, **ρ(x)** is the local oil density in kg/m^3, $H_{fr}(x)$ presented the local friction head and f (x) is a local friction factor.

⇒ ***For Turbulent flow (Re>4000)*** **, Petukhov, 1970**

The Colebrook–White formula Used to obtain friction factor, as following:

$$Re(x) = \frac{\rho(x) * V(x) * D}{\mu(x)} \quad ,\forall x \in (0, L) \qquad (34)$$

$$\frac{1}{\sqrt{f(x)}} = -2\, log_{10}\left(\frac{(\varepsilon_R/D)}{3.7} + \frac{5.74}{Re(x)^{0.9}}\right) \qquad (35)$$

Where f(x) presented the local coefficient of friction, **ε** is absolute roughness in m for carbon steel pipe lines [ε_R=0.035 m], and **Re (x)** is the local Reynolds number.

9. The mass flow rate m˙ can prediction , Henryk, 2012

From **Eq. 31** , the relation between the pressure drop and mass flow rate can obtain as following: **Henryk, 2012**

$$m^{\bullet} = \sqrt{\frac{\Delta P * g * D^5}{0.8 \int_0^L \frac{f(x)}{\rho(x)} dx}} \quad (36)$$

10. Mean average boiling point formula MeABP, Liu al et , 2018

The mean average boiling point of the oil must be determined to constraint the maximum limit of heating the oil to avoid its evaporization; this temperature can be calculated as following:

$$MeABP = \left(\frac{MABP + CABP}{2}\right) \quad (37)$$

$$MABP = \sum_{i=1}^{n} M T_B \quad (38)$$

$$CABP = \left(\sum_{i=1}^{n} V_F T_B^{\frac{1}{3}}\right)^3 \quad (39)$$

Where T_B refers to the oil boiling point, M is the molar fraction of the oil, and V_F is the oil volume fraction.

11. Heat duty formula

The amount of heat needed to increase the oil temperature by ΔT, can be calculated as follows:

$$q = m^{\bullet} c_p \ \Delta T \quad (40)$$

Where ΔT indicated to the temperature change in the oil normally calculated as the difference between oil temperatures before and after heating system in °C.

Case study: [modification of an existing pipeline to transport heavier oils**]**

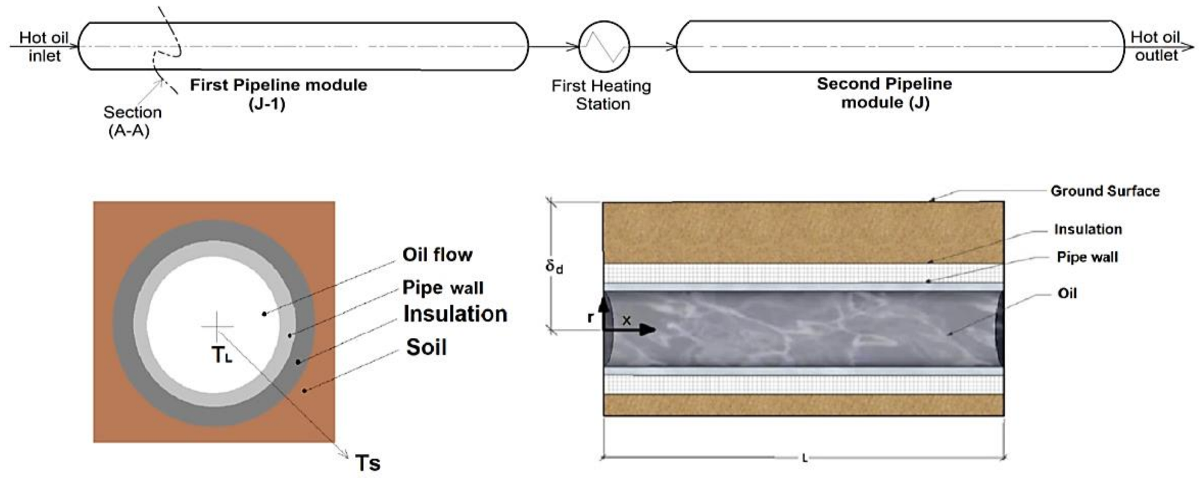

Fig 1.Cross section area in unheated insulated underground pipeline, pipeline module and modifications

The mathematical model was implemented in **MATLAB R2013a** as a model solver. The case of this study performed for an unheated underground Pipeline designed to transmit light oils insulated by **EPS** material with thickness **X =0.1304 m** , which modification to transport heavier oils [mazut] from one end to the other have total length L= 100 km, OD = 200 mm , *as shown in figure (1), table 1 , and table 2*. Consider a situation where a pipeline is limited in throughput due to maximum allowable operating pressures MAOP=11 Mpa. Let us assume the pressure drop ΔP_{MAOP} in this MAOP limited pipeline is 9.16 Mpa at throughput 8 Mtpa, **E.Shashi, 2014** .The analysis performed to study the temperature, viscosity and pressure drop profile of different heavy oils along each pipeline section in order to determine the thermal modifications that guaranty the continuity of flow of heavy oils along this pipeline . This study allowing to added or removed new elements to improve the performance of pipeline without effecting on existing element structure and without needing a global element or renaming the node.

II. RESULTS AND DISCUSSION

In this study, the pipeline considered is recently constructed to transport light oil needs modification to be suitable for transporting heavier oil from the port to the factory. The physical properties of different oils used in these study at reference temperature **40 °C** taken from these references **Sheng et al,2010** ,**Yang et al , 2010** , *as shown in table 3* where the oil currently transported into pipeline known as **oil (1)** which is a very light oil with very low viscosity , and a **pour point** equal **-36 ºC** , **Platts, 2010** .

The inlet temperature of the oil to the pipeline is 10 ºC when the transportation occurs in cold conditions was allowed. Despite the extreme cold conditions in winter 5º C and below .the original design of insulation for **oil (1)** regards to prevent extreme cooling of the oil, which could lead to complete blockage in the pipeline and stopping the flow.

The pipeline section between two pumping stations is considered of length $\mathbf{L_{oil(1)} = 100\ km}$. this data was important for the exact determination of the pressure drop, such as elevation of the ground, estimation of the maximum allowable pressure drop $\Delta \mathbf{P_{MAOP}}$ by using the proposed model with the properties of the **oil (1)** , *as shown in table 3*.

The evaluation of oil as a result of gradual change in quality potential from **Light oil** [**oil (1)]** to other **four heavier oils** is very important because it's necessary to rehabilitate this pipeline to transport heavier oil, which is **mazut**, where mazut very heavier than Light oil. Table 3 illustrates the properties of oils at 40 ºC. Guarantee is also achievable for the maximum capacity of heavy oil transported through pipeline.

The variation of kinematic viscosity with temperature for different oils which predicted from **eq. 25** and the variation of density predicted from **eq. 31,** *as illustrated in table 4.* Moreover, refer to the **highly viscous oils** from [**2 to 5**] are all much more viscous than **Light oil** at low temperatures. Where the viscosity of **Light oil** [oil (1)] decreases from **8.376 to 5.648 cSt** and density decreases from **868.71 to 798.6 kg/m^3** with temperature increases from **5 to 100 ºC**. For **oil (2)**, the viscosity decreases from **73.01 to 1.794 cSt** and density decreases from **919.084 to 859.35 kg/m^3** with temperature increases from **5 to 100 ºC**.

With the temperature decreases from 5 **to 100 ºC**, the viscosity of o**il (3)** decreases from **147.62 to 3.443 cSt**, and density decreases from **942.63to 885.89 kg/m^3** when temperature increases from **5 to 100 ºC**. For **oil (4)**, the viscosity decreases from **215.047 to 5.034 cSt** and density decreases from **954.87 to 899.696 kg/m^3** with temperature increases. For the heaviest oil, which was **mazut** [oil (5)] its viscosity decreases from **359.2 to 8.88 cSt**, and density decreases from **929.22 to 870.78 kg/m^3**, *as shown in table 4.*

Initially, for the heaviest oils, the oil must be heated before pumping at inlet pipe section and considered the capacity reducing because of the friction that produced from high viscosity that result from changing the light oil which transported to heavier. After that, the pipeline modification represented in heating the heaviest oils at the middle of the pipeline .So, heating stations must be added to decrease the reduction in pipe capacity for the heaviest oils transportations. The maximum oil viscosity can transported through the pipeline was the only constraint of temperature considered and given by the design of the pipeline, which is fixed at **80 ºC** to keep the oil since the temperature range is **normally 60–100 ºC** that give a limitation in the increasing of temperature to avoid the flash point of the transported oils .

1- Effects of the variation of viscosity and inlet temperature of the oil on the pipeline capacity transmission

The **Light oil** can be transported over long distances without needing any additional heating, because of its lower viscosity. And the pressure drop for it over **100 km** length which predicted from **eq. 33** varies from **0 to 9.16 Mpa**, *as shown in figure (4).* For the heaviest oils, the friction along with the pipeline increases, and the flow becomes so cold due to increase the temperature drop, so that the oil flowability through the pipeline without re-heating is no longer possible and these depend on the maximum distance achievable for the given pressure drop at maximum allowable operating pressures ,MAOP is $[\mathbf{L}_{(\Delta \mathbf{P_{MAOP}})} = \mathbf{100}\ \boldsymbol{km}]$.

The inlet heating temperature of each oil restricted by the pour point as a minimum limit and the flash point as a maximum limit, considered the inlet temperature of light oil **[oil (1)]** equal (10 °C), **oil (2)** equal (60°C) and for **oil (3)**, **oil (4)** and **oil (5) [MAZUT]** equal (80°C), these values guaranty the liquidity of each oil without reach to its flash point limit.

The pressure at the inlet is assumed to be constant. The preferred option is a thermal improvement by increasing the inlet oil temperature before pumping, given that suitable facilities are likely to exist already or to be easily installed at the extraction and pumping terminals. *For case (1) in table 5* , for the given $\Delta \mathbf{P_{MAOP}}$,and cold flow, as a result of the drag effect and high viscosity of each oil , the pressure drop along the distance of pipeline increased and that makes the oil reach the maximum value of pressure drop $\Delta \mathbf{P_{MAOP}}$ before arrived the end of pipeline at a length named the maximum achievable distance $\boldsymbol{L}_{(\Delta P_{MAOP})}$, which leads to exceeding the value of the maximum allowable operating pressures MAOP can cause a blockage in the pipeline and stopping the flow.

By using **eq. 31** and take the value of $\mathbf{\Delta P_{MAOP}}$ and maximum capacity which is given in table 1 we can predict the maximum distance achievable by each oil illustrated in table 3 as follows: the maximum distance achievable by **oil (2)** flow with inlet temperature 60 ºC and no heating during the transportation is become only $\mathbf{L_{(\Delta P_{MAOP})}}$ =96.4 km , and the maximum distance achievable with inlet heating to 80 ºC by **oil (3)** is $\mathbf{L_{(\Delta P_{MAOP})}}$= 92.8 km , $\mathbf{L_{(\Delta P_{MAOP})}}$ =93.4 km by **oil (4)** and $\mathbf{L_{(\Delta P_{MAOP})}}$=89.2 km by **Mazut [oil (5)]** , *as shown in case(1) in table 5.*

For **oil (2)**, the temperature at the inlet must be raised to the maximum value as 60 ºC to preserve 100% in the transmission of capacity [throughput], *as shown in case (2) in table 5*. The first thermal improvement solution represented in a heating station at the inlet of the pipeline named H.Sta.0, for heat station 0 to enable oils transportation at maximum production [Throughput] for oils with a lower viscosity or equal to that of Oil (2). The corresponding temperature, viscosity, and pressure drop profiles achieved by this thermal improvement are *shown in figure (2), figure (3), and figure (4),* respectively.

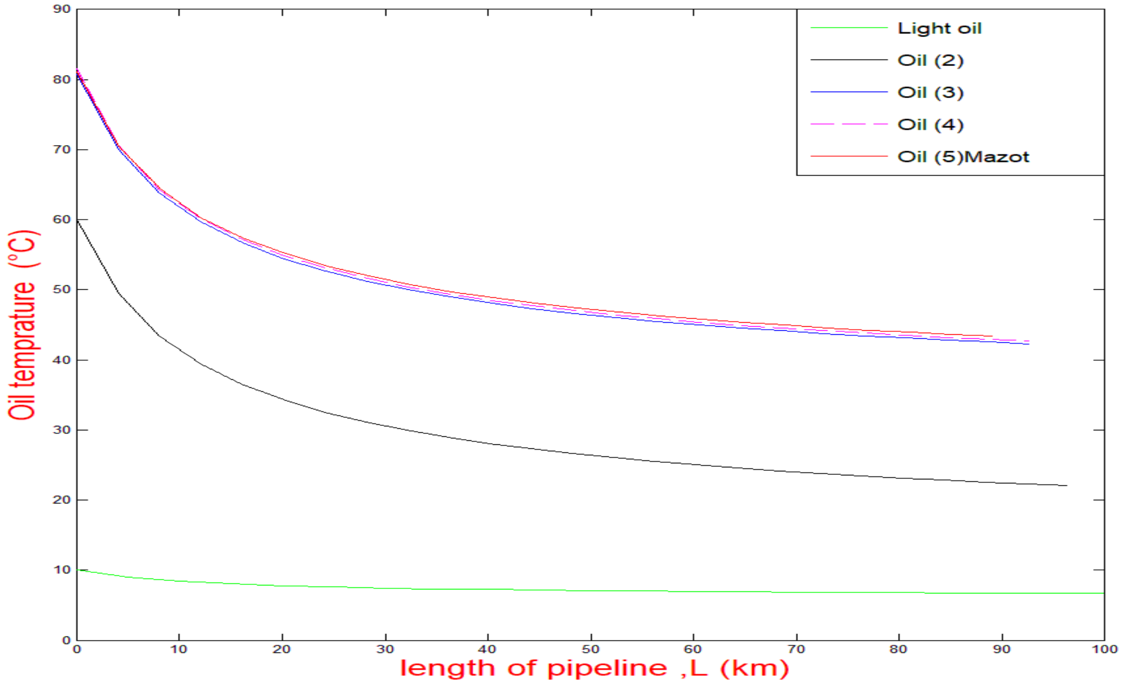

Fig 2.Temprature distribution along the pipeline

The inside , and outside heat transfer coefficient along the length of the pipeline h_i and h_o , which calculated from **eq.11** and **eq.13** , on the oil, inside wall and oil temperature profile T_p , T_f and T_{ins} for each oil type which are calculated from **eq.7** ,**eq.28** and **eq.10** , respectively the effect on overall heat transfer coefficient $\mathbf{U_{EX}}$ also has been studied. It can be calculated using **eq.**14 for thick-walled pipes. A high overall heat transfer coefficient will cause the temperature to drop rapidly towards ambient temperature. Therefore, the overall heat transfer coefficient is the most important factor in the temperature profile development.

For **light oil** , the convection heat transfer coefficients for the inside surfaces of piping system $\mathbf{h_i}$ is decreased from $\mathbf{715.23\ to\ 941.11}$ **W/m²**.**°k** , the convection heat transfer coefficients for the outside surfaces of insulated the piping system $h_{o,ins}$ is decreased from **7.342 to 4.42** $\mathbf{W/m^2.°k}$, and the overall heat transfer coefficient $\mathbf{U_{EX}}$ is decreased from **22629.99 to 22319** $\mathbf{W/m^2.°k}$, by substituted in **eq.7** , **eq.28 , and eq.10** , the inside pipe wall temperature T_p which decreases from **6.02 to 5.076 ºC** , oil temperature T_f ,which decreases from **10 to 6.667 ºC** , and finally the outside insulation surface temperature T_{ins} which decreases from **2.96 to 2.57 ºC**.

For **oil** (2) , the convection heat transfer coefficients for the inside surfaces of the piping system $\mathbf{h_i}$ is decreased from **1199.64 to 232.31 W/m²**.**°k ,** the convection heat transfer coefficients for the outside surfaces of the insulated piping system $h_{o,ins}$ is decreased from **8.63 to 3.67** $\mathbf{W/m^2.°k}$, and the overall heat transfer coefficient $\mathbf{U_{EX}}$ is decreased from **22707.16 to 22651.81** $\mathbf{W/m^2.°k}$, by substituted in **eq.7** , **eq.28 ,and eq.10** , the inside pipe wall temperature T_p ,which decreases from **21.05 to 20.52 ºC** , oil temperature T_f ,which decreases from **60 to 22.09 ºC** , and finally the outside insulation surface temperature T_{ins} which decreasing from **15.72 to 11.34 ºC**.

For **oil** (3) , the convection heat transfer coefficients for the inside surfaces of the piping system $\mathbf{h_i}$ is decreased from **1167.94 to 284.64 W/m²\.k ,** the convection heat transfer coefficients for the outside surfaces of the insulated piping system $\boldsymbol{h_{o,ins}}$ is decreased from **9.816 to 6.87** $\mathbf{W/m^2.k}$, and the overall heat transfer coefficient $\mathbf{U_{EX}}$ is decreased from **22756.9 to 22578.22** $\mathbf{W/m^2.k}$, by substituting in **eq.7** , **eq.28 ,and eq.10** , the inside pipe wall temperature $\boldsymbol{T_p}$ which decreasing from **31.071 to 20.602 °C** , oil temperature $\boldsymbol{T_f}$ which decreases from **80 to 42.285 °C** and finally the outside insulation surface temperature $\boldsymbol{T_{ins}}$ which decreasing from **18.05 to 13.57 °C**.

For **oil** (4) , the convection heat transfer coefficients for the inside surfaces of the piping system $\mathbf{h_i}$ is decreased from $\mathbf{1069.33}$ **to** $\mathbf{254.84}$ **W/m²\.k,** the convection heat transfer coefficients for the outside surfaces of the insulated piping system $\boldsymbol{h_{o,ins}}$ is decreased from **9.88 to 6.98** $\mathbf{W/m^2.k}$, and the overall heat transfer coefficient $\mathbf{U_{EX}}$ is decreased from **22758.39 to 22582.27** $\mathbf{W/m^2.k}$, by substituting in **eq.7** , **eq.28 ,and eq.10** , the inside pipe wall temperature $\boldsymbol{T_p}$, which decreases from **31.07 to 20.51 °C** , oil temperature $\boldsymbol{T_f}$ which decreases from **80 to 42.564 °C** and finally the outside insulation surface temperature $\boldsymbol{T_{ins}}$ which decreasing from **18.19 to 13.67 °C**

For **oil** (5) , the convection heat transfer coefficients for the inside surfaces of piping system $\mathbf{h_i}$ is decreased from **1086.62 to 237.39 W/m²\.k ,** the convection heat transfer coefficients for the outside surfaces of the insulated piping system $\boldsymbol{h_{o,ins}}$ is decreased from **9.854 to 7.031** $\mathbf{W/m^2.k}$, and the overall heat transfer coefficient $\mathbf{U_{EX}}$ is decreased from **22757.74 to 22583** $\mathbf{W/m^2.k}$, by substituting in **eq.7** , **eq.28 ,and eq.10** , the inside pipe wall temperature $\boldsymbol{T_p}$ can, which decreases from **31.08 to 20.51 °C** , oil temperature $\boldsymbol{T_f}$,which decreasing from **80 to 43.36 °C**, and finally the outside insulation surface temperature $\boldsymbol{T_{ins}}$, which decreases from **18.135 to 13.716 °C**.

Figure (2), figure (3) , and figure (4) shows that the drop in oil temperature which calculated from **Eq. 28 ,** raise in viscosity profile which calculated from **eq.25** , and pressure drop profile along the length of the pipeline , which calculated by taking the drop in temperature and increases in viscosity in consideration from **eq.33** , respectively. through the **100 km** length, the **light oil** [oil (1)] the temperature decreased from **10 to 6.67 °C** , the drop in temperature is 3.333 °C and the oil temperature at the outlet of the pipeline is **6.67 °C** and the **Light oil** viscosity increased slightly from **7.92 to 8.05 cSt** , the temperature of the **oil (2)** decreased from **60 to 22.09 °C** , the drop in temperature is **37.91 °C** and the oil temperature at the outlet of the pipeline is **22.09 °C** and its viscosity increased from **12.605 to 26.83 cSt** , For the **oil (3)** the temperature decreased from **80 to 42.29 °C** , the drop in temperature is **37.72 °C** and the oil temperature at the outlet of the pipeline is 42.29 °C, the viscosity increased from **18.78 to 29.23 cSt** , For the **Oil (4)** the temperature decreased from **80 to 42.56 °C** , the drop in temperature is **37.438 °C** and the oil temperature at the outlet of the pipeline is **42.56 °C** , the viscosity increased from **25.46 to 40.87 cSt** and for **mazut** [oil (5)] the temperature decreased from **80 to 43.36 °C** , the drop in temperature is **36.643 °C** and the oil temperature at the outlet of the pipeline is **43.36 °C** , the viscosity increased from **31.81 to 57.86 cSt** .

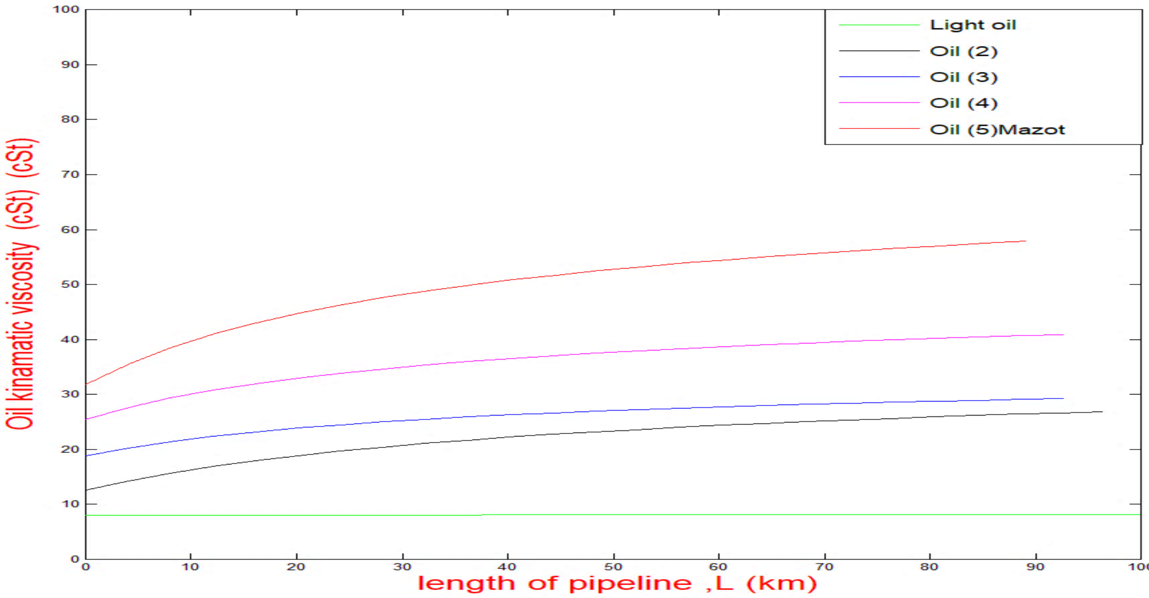

Fig 3.Viscosity profile along the pipeline

For case (2) in table 5 , the most viscous oils as **oil (3)**, **oil (4)** ,and **mazut** inlet heating are not enough and, if no other drag reduction techniques are applied, the only alternative is to reduce capacity to overcome the effect of friction and cover the increase in pressure drop without exceeding the mean allowable operating pressure MAOP . The reduction in capacity, which covers this increase in pressure drop, can calculate from **eq. 33** by using the value of ΔP_{MA}.

Inlet heating is not enough for the heaviest oils with higher viscosities, if no other technologies are applied for reducing the drag. the capacity reduction is the only alternative solution with the maximum inlet heating in **H.Sta.0**. (At maximum capacity, inlet heating to 80 ºC and $\mathbf{\Delta P_{MAOP}}$ **= 9.16 Mpa** , the maximum length $\mathbf{L_{(\Delta P_{MAOP})}}$ that **oil (3)** can be transported is **92.8 km**. the percentage of reduction in capacity that can reduce the drag and cover these increases in pressure drop is **11.62%** equivalent to **1.743 Mtpa** , For **oil (4)**, the maximum length $\mathbf{L_{(\Delta P_{MAOP})}}$ that can be transported is **93.4 km** and the percentage of reduction in capacity that can reduce the drag , and cover these increasing in pressure drop is **13.85%** equivalent to **2.08 Mtpa** and for **mazut** [oil (5)], the maximum length $\mathbf{L_{(\Delta P_{MAOP})}}$ that can be transported is **89.2 km** and the percentage of reduction in capacity that can reduce the drag and cover these increasing in pressure drop is **18.2%** equivalent to **2.73 Mtpa** *,as shown in case(2) in table 5.*

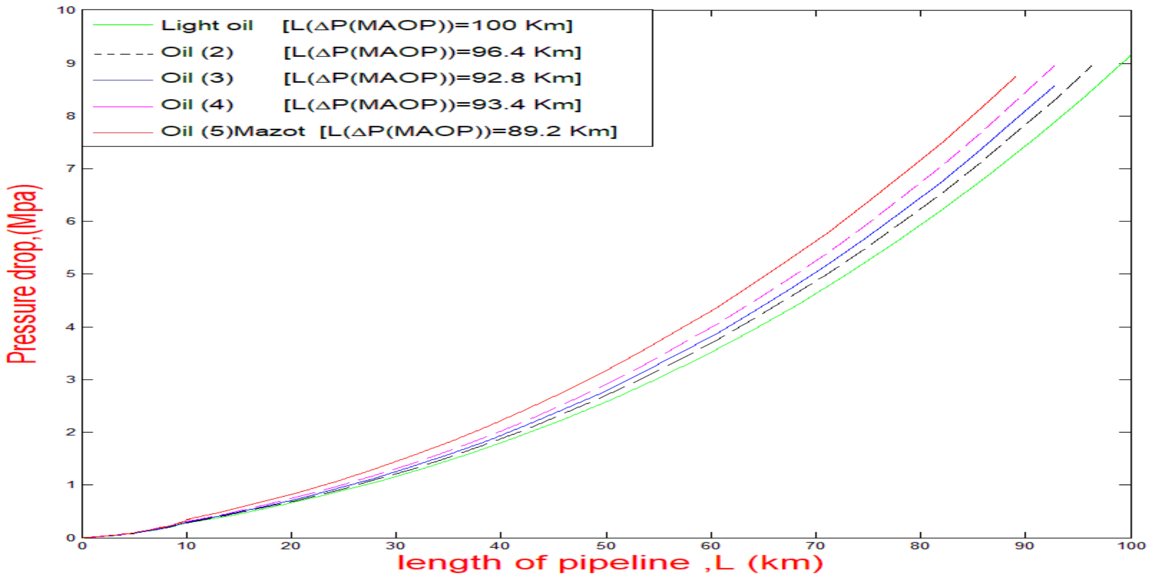

Fig 4.Effect of oil type on the pressure drop along the pipeline

2- **Minimization of the reduction in capacity by using the heating station in the middle of the pipeline section between two pumping station <u>to reduce the effect of drag and maintain the pressure drop at its constraints value</u>**

Because of the reduction in capacity transmitted through the pipeline after replacing the transmission of light oil by heavier oils to overcome the drag effect that results from increasing the viscosity of oil transported through the pipeline, instilling of intermediate heating stations at main locations and increasing the length for which the oil can be transported by decreasing the drag and don't allow the pressure drop in pipeline exceeding the value of pressure drop at a maximum allowable operating pressure of the pipeline. The oil temperature can be increased by the amount of ΔT in each intermediate heating station to make the outlet temperature of the oil not higher than 80 ºC. For the retrofit by intermediate heating, <u>**the variables** discussed</u> to consider these options are *the location of the heating stations, required heat duty* **q** *in each* station, which can calculate from **eq.40,** and *the intermediate heating point's numbers*.

The main objective of the thermal modification is to decrease the reduction in pipeline transportation capacity to maintain the original capacity in which pipeline transportation light oil at constant by heat adding to overcome the drag effect and decreasing the pressure drop as much as possible. The minimization of reduction in capacity [throughput] can be obtained by decreasing heat adding as much as possible because it increases the accounts of additional operating cost and effect on the environment (from the combustion of fuels in heaters, and steam or electricity generation, etc.). Moreover, this should be applicable with a minimum number and capacity of intermediate heating stations, which also increases the capital costs. In this case, evaluate the number of thermal modification options, including the varied amount of heat adding, location, and numbers of heating stations.

Figure (5) represented The probability of the number and locations of heating stations can be instilled and considered in the case studied from [A] to [G] , where L is the length of the pipeline equal to 100 km and L has a fractions refer to the distance between the inlet of the oil and the heating station location.

Where in **case (A)**, the thermal modification represented in locate a heating station H.Sta.1 at distance **L/2** which means that the heating station located at **50 km** from the oil inlet, In **case (B)**, the thermal modification represented in locate a heating station H.Sta.1 at distance **L/3** which means that the heating station located at **33 .33 km** from the oil inlet, In **case (C)**, the thermal modification represented in locate a heating station H.Sta.1 at distance **L/4** which means that the heating station H.Sta.1 located at **25 km** from the oil inlet , In **case (D)**, the thermal modification represented in locate a heating station H.Sta.1 at distance **2L/3** which means that the heating station located at **66.67 km** from the oil inlet , In **case (E)**, the thermal modification represented in locate a heating station H.Sta.1 at distance **3L/4** which means that the heating station located at **75 km** from the oil inlet , In **case (F)**, the thermal modification represented in locate a heating stations H.Sta.1 at distance **L/3** and other at distance **2L/3** which means that the heating station H.Sta.1 located at **33.33 km** and the heating station H.Sta. 2 located at **66.67 km** from the oil inlet ,respectively, and In **case (G)**, the thermal modification represented in locate a heating stations at distances **L/4** , **L/2** and **3L/4** which means that the heating stations H.Sta.1 located at **25km** , H.Sta.2 located at **50 km** and H.Sta.3 located at **75 km** from the oil inlet ,respectively.

Case	L/4	L/3	L/2	2L/3	3L/4	NUMBER OF HEATING STATIONS
A			ΔT_A			1
B		ΔT_B				1
C	ΔT_C					1
D				ΔT_D		1
E					ΔT_E	1
F		$\Delta T_F/2$		$\Delta T_F/2$		2
G	$\Delta T_G/3$		$\Delta T_G/3$		$\Delta T_G/3$	3

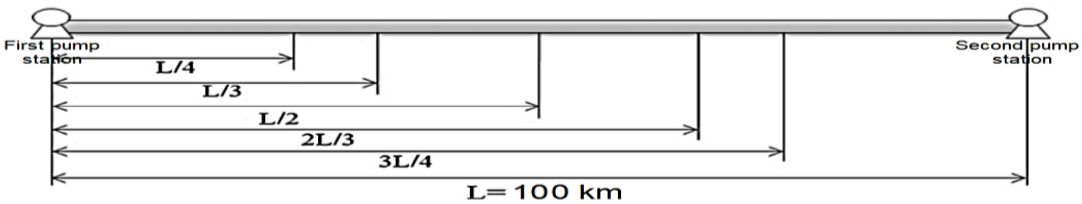

Fig 5.The odds of Locations [A-G] that can instilled the heating stations along the pipeline length to increase the temperature of the heavy oil during transmission

2.1 Single-point intermediate heating as in cases [A, B, C, D , and E]

Firstly, assumed in **[Case (A)]**, the line has single-point heating in the middle. *Figure (6) , figure (7) ,and figure (8)* represented the effects of intermediate heating on the variation of temperature, viscosity and pressure drop for **Oil (4)** in Case (A) , and maximum capacity production. For minimum reduction on pipeline transported capacity [Maximum Throughput] and inlet heating only H.Sta.0, the temperature decreased from **80 to 42.65 ºC**, the viscosity increased from **25.46 to 40.87 cSt**, and the pressure drop changed from **0 to 10.4 Mpa** with maximum transportation length **93.4 km** along the pipeline section between two pumping stations that equal **100 km** where that not cover the constraints of max pressure drop.

For case (A), After instill an intermediate thermal improvement H.Sta.1 in the middle of the line at **L/2** the temperature decreased from **80 to 46.838 ºC** , the viscosity increased from **25.46 to 36.49 cSt** and pressure drop increased from **0 to 2.895 Mpa** where that from the inlet to **L/2** through the length of the pipeline , in the location of heating station H.Sta.1 at point **L/2** , the temperature increased from **46.84 to 80 ºC** , viscosity decreased from **37.58 to 25.46 cSt** and pressure drop increased from **2.89 to 0.368 Mpa** . finally , from **L/2 to L** where the outlet of the pipeline , the temperature decreased from **80 to 46.12 ºC** , the viscosity increased from **25.457 to 37 cSt** and pressure drop increased from **0.3683 to 3.0478 Mpa** , *as shown in figure (6) , figure (7) and figure (8) .*

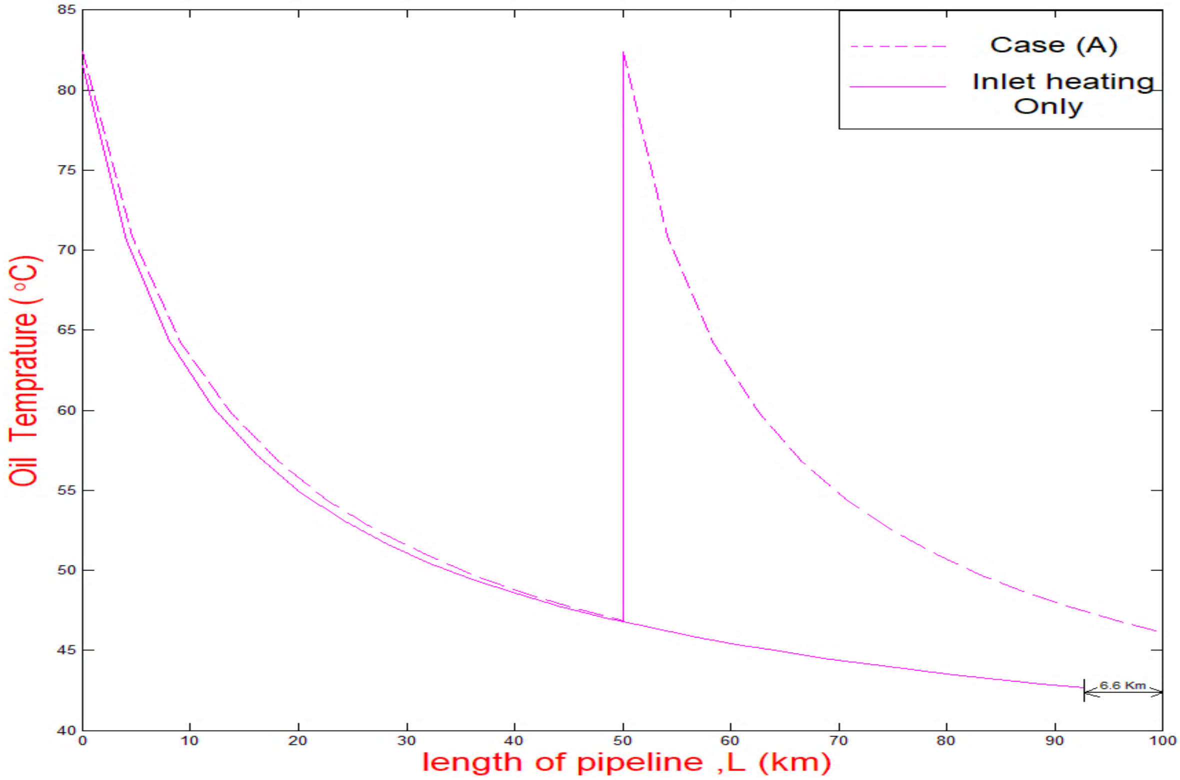

Fig 6.Comparison between temperature distributions of oil (4) transmitted along the pipeline at single heating point [case (A)] and maximum throughput

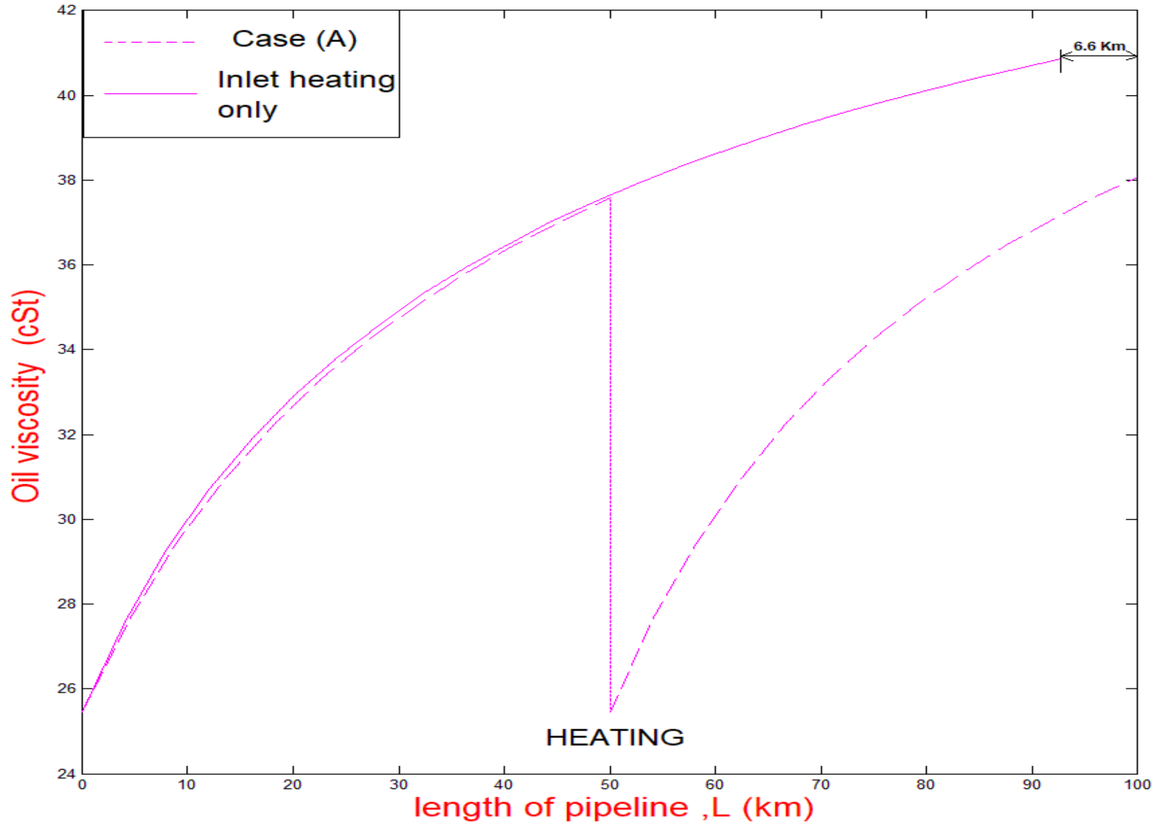

Fig 7.Comparison between viscosity distributions of oil (4) along the pipeline with single heating point [case (A)] and maximum throughput

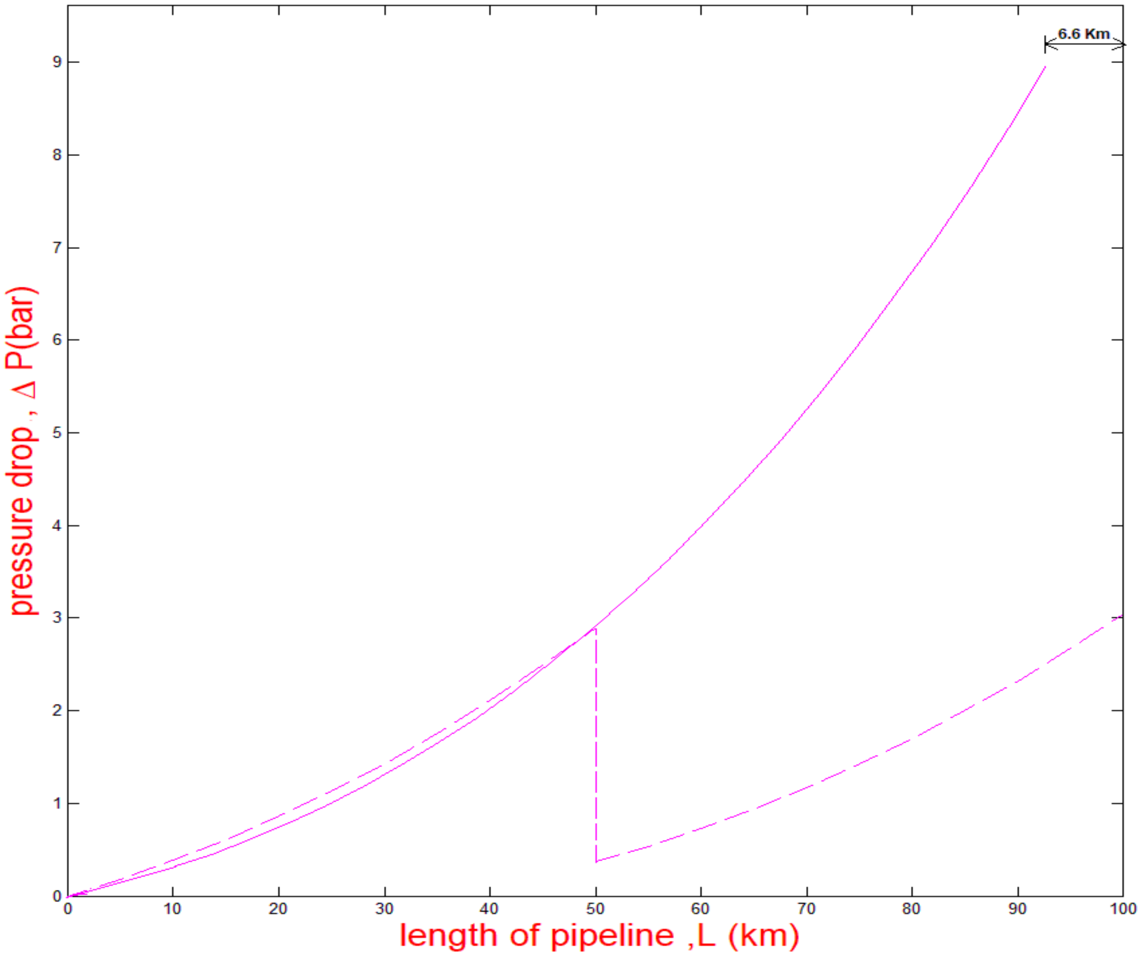

Fig 8.Comparision between pressure drop for oil (4) with single heating in the middle point [case (A)] and at the case of inlet heating only

For **Oil (2)**, the temperature decreased from **60 to 28.06 ºC**, the viscosity increased from **12.61 to 22.18 cSt** and pressure drop increased from **0 to 2.581 Mpa** where that from the inlet to **L/2** through the length of the pipeline, in the location of heating station H.Sta.1 at point **L/2**, the temperature increased from **28.06 to 60 ºC**, viscosity decreased from **22.18 to 12.6 cSt** and pressure drop increased from **2.58 to 0.284 Mpa**. finally , from **L/2 to L** where the outlet of the pipeline, the temperature decreased from **60 to 28.06 ºC** , the viscosity increased from **12.6049 to 22.18 cSt** pressure drop increased from **0.29 to 2.354 Mpa** , *as shown in figure (9) , figure (10) and figure (11)* .

For **Oil (3)**, the temperature decreased from **80 to 46.64 ºC** , the viscosity increased from **18.78 to 26.91 cSt** and pressure drop increased **from 0 to 2.8 Mpa** was that from the inlet to **L/2** through the length of the pipeline, in the location of heating station H.Sta.1 at point **L/2** , the temperature increased from **46.64 to 80 ºC** , viscosity decreased from **26.91 to 18.78 cSt** and pressure drop increased from **2.8 to 0.029 Mpa** . finally , from **L/2 to L** where the outlet of the pipeline, the temperature decreased from **80 to 47.31 ºC** , the viscosity increased from **18.78 to 26.59 cSt** and pressure drop increased from **0.294 to 2.756 Mpa** , *as show in figure (9) , figure (10) and figure (11)* .

For **MAZUT [Oil (5)]**, the temperature decreased from 80 **to 48.86 ºC,** the viscosity increased from **31.812 to 50.84 cSt** and pressure drop increased from **0 to 3.1474 Mpa** where that from the inlet to **L/2** through the length of the pipeline, in the location of heating station H.Sta.1 at point **L/2**, the temperature increased from 48.8615 **to 80 ºC**, viscosity decreased from **50.84 to 31.812 cSt** and pressure drop increased from **0.413 to 3.33 Mpa**. finally , from **L/2 to L** where the outlet of the pipeline, the temperature decreased from **80 to 48.86 ºC** ,the viscosity increased from **31.81 to 50.84 cSt** , and pressure drop increased from **0.413 to 3.33 Mpa** , *as shown in figure (9) , figure (10) , and figure (11)* .

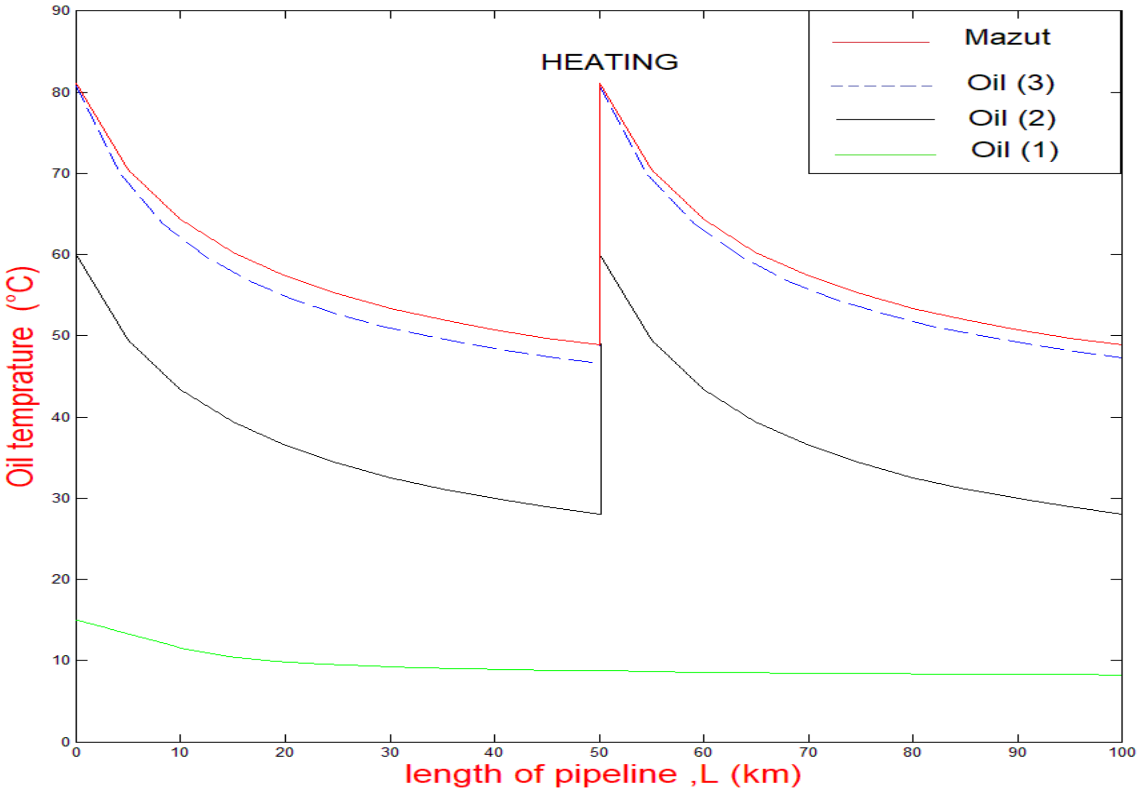

Fig 9.Temperature distribution along the pipeline has one heating station at the middle [case (A)] for oil (5) [mazut], oil (3), oil (2) and oil (1) [Light oil]

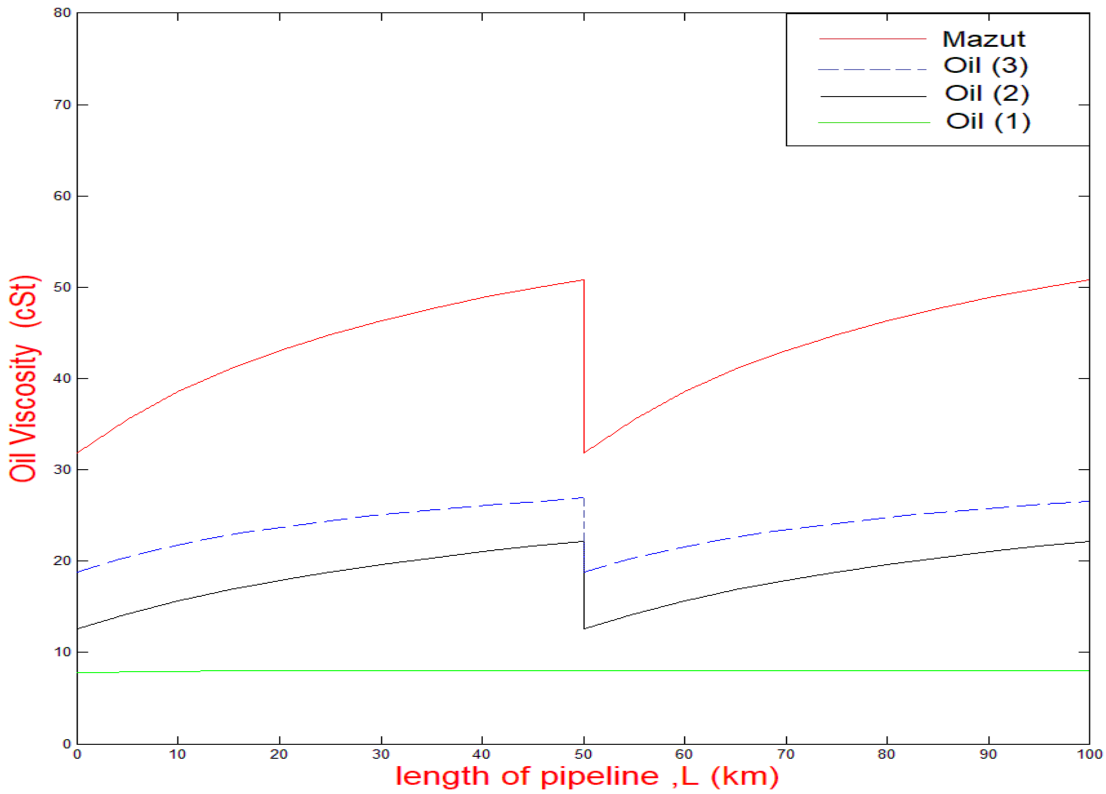

Fig10.Viscosity profile along the pipeline has one heating station at the middle [case (A)] for oil(5)[mazut], oil (3) , oil (2) and oil (1) [Light oil]

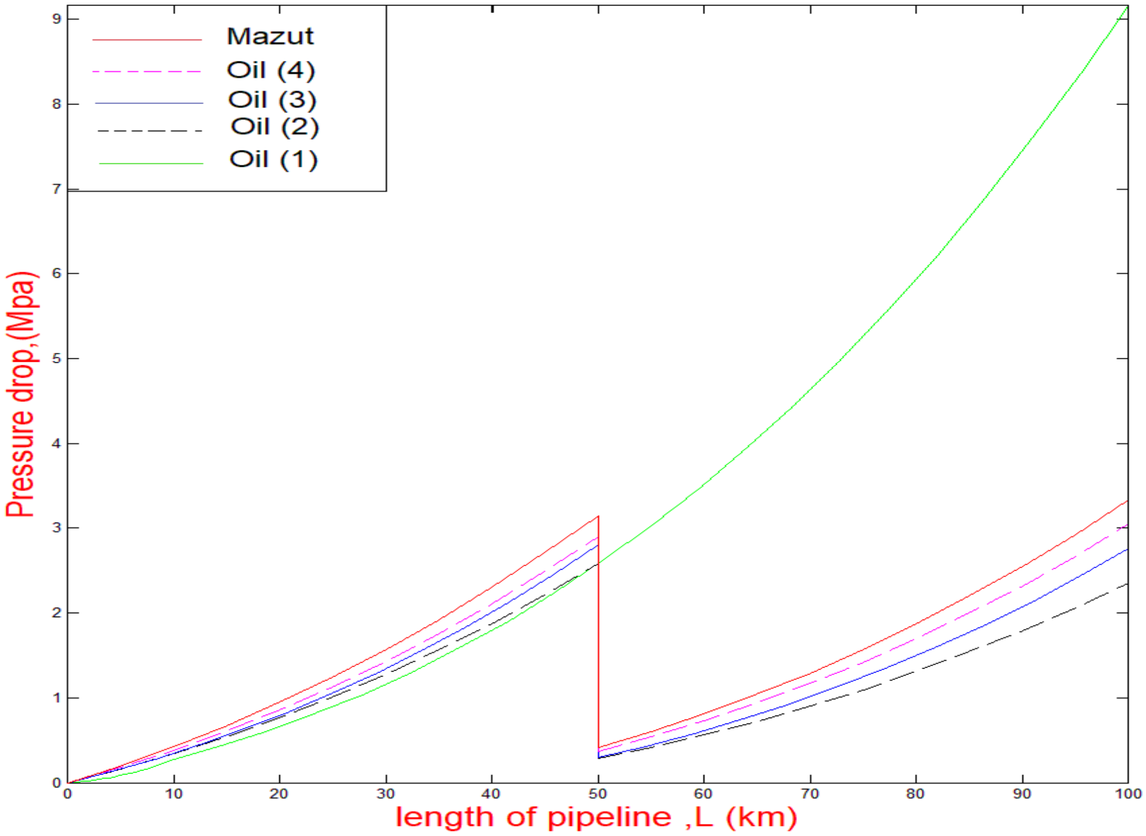

Fig 11.Effect of temperature on the pressure drop through a pipeline with one heating station in the middle [case (A)]

To cover the max pressure drop and reduce the drag effect, reduction in capacity production must be reached to a certain value to obtained maximum capacity production for **oil (3**), reduction in capacity still **11.62%** equivalent to **1.743 Mtpa** , **13.85%** equivalent to **2.078 Mtpa** for **Oil (4**) , and **18.2 %** equivalent to **2.73 Mtpa** for **mazut** [**oil (5**)] after inlet heating at H.Sta.0 and that still not sufficient to overcome the constraints of max pressure drop , if instill another intermediate heating station H.Sta.1 at key points on the line as in cases [A-E], *as shown in figure (5)*. the reduction in capacity decreased to **zero** for **oil(3)** were achieved the maximum throughput and minimum reduction in capacity that means that transported all certain quantity of oil through the pipeline and the second thermal improvement represented in H.Sta.(1) is sufficient for the transportation process for **oil(3)**, the reduction in capacity decreased to **2.03%** equivalent to **0.304 Mtpa** for **oil(4)** and **6.17%** equivalent to **0.93 Mtpa** for **mazut** [**oil (5**)] in intermediate heating station H.Sta.(1), *as shown in table 6*.

Increasing in the temperature of the oil to the maximum value may not be the optimum solution. *Figure (12), figure (13) ,and figure (14)* show the variation of reduction in capacity for different oils with temperature increasing by heating station H.Sta. 1 **in case (A)**, for **oil (2)** inlet heating option H.Sta.(0) which located at point (0,0) in the *figure (12*) can be sufficient to preserve the capacity reduction without needing the intermediate heat input H.Sta.1 .

For heavier oils, the achieving of throughput increased according to the temperature difference **ΔT** raises by the intermediate heating station H.Sta. 1 as in **cases [A, B, C, D , and E]** . For **Oil (3)**, it's not necessary more heating up to 80 ºC because the temperature increasing **ΔT= 0 ºC** where no heating corresponds to the reduction in capacity **$\%\dot{m}_{RED}$=11.62 %**, *as shown in figure (12*) and where the temperature increasing **ΔT=42.67 ºC**, Heat added **q= 9.14 MW** at the heating station H.Sta.1 in the middle of pipeline **cases (A**) , and that sufficient to preserve the maximum throughput , which zero reduction in capacity occurs **$\%\dot{m}_{RED}$ =0 %** at [point (0, 0)], where the amount of heat adding **q** can decrease the viscosity and friction to maintain the pressure drop without exceeding its constraints and guarantee the oil flowability without any reduction in the original pipeline capacity production in the same time.

According to the average oil prices in 2015, the cost of fuel for Intermediate heating is about **\$1.9 m^3/year** for every **ΔT=10 ºC** of increase in temperature. On the other hand, the cost of each**1%** loss in throughput, which equivalent to **0.150 Mtpa** equal 50.6 \$/ (m^3/year), **IMF, 2015**.

Thus, the economistic constraints mainly depending on maintaining the capacity production at its ordinary value, which the pipeline designed on it when transported the light oil when designing a thermal modification system, the decrease of heating cost is not to be ignored to balancing the economic and return fastly on the investment. Although this would depend on the capital costs that represented the particular heating technique used, and the idea of optimal heat adding needed for each oil type was clarified in the previous analysis. However, if the quality of the oil changes gradually, it is necessary that adopting the heating system.

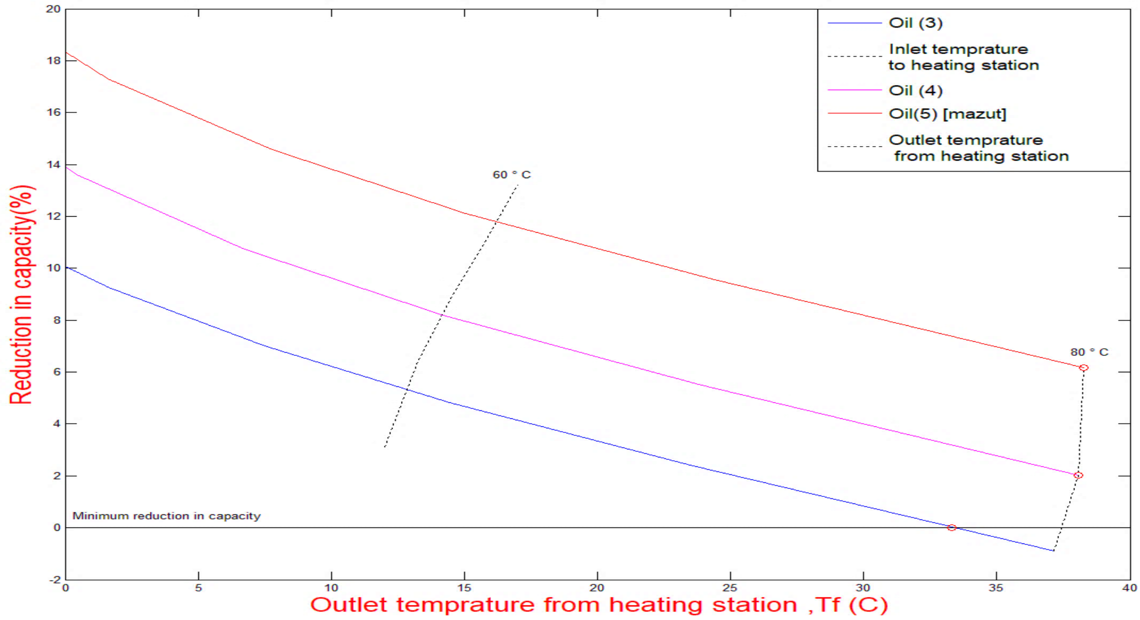

Fig 12.Reduction in capacity with the increase in temperature for single heating in case (A)

Figure (12) Show the effect of temperature increasing in the throughput loss for **Case (A)** as the oil becomes gradually heavier. When the oil changes from **Light oil** [oil (1)] to **oil (2)**, the installation of heating station H.Sta.0 at the inlet of the pipeline can sufficient to guaranty the transportation at full throughput, The installation of an additional single intermediate heating station H.Sta.1, providing an increase in temperature about **ΔT=42.67 ºC** in **Case (A)** where it enough to convert oils from **Oil (2)** to **Oil (3)** .

If no more thermal modifications are applied and the viscosity increases further more than of **oil (4)**, the reduction in capacity raises from **0 to 11.62 %**. For the slightly decreased in capacity reduction and increasing temperature difference **ΔT** can be performed by developing the intermediate heating station. a heat adding raise at the heat station H.Sta.1 in the middle of pipeline as in case (A) by **q=12.51 MW** to reach the maximum temperature of oil **80 ºC** and minimizing the reduction in capacity to **2.025 %** to achieve a total increase in capacity equal **9.595 %** that equivalent to **1.44 Mtpa** .

Because of the constraints of maximum operating temperature, this heating station H.Sta. (1) cannot use as a retrofit for transmitting the heaviest oils. The savings obtained with the oils with higher viscosities in terms of reduction in pipeline transmissions capacity , after this second improvement in **case (A)** are substantial compared with the case of inlet heating station only H.Sta. 0. as in the transmission of **mazut [oil (5)]** the reduction in capacity decreased to **6.167 %** that equivalent to **0.9251 Mtpa** and heat adding raise at the heat station H.Sta.1 by **q=15.25 MW**, as shown in *figure (12)* compared to **18.2%** that equivalent to **2.73 Mtpa** without a heating station in the middle of the pipeline to achieve a total increase in capacity equal **12.033%** that equivalent to **1.8 Mtpa** , as shown in *table 6*.

Figure (13), figure (14) , and figure (15) show the effect of the intermediate heating station H.Sta. 1 location variation as in **cases from [(A) to (E)].** The variation in the temperature increase **ΔT** is more noticeable beyond for the **cases [A, D ,and E]** after the middle of the pipeline , while the **cases [B and C]** that the location in the first half of the pipeline need the same temperature increase **ΔT** nearly, maximum oil throughput is obtained by all locations between **case (C)** in location where **L/4 = 25 km** and **case (E)** in the location where **3L/4 = 75 km**. Where the cases that locations towards the start of the pipeline need a minimal increase in temperature **ΔT** , and heating option with saving more energy efficiency.

For **oil (3)**, in case (C) where intermediate heating station H.Sta.1 is located at **L/4 = 25 km**, the maximum throughput can be obtained by temperature increase **ΔT=22.47 ºC** with Heat adding **q= 6.73 MW**, case (B) where intermediate heating station H.Sta. (1) Located at **L/3 = 33.33 km**, the maximum throughput can be obtained by temperature increase **ΔT= 29.56 ºC** with Heat adding **q= 7.727 MW**, on the other hand, if case (D) where intermediate heating station H.Sta. (1) Located at **2L/3 = 66.67 km**, the maximum throughput can be obtained by temperature increase **ΔT= 40.79 ºC** with Heat adding **q= 8.952 Mw**, case (E) where intermediate heating station H.Sta. 1 Located at **3L/4 = 75 km**, the maximum throughput can be obtained by temperature increase **ΔT= 42.67 ºC** with Heat adding **q= 9.136 MW**, *as shown in figure (13)*.

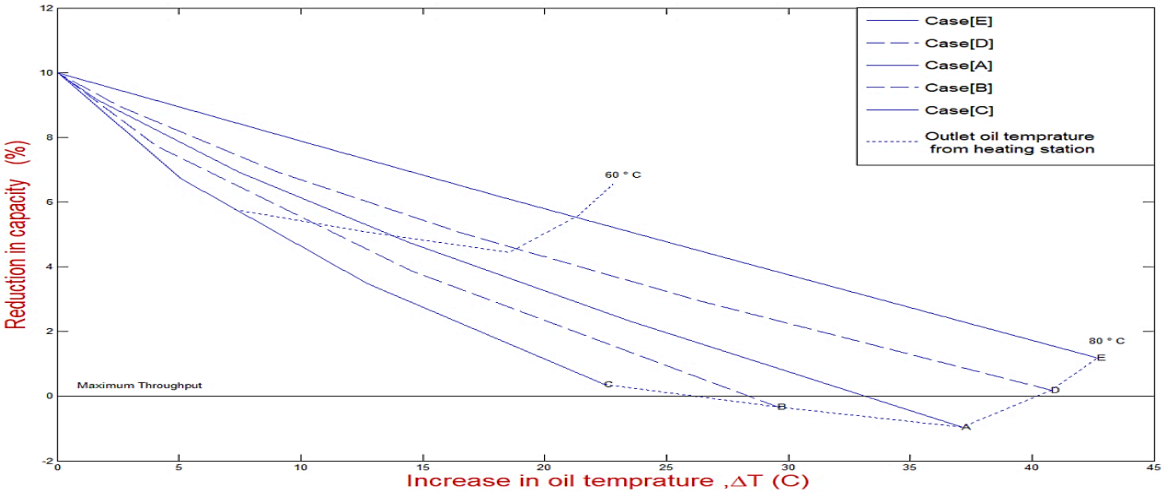

Fig 13.Reduction in capacity variation with temperature increase for oil (3), cases [A-E]

For **Oil (4)**, in case (C) where intermediate heating station H.Sta.1 Located at **L/4 = 25 km**, the maximum throughput can be obtained by temperature increase **ΔT=21.297 ºC** with Heat adding **q= 7.32 MW**, case (B) where intermediate heating station H.Sta.1 Located at **L/3 = 33.33 km**, the maximum throughput can be obtained by temperature increase **ΔT= 31.91 ºC** with Heat adding **q= 10.567 MW**, On the other hand, if case (D) where intermediate heating station H.Sta.1 Located at **2L/3 = 66.67 km**, the maximum throughput can be obtained by temperature increase **ΔT= 40.14 ºC** with Heat adding **q= 11.83 MW**, case (E) where intermediate heating station H.Sta.1 Located at **3L/4 = 7.5 km**, the maximum throughput can be obtained by temperature **increase ΔT= 41.17 ºC** with Heat adding **q= 13.59 MW**, *as shown in figure(14)* .

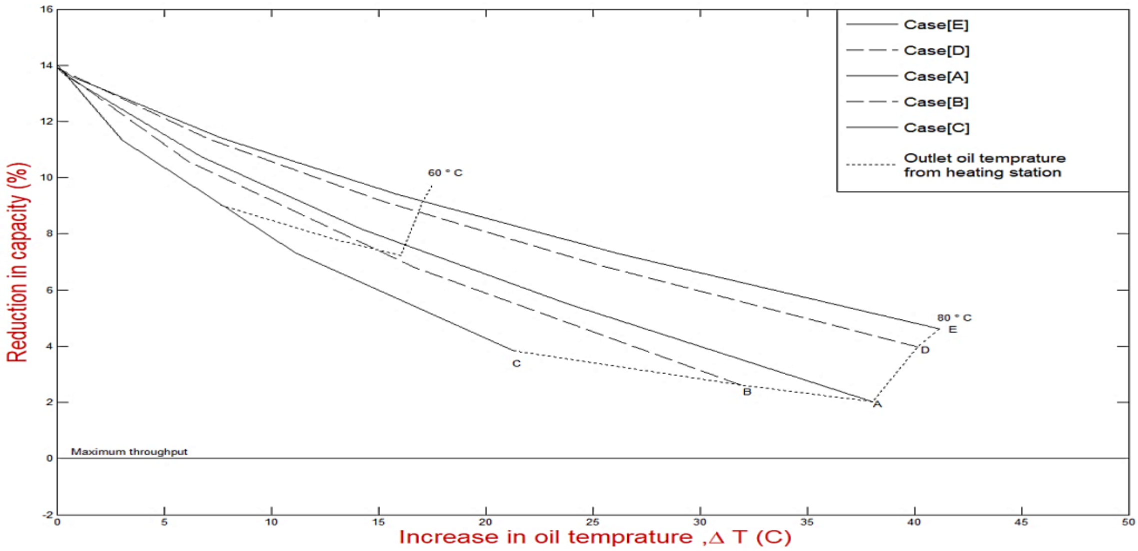

Fig 14.Reduction in capacity variation with the increase in temperature for oil (4), cases [A-E]

For **MAZUT [Oil (5)]**, if case (C) where intermediate heating station H.Sta.1 Located at **L/4 = 25 km,** the maximum throughput can be obtained by temperature increase **ΔT=30.36 ºC** with Heat adding **q= 5.27 MW**, case (B) where intermediate heating station H.Sta. (1) Located at **L/3 = 33.33 km**, the maximum throughput can be obtained by temperature increase **ΔT= 34.6 ºC** with Heat adding **q= 9.96 MW**, on the other hand, if case (D) where intermediate heating station H.Sta.1 Located at **2L/3 = 66.67 km**, the maximum throughput can be obtained by temperature increase **ΔT= 40.38 ºC** with Heat adding **q= 11.123 MW**, case (E) where intermediate heating station H.Sta. 1 Located at **3L/4 = 75 km**, the maximum throughput can be obtained by temperature increase **ΔT= 40.88 ºC** with Heat adding **q= 13.38 MW**, *as shown in figure (15).*

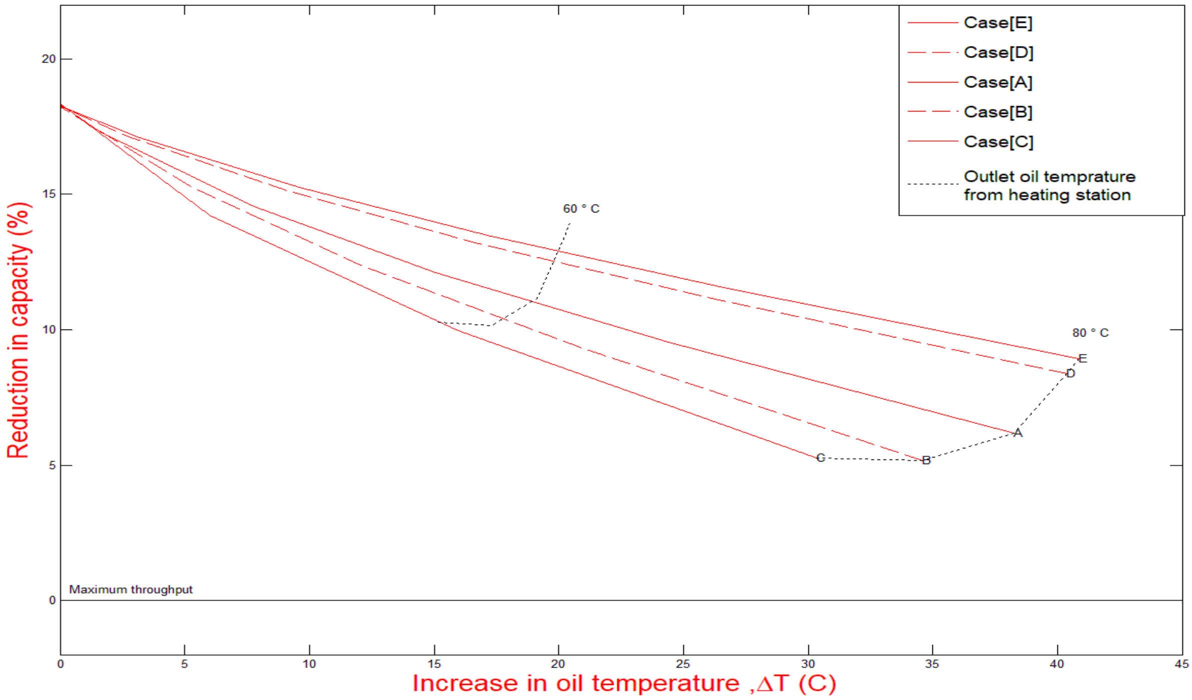

Fig 15. Reduction in capacity variation with the increase in temperature for oil (5) [mazut], cases [A-E]

As observed before, a single intermediate heating station **H.Sta. 1** Is not enough, and with the prior thermal modification **[H.Sta.0 and H.Sta.1]** some reduction in capacity is inescapable. For the same throughput, for the cases the location of the intermediate heating station **[H.Sta.1]** near to the pipeline inlet as in cases [B,C] is more profitable in terms of energy efficiency. Nevertheless, for both **Oil (3)** and **Oil (4)** the low reduction in capacity is spotted for locations near the outlet of the pipeline as in cases [D, E] for similar outlet temperature from the station 80 ºC.

The careful of choosing the location of the heating station is very important for expecting the change in the quality of the transmitted oil. For example, the optimal thermal modification option for **oil (3)** in the **case (C)** where the thermal modification heating station located at **L/4**, where obtained full throughput and **zero** reduction in pipeline transmission capacity by minimum heat input. Although, in this case, the heavy oil is heated to the maximum allowable temperature. This is an important point to modification the heating system to heavier oil since no possibility for more heat adding. But , **in cases [B or A]** could still be a further modification in a future improvement with more heat adding if oils become heavier than **Oil (3)** , to transmitted the maximum increasing in temperature **ΔT** and further decreased in throughput reduction . For these options, the best case would be for the intermediate heating station to be closed to the middle of the pipeline.

So that, the optimum thermal modification depends on the expectation of change in oil quality to heavier happen, how exactly this changing is expected to be, edges of flexibility margins for future improvement and thermal modification and calculated the maximum allowable temperature by the construction of the pipeline.

For allowing heating above **80 ºC**, an improvement of the pipeline in the heating station and its proximity must be instilled. This modification may include more capital expenditures and potential safety hazards, which should be taken into consideration besides the operating cost represented by fuel consumption against the advantage of capacity increases.

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2.2 Multiple-point intermediate heating as in cases [(F) and (G)]

In this partition, the variety of intermediate heating stations is considered. For simplicity , assume uniformed distribution for heating stations along the pipeline with the same needed in temperature increasing **ΔT** for each station distributed between them as in **Cases [(F) and (G)]** which , *as shown in figure (5)* . Assumed H.Sta. 2 and H.Sta. 3 Intermediate heating stations, respectively. By instilled more than one intermediate heating station that gives a possibility to preserve the oil at an average maximum temperature and subsequently relatively minimal viscosity along the pipeline.

Figure (16) and *figure (17)* show the temperature and viscosity distribution along the pipeline for different heavy oils if applied **case (F)** where intermediate heating stations H.Sta. 1 *and* H.Sta. 2] located in **L/3** and **2L/3** , respectively. For **Oil (2)**, the temperature decreased from **60 to 28.93 ºC** and the viscosity increased from **12.6 to 21.636 cSt** from the inlet to **L/3** through the length of the pipeline, in the location of heating station H.Sta. 1 at **L/3** , the temperature increased from **28.93 to 60 ºC** and viscosity decreased from **21.636 to 12.605 cSt** , from **L/3 to 2L/3** , the temperature decreased from **60 to 28.93 ºC** and the viscosity increased from **12.61 to 21.64 cSt** , in the location of heating station H.Sta.2 at **2L/3** , the temperature increased from **28.93 to 60 ºC** and viscosity decreased from **21.64 to 12.61cSt** and finally from **2L/3 to L** where the outlet of the pipeline ,the temperature decreased from **60 to 28.93 ºC** and the viscosity increased from **12.61to 21.64 cSt** , *as shown in figure (16) and figure (17)* .

For **oil (3)** oils if applied **case (F)** , the temperature decreased from **80 to 51.2 ºC** and the viscosity increased from **18.783 to 26.25 cSt** from the inlet to **L/3** through the length of the pipeline , in the location of heating station H.Sta.1 at **L/3** , the temperature increased from **51.2 to 80 ºC** and viscosity decreased from **26.25 to 18.78 cSt** , from **L/3 to 2L/3** , the temperature decreased from **80 to 46.64 ºC** and the viscosity increased from **18.78 to 26.91 cSt** , in the location of heating station H.Sta.2 at **2L/3** , the temperature increased from **46.64 to 80 ºC** and viscosity decreased from **26.91 to 18.78 cSt** and finally from **2L/3 to L** where the outlet of the pipeline , the temperature decreased from **80 to 48.09 ºC** and the viscosity increased from **18.78 to 26.25 cSt** , *as shown in figure (16) and figure (17)* .

For **mAZUT** [**oil (5)**] oils if applied **case (F)** , the temperature decreased from **80 to 49.744 ºC** and the viscosity increased from **31.81 to 49.89 cSt** from the inlet to **L/3** through the length of the pipeline, in the location of heating station H.Sta.1 at **L/3** , the temperature increased from **49.74 to 80 ºC** and viscosity decreased from **49.89 to 31.81 cSt** , from **L/3 to 2L/3** , the temperature decreased from **80 to 48.097 ºC** and the viscosity increased from **31.812 to 51.706 cSt** , in the location of heating station H.Sta.2 at **2L/3** , the temperature increased from **48.097 to 80 ºC** , and viscosity decreased from **51.71 to 31.812 cSt** and finally from **2L/3 to L** where the outlet of the pipeline, the temperature decreased from **80 to 49.737 ºC** and the viscosity increased from **31.812 to 49.887 cSt** , *as shown in figure (16) and figure (17)* .

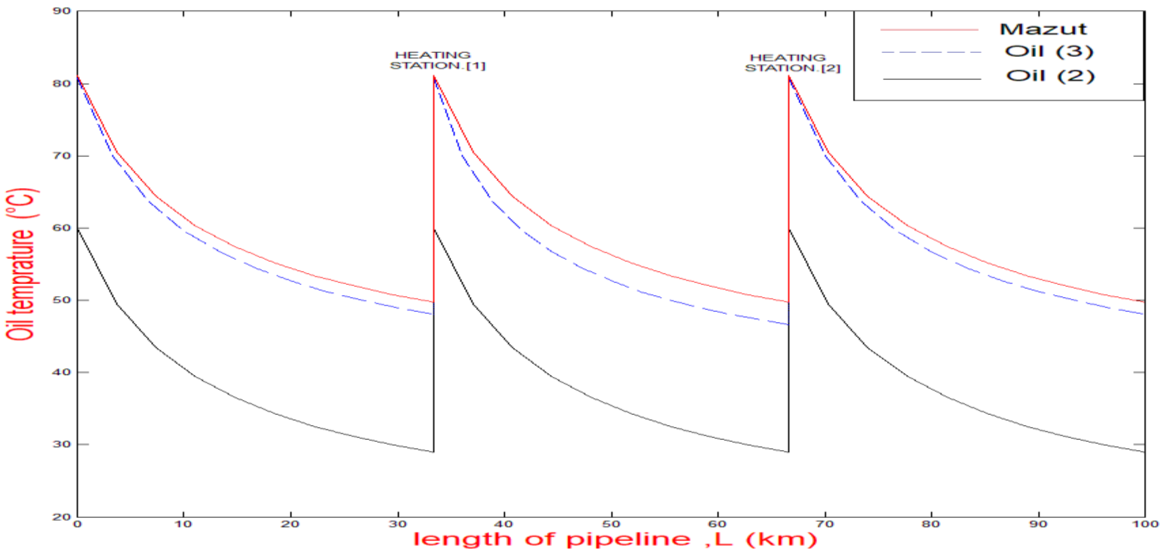

Fig16.Temperature distribution along the pipeline for oil (5) [mazut] , oil (3) and oil (2) , case (F)

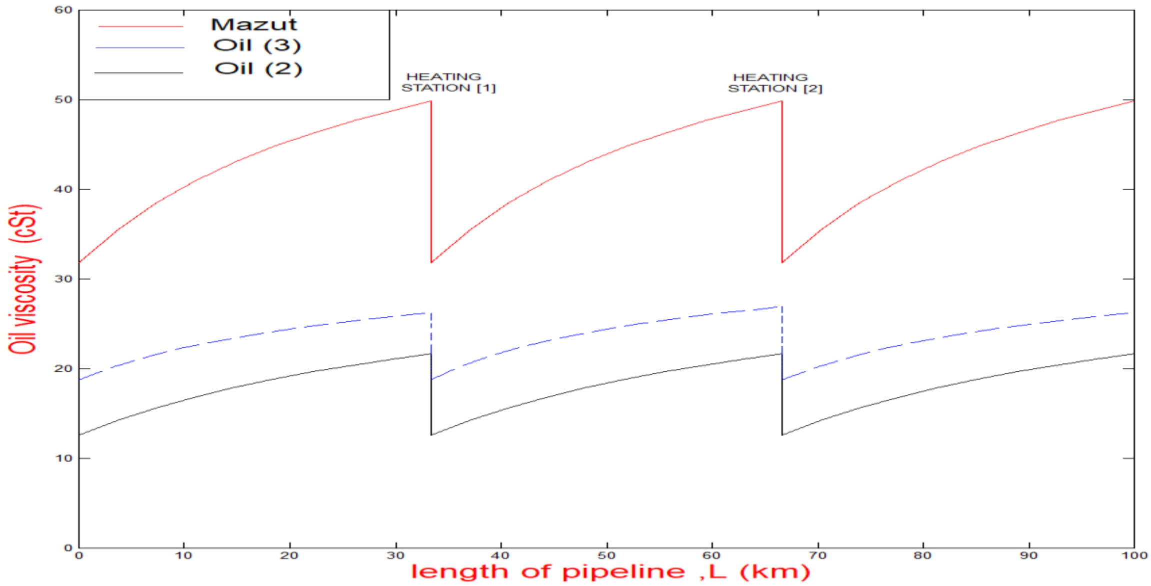

Fig 17. Viscosity profile along the pipeline for oil (5) [mazut] , oil (3) and oil (2) , case (F)

Figure (18) shows a comparison between single point heating in **case (A)** and two intermediate heating points [H.Sta.1, H.Sta.2] in **case (F)** and the oil re-heated to the maximum temperature of **80 ºC** in each station for **Oil (4)**. *Figure (19*) shows a comparison between single point heating in **case (A)** and three intermediate heating points [H.Sta. 1, H.Sta.2 and H.Sta.3] in **case (G)** and the oil re-heated to the maximum temperature of **80 ºC** in each station for **Oil (4)**.

For **Oil (4)** oils if applied **case (A)**, After instill an intermediate thermal improvement H.Sta.1 In the middle of the line at **L/2** the temperature decreased from **80 to 46.838 ºC** and the viscosity increased from **25.4573 to 36.494 cSt** where that from the inlet to **L/2** through the length of the pipeline , in the location of heating station H.Sta.1 at point **L/2**, the temperature increased from **46.839 to 80 ºC** and viscosity decreased from **37.58 to 25.457 cSt.** Finally, from **L/2 to L** where the outlet of the pipeline , the temperature decreased from **80 to 46.12 ºC** , and the viscosity increased from **25.457 to 37 cSt** and pressure drop increased from **0.3683 to 3.0478 Mpa**, *as shown in figure (18) and figure (19)* .

If applied **case (F)** , the temperature decreased from **80 to 52.61 ºC** and the viscosity increased from **25 to 34.715 cSt** from the inlet to **L/3** through the length of the pipeline, in the location of heating station H.Sta.1 at **L/3** , the temperature increased from **52.61 to 80 ºC** , and viscosity decreased from **34.715 to 25.102 cSt** , from

L/3 to 2L/3 , the temperature decreased from **80 to 52.618 ºC** and the viscosity increased from **25.102 to 34.815 cSt** , in the location of heating station H.Sta.2 at **2L/3** , the temperature increased from **52.62 to 89 ºC** and viscosity decreased from **34.82 to 25.1 cSt** , and finally from **2L/3 to L** where the outlet of the pipeline, the temperature decreased from **80 to 53.41 ºC** and the viscosity increased from **25.1 to 34.32 cSt** , *as shown in figure (18)* .

For **Oil (4)** oils if applied **case (G)**, the temperature decreased from **80 to 46.84 ºC** and the viscosity increased from **25.457 to 36.494 cSt** from the inlet to **L/4** through the length of the pipeline, in the location of heating station H.Sta.1 at **L/4** , the temperature increased from **46.84 to 80 ºC** , and viscosity decreased from **36.494 to 24.95 cSt** , from **L/4 to L/2** , the temperature decreased from **80 to 56.46 ºC** , and the viscosity increased from **24.95 to 33.12 cSt** , in the location of heating station H.Sta. 2 at **L/2** , the temperature increased from **56.46 to 80 ºC** , and viscosity decreased from **33.118 to 24.95** cSt , from **L/2 to 3L/4** , the temperature decreased from **80 to 56.459 ºC** and the viscosity increased from **24.95 to 33.12 cSt** , in the location of heating station H.Sta. 3 at **3L/4** , the temperature increased from **56.46 to 80 ºC** , and viscosity decreased from **33.118 to 24.95 cSt** , and finally from **3L/4 to L** where the outlet of the pipeline, the temperature decreased from **80 to 56.46 ºC** and the viscosity increased from **24.95 to 33.12 cSt** , *as shown in figure (18)* .

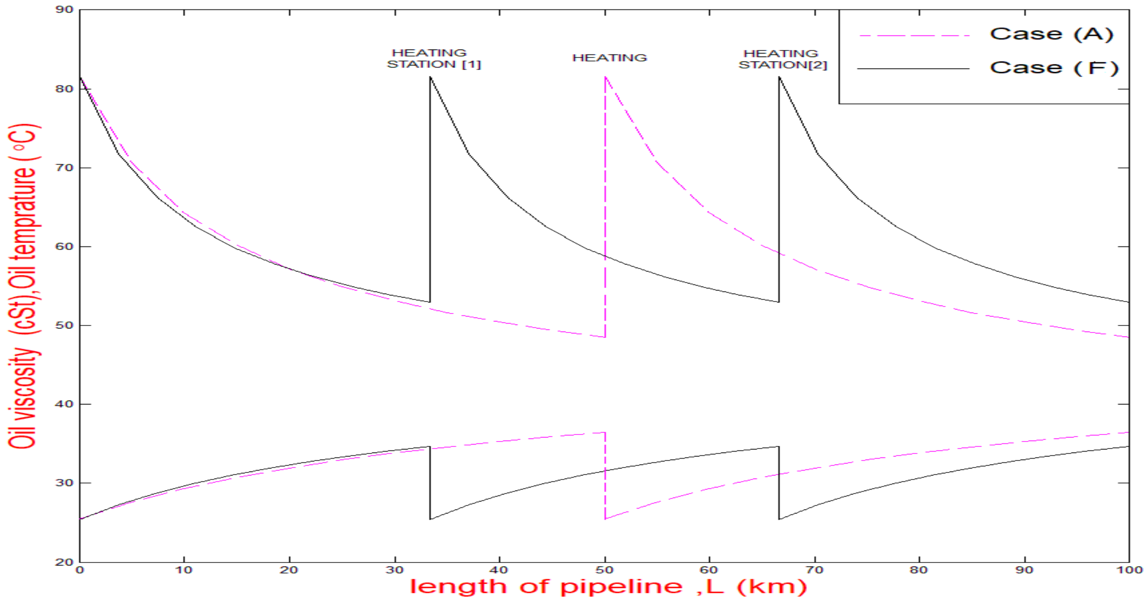

Fig 18.Comparison between temperature distribution and viscosity profile for oil (3) transmitted through the pipeline, [case (A) and case (F)]

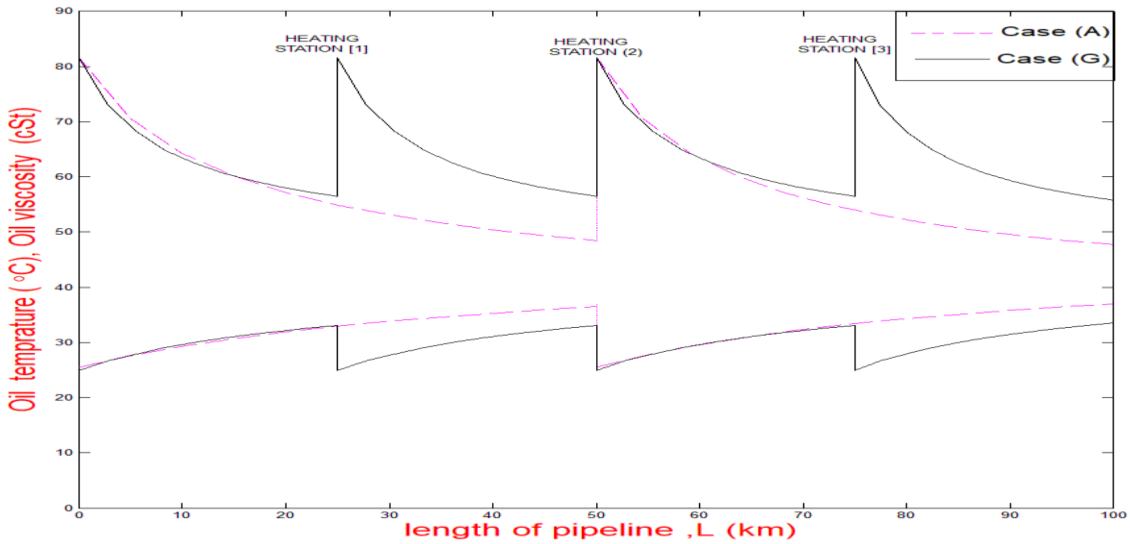

Fig 19.Comparison between temperature distribution and viscosity profile for oil (4) transmitted through the pipeline, [case (A) and case (F)]

As shown in figure (19), in **case (G)** the oil has low average viscosity and high temperature along the pipeline compared within **Case (A)**, which leads to high reduction in capacity for **Oil (4)**. *Figure (20) and figure (21)* shows that for different heavy oils in a various method, by the relationship between the reduction in capacity and the total increasing in temperature [the summation of increasing in temperature **ΔT** for each separate heating station] with H.Sta.1, H.Sta.2 and H.Sta.3 intermediate heating stations in **cases [A, F and G]**.

There is interference between the lines of three cases. This refers to the increasing in temperature **ΔT** supplied by the heating station at the middle of the pipeline [H.Sta.1] as in **Case (A)**.And the smellier increase in temperature ΔT equally divided between different points around the middle of the pipeline resulting in the same reduction in capacity.

For **oil (4)**, *In **case (A)***, the maximum increase in temperature at the intermediate station is **ΔT =35.059 ºC** with a heat added **q = 12.51 MW** , which is limited by the maximum oil temperature of **80 ºC** , in **Case (F)**, the maximum increase in temperature at the intermediate station is **ΔT =37.67 ºC** with a heat added **q = 13.7 MW** per station can be supplied without exceeding the oil temperature constraints, which total increase in temperature **ΔT = 39.84 ºC** with total heat added **q = 14.69 MW** for three heating stations instilled in **case (G)**, *as shown in table 7 and figure (20)* .

Figure (20) the reduction in capacity variation with an increase in temperature for **Oil (4)** with [H.Sta. 1, H.Sta.2 and H.Sta.3] intermediate heating stations in **cases A, F , and G** , the reduction in capacity achieved by **Oil (4)** by applying the inlet heating was **13.85%**. The total increase in temperature **ΔT_A = 35.059 ºC** located at the midpoint, which presented on the maximum increase for **case (A)** , and the reduction in capacity was decreased to **2.025%** . If this total increase in temperature **ΔT_F** was divided into two heating stations as in case (F), the increase in temperature was **ΔT_F/2=18.835 ºC** per station, and the reduction in capacity was decreased to **0.348 %** , and If this total increase in temperature **ΔT_G** was divided into three heating stations as in case (G), the increase in temperature is **ΔT_G/3=13.28 ºC** per station, and the reduction in capacity was decreased to **zero %** , which obtained when the temperature increases were less than the maximum temperature constraints that could be applied by the same effect on capacity reduction on three cases .

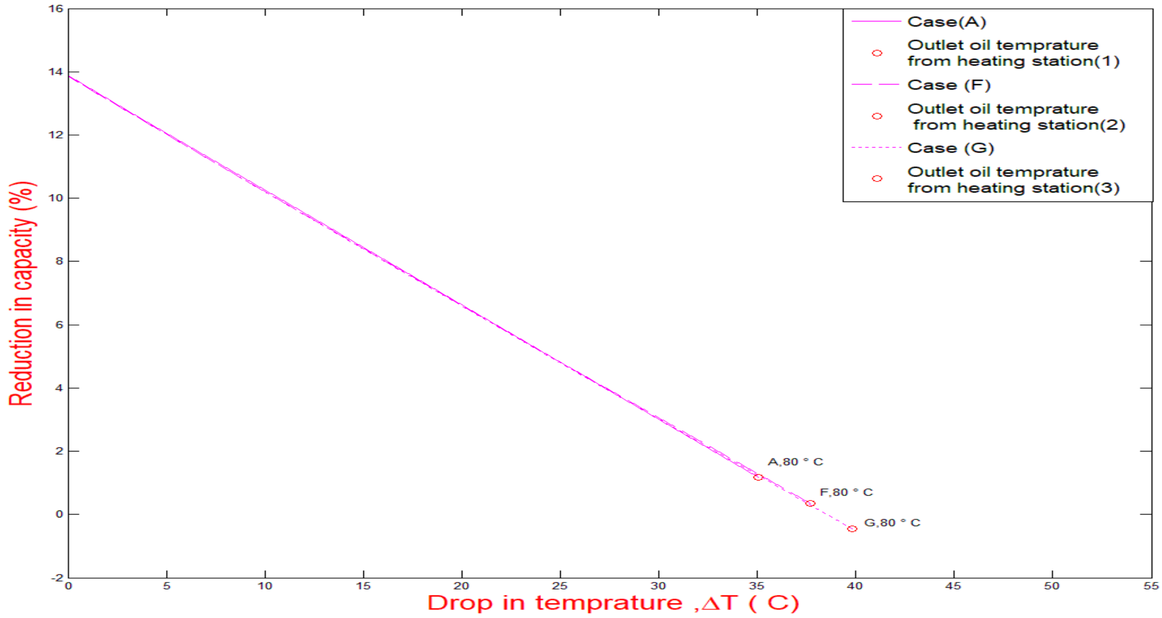

Fig 20.Reduction in capacity variation with the increase in temperature for oil (4), cases [A, F and G]

Figure (21) Show the reduction in capacity variation with an increase in temperature for **MAZUT, Oil (5),** with H.Sta. 1, H.Sta. 2 , and H.Sta. 3 intermediate heating stations in **cases [A, F , and G]**, the reduction in capacity achieved by **Oil (4)** by applying the inlet heating is **18.2 %**. A total increase in temperature **ΔT_A =38.26 ºC** Located at the midpoint , which presented on the maximum increase for **case (A)** , and the reduction in capacity was **3.763%**.

The increase in temperature is ΔT_G/3=16.14 ºC per station, and the reduction in a capacity decreased to 2.49 % , which be obtained with increases in temperature less than the maximum temperature constraints that could be applied by the same effect on capacity reduction in three cases.

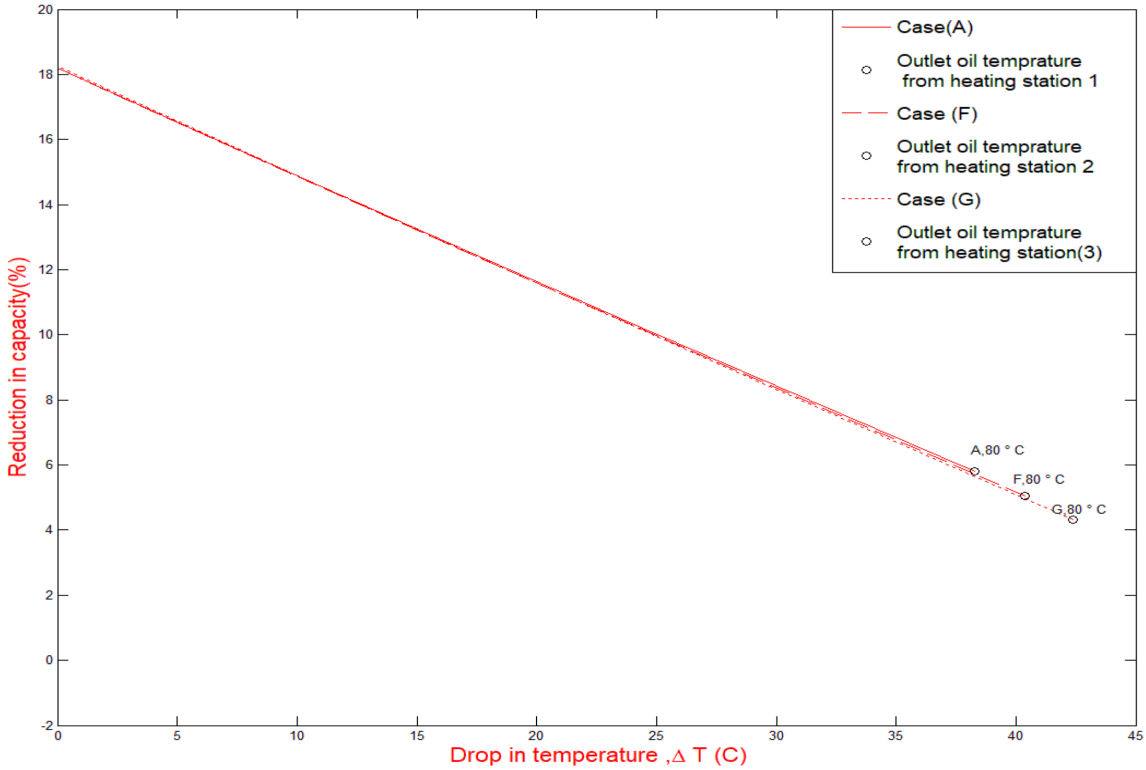

Fig 21.Reduction in capacity variation with the increase in temperature for oil (5) [mazut], cases [A, F and G]

Table 6 concludes the minimum reduction in capacity gained from each heavy oils and the thermal modification options *considered in figure (5).* Table 7 concludes the total increasing **ΔT** and heat added q for H.Sta.1, H.Sta.2, and H.Sta.3 intermediate heating stations and the minimum losses in capacity [throughput], *as in table 6*. Which the indication of higher temperature raises **ΔT** does not necessarily mean that greater of the amount of heat added **q**, where the heat added more depends on the oil transmission capacity [throughput]. The gradually upgrading incapacity is decreased when the number of heating stations is raised. When the number of heating stations is large, that leads to much more capital and maintenance costs that are not taken into account in this analysis.

2.3 Thermal modification in the heating procedure and requirements of potential heating techniques

The results show that the best thermal modification depends on the type of oil. The Single intermediate heating point as in **cases [A, B, C, and D]** is enough for transmitted medium viscosity oils through the pipeline such as **Oil (2)**. While multiple intermediate heating points are needed to decrease the reduction in capacity when transmitted heavier oils via pipeline. The main problem concentrated on predicting the development of oil quality for a long time. When applied the thermal modifications, it is important to look for an optimal design from economic and energy for an existing case study, for avoiding any blockage that may be resulting from transmitted more viscous oils in the future .

For the case studied here, and depending on the analysis of the reduction in capacity and heat added, a suitable thermal modification procedure for the entire quality range of the oil transmitted and improvement steps would be:

1- Starting with the installation of the inlet heating station H.Sta.0 to raise the temperature of the incoming oil up to the maximum temperature constraints, which is 80 ° C, in this case before transmitted through the pipeline.

2- Heat added of 13.598 MW. This will preserve the reduction in capacity between 100% and 95% for oils of viscosity value middle between Oil (3) and Oil (4), respectively.

3- When the oil becomes heavier than Oil (3) and nearer to Oil (4), the second heating station H.Sta.2 must be installation at location 2L/3=6.33 km from the inlet of the pipeline, and gradually increasing heat added up to 13.59 MW by instillation of two intermediate heating stations H.Sta.1 and H.Sta. 2 , as in Case (F) that lead to more savings in a capacity reduction for Oils (4) and oil (5) by just adding a single station H.Sta.2 to the first retrofit H.Sta.1 as in case (A).

4- The same heat added must be divided over three heating stations with a minor range of heat added by H.Sta.3 as in case (G) to enable moreover retrofits in pipeline transmission capacity with the heavier oils.

III. CONCLUSION

In this study, thermal modification of an existing pipeline initially was constructed to transport light oil for transporting heavier oils by using the single and multi-intermediate heating equipment. Where decreased the oil viscosity by using these intermediate heating stations and improved the pipeline capacity. The amount of heat added was predicted from the thermo-hydraulic analysis mainly depending on the location of each heating station, which used to decrease the effect of friction produced as a result of high viscosity by minimizing the viscosity by these heat adding and maintain the pressure drop inside the pipeline in its constraints to avoid exceeding the maximum allowable operating pressure. The strategy of thermal improvement is mainly aimed at keeping the maximum pipeline transmission capacity for the gradual changes in the oils viscosities and aimed to achieve the constraints of maximum overall pressure drop and maximum oil temperature. The variation of intermediate heating station location must be taken into consideration with the heat added and increases in temperature by each station for not exceeding of the maximum constraints because that these suggested procedures depending mainly on the gradual addition and changing in a location of heating added as the oils gradually become more viscous. These thermal improvements will be applied with particular benefits over other methods such dilution, emulsion, or new pumping stations installation of where that can be developed easier in the installation of heating stations, high efficiency, and low-cost heating technique.

Appendix

Table 1– Oils physical properties [°API gravity for Oil , mean average boiling point, (MeABP) , Fluid kinematic viscosity at 40 °C ,($\nu_{40°C}$)]

Oil-type	°API gravity	MeABP (°C)	$\nu_{40°C}$ (m^2 /sec)
1 [Light oil]	34	280	$0.051*10^{-4}$
2	24	350	$1.2*10^{-4}$
3	20	400	$1.5*10^{-4}$
4	18	450	$4.5*10^{-4}$
5 [Mazut]	21.8	550	$5*10^{-4}$

Table 2– Stainless steel pipe properties from [ANSI B36.10] used in heating pipelines

Nominal Pipe size, (mm)	Outer diameter ,r_1 (mm)	Wall thickness,t, (mm)	Unit Weight , (kg/m)	Conductivity, K (W/m .°k)
200	219.1	8.18	42.55	54

Table 3 – Geometry and operating conditions of the pipeline

Inside radius of pipe, $R_{p,i}$ [m]	0.1
distance from the center of pipeline to the ground surface , δ_d [m]	1.2094
Soil thermal conductivity ,K_{Gr} [W/m.ºK]	1.2
Insulation thickness , X_{ins} [m]	0.09055
Insulation thermal conductivity K_{ins} [W/m.°K] (EPS)	0.036
Flow improvement desired ,m'_{Max} (Mtpa)	8.205
Oil inlet velocity ,V_{in} [m/s]	1.16
MAOP [MPa]	11
ΔP_{MAOP} [MPa]	9.16
T_a [ºC]	20
$T_{s,a}$	12 °C
T_S	8 °C

Table 4– Effect of increasing in temperature in physical properties of oils [1-5]

Inlet oil Temperature	T(°C)	5	10	20	30	40	50	60	70	80	90	100
Oil (1)	ν[cSt]	8.376	7.98	7.623	7.297	7	6.727	6.477	6.245	6.031	5.833	5.648
[Light oil]	ρ [kg/m^3]	869.71	861.69	854.7	847.68	840.67	833.67	826.65	819.63	805.61	805.61	798.6
Oil (2)	ν[cSt]	73.017	37.087	20.622	17.26	12.365	7.896	5.318	3.746	2.74	2.072	1.794
	ρ [kg/m^3]	919.09	912.796	905.13	902.79	898.15	891.17	884.186	877.21	870.23	863.25	859.89
Oil (3)	ν[cSt]	147.62	116.336	60.593	34.234	20.714	15.312	10.16	7.919	5.636	4.152	3.444
	ρ [kg/m^3]	942.63	940.36	933.55	926.74	919.93	915.39	908.58	904.05	897.24	890.43	885.89
Oil (4)	ν[cSt]	215.04	170.28	89.607	50.904	30.856	22.8	15.089	11.739	8.316	6.093	5.034
	ρ [kg/m^3]	954.9	952.67	946.04	939.423	932.8	928.39	921.77	917.35	910.73	904.11	899.69
Oil (5)	ν[cSt]	359.2	287.19	154.63	89.192	54.575	40.478	26.85	20.88	14.769	10.779	8.88
[mazut]	ρ [kg/m^3]	929.23	926.89	919.82	912.86	905.85	901.18	894.16	889.48	882.47	875.46	870.78

Table 5-The Maximum transported length with and without heating oil at inlet and the reduction in capacity needed for heavy oils to reduce the drag effect and overcome the constraint of maximum pressure drop resulting from the maximum allowable operating pressure of this pipeline (*MAOP*)

Oil Type	Oil (1)[Light oil]	Oil (2)		Oil (3)		Oil (4)		Oil (5) [MAZUT]	
Case	1	1	2	1	2	1	2	1	2
Inlet Heating	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
T_{in} [ºC]	15	60	60	80	80	80	80	80	80
Capacity	Max.	Max	Max.	Decreased	Max.	Decreased	Max.	decreased	Max.
V_{in} [m/sec]	1.16	1.16	1.16	1.16	1.11	1.16	1.11	1.16	1.11
$L_{(\Delta P_{MAOP})}$ [km]	100	96.4	100	92.8	100	93.4	100	89.2	100
$L_{(EPSO)}-L_{(\Delta P_{MAOP})}$ [km]	0	-3.6	0	-7.2	0	-6.6	0	-10.8	0
$\%\dot{m}_{RED}$ [%]	-	-	0	-	11.62	-	13.85	-	18.2
$\dot{m}_{RED}$ [Mtpa]	-	-	0	-	1.743	-	2.078	-	2.73

Table 6 – Reduction in pipeline capacity with different thermal modification options

Oil type	Oil (2)		Oil (3)		Oil (4)		Oil(5) [MAZUT]	
Modification option	(%)	Mtpa	(%)	Mtpa	(%)	Mtpa	(%)	Mtpa
Heating only at inlet	0	0	11.62	1.743	13.85	2.078	18.2	2.73
Case [A-E]	-	-	0	0	2.025	0.304	6.167	0.925
Case (F)	-	-	-	-	0.348	0.0522	3.763	0.565
Case (G)	-	-	-	-	0	0	2.49	0.374

Table 7– Increasing in temperature and amount of heat added by intermediate Heating stations for different thermal modificatio options

	Oil (2)		Oil (3)		Oil (4)		Oil(5) [MAZUT]	
Modification option	ΔT (°C)	q(Mw)	ΔT (°C)	q (Mw)	ΔT (°C)	q (Mw)	ΔT (°C)	q (Mw)
Heating only at inlet	0	0	0	0	0	0	0	0
Cases[A-E]	-	-	42.67:22.5	6.73: 9.14	41.14:21.29	12.51:7.32	40.88:30.4	13.4:5.27
Case (F)	-	-	-	-	37.67	13.7	44.38	15.25
Case (G)	-	-	-	-	39.84	14.69	48.4	16.73

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