Proceedings of ENCIT 2012
14th Brazilian Congress of Thermal Sciences and Engineering
November 18-22, 2012, Rio de Janeiro, RJ, Brazil

EXERGY AND ENVIRONMENTAL ANALYSIS OF A PETROLEUM PIPELINE TRANSPORTATION SYSTEM

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Abstract. *An exergetic and environmental analysis is performed on a low temperature conditions pipeline transportation system for petroleum. Problems of energy efficiency and also environmental problems in relation to the conservation of natural habitat are considered when transportation to the oil terminals is necessary. It is evaluated in this work the energy costs of oil pumping and heating during transportation throughout the pipelines. Losses generated by irreversibilities associated with the oil viscosity and the heat losses to the surroundings are considered and we learned that it would be possible to avoid up to 16.12% of the exergy destruction by increasing from 0.05 m to 0.10 m the pipeline insulation thickness. Environmental problems in this case are related to the need for conservation of the permafrost layer where the pipeline is buried at temperatures below 0* ^{0}*C. Accounting for several thicknesses for the insulating layer on the outside of the pipeline and possible taxes to be paid per kilogram of carbon dioxide emitted, estimated energy and monetary costs for an Arctic pipeline steady-state operation are calculated. Energy costs of oil pumping and heating during transport throughout the pipelines decreases 21.62%, from 1.85% to 1.45%, when the pipeline insulation thickness increases from 0.05 m to 0.10 m. Assuming the energy for oil heating and pumping to be extracted from the pumped petroleum, we calculated 6.12 to 7.86 kg* CO_2*/BBL of oil transported through a 4000 km long pipeline.* CO_2 *emission cost, if taxes applied according to Australian regulations, should add from 16 to 20 cents to the petroleum cost. Therefore investing in the insulation cost to reduce* CO_2 *emission makes sense since it would reduce payments with the taxes.*

Keywords*: petroleum, pipelines transport system, exergy analysis, carbon dioxide emission.*

1. INTRODUCTION

Oil exploration on firm ground is being performed actually in some very remote regions of the planet. This ends up creating problems of energy efficiency for the extraction process and also environmental problems in relation to the conservation of natural habitat along thousands of miles of pipeline, where transportation to the oil terminals is necessary.

Regarding the issue of energy efficiency, it is evaluated in this work the minimum energy costs of oil pumping and heating during transportation throughout the pipelines to quantify losses generated by the mechanisms of irreversibility associated with the internal friction due to viscosity of the oil itself, and the heat losses to the surroundings. By adding these values to the necessary mechanical energy to pump the oil, when the pressure losses during the flow must be restored, it is estimated the amount of oil extracting own energy being spent for its transportation along the pipeline.

This work evaluates a pipeline project to transport oil in the Arctic region. Environmental problems in relation to the conservation of natural habitat in this situation are generated by the need for conservation of the permafrost layer where the pipeline is buried at temperatures below 0 ^{0}C. The permafrost is a type of soil that is kept frozen by million years absorbing carbon and storing it as organic matter.

During transportation in the pipeline oil needs to be heated up to reduce its viscosity and thus reducing pumping costs. Assuming the energy for oil heating and pumping to be extracted from the pumped petroleum, we calculated carbon dioxide emissions per barrel of oil transported.

Taking into account several thicknesses for the insulating layer on the outside of the pipeline, used to reduce heat losses to the surroundings, and possible fees to be paid per kilogram of carbon dioxide emitted, estimated energy and monetary costs for an Arctic pipeline steady-state operation are calculated.

2. PIPELINES FUNDAMENTALS

2.1 Physical modeling

An exergy and environmental analysis of petroleum pipeline transportation - throughout the Arctic region - system is developed in terms of entropy generation, or exergy destruction, when thermal restrictions are imposed to avoid the melting of the permafrost surrounding the pipelines.

Physical configuration of the pipeline is represented by an ensemble of various transportation modules of length L and internal diameter D, allowing the petroleum pumping such that to maintain its pressure to a certain level $P_{min} \leq P \leq P_{max}$. To reduce the energy consumption for pumping the crude oil throughout the pipeline, one heat exchanger (HE) is mounted as showed in the Fig. 1 at the entrance of each pumping station for reducing the crude oil viscosity. It is considered that the pumping system (P) of each module is powered by a thermal engine (E) and fueled by some of the crude oil flowing into the pipeline. The thermal interaction into the heat exchanger allow heating up the flowing petroleum to reduce its viscosity.

It is supposed the pipeline to be buried in the permafrost layer, where the nominal temperature is -4ºC. Then, one of the most important conditions imposed for the project to be successful is to keep the permafrost frozen. Therefore, temperature of the external pipeline surface should be kept below 0ºC.

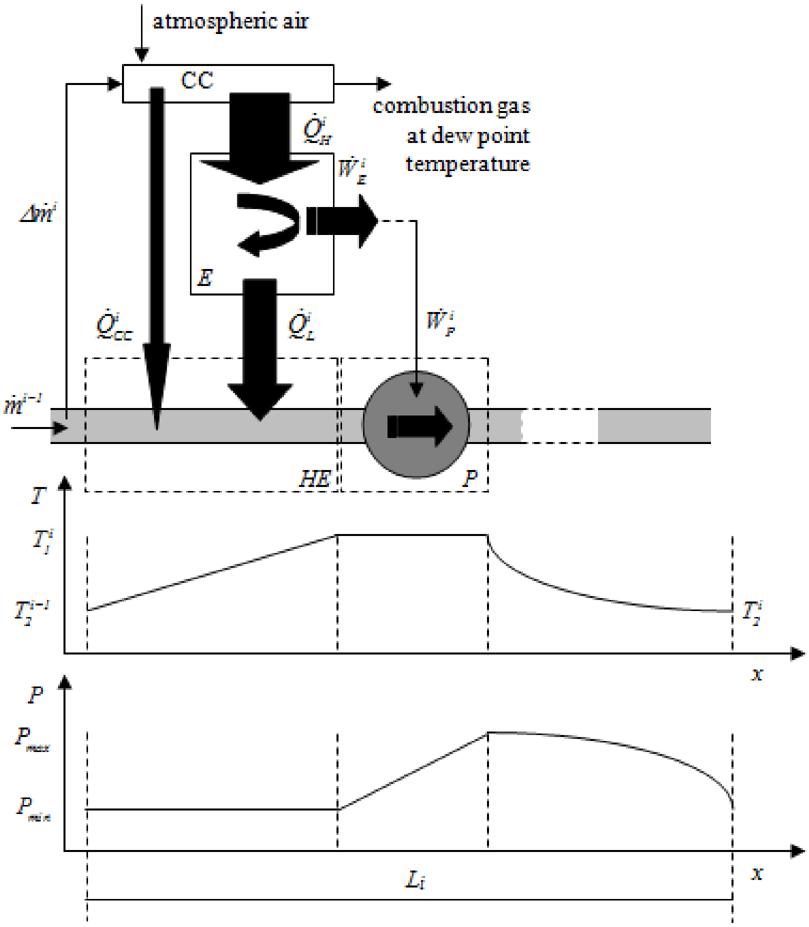

Figure 1 – The i-th transportation module of length L_i equipped with the combustion chamber (CC), the heat exchanger (HE) and the pumping system (P) powered by a thermal engine (E).

2.2 Mathematical modeling

The mathematical model employed was derived from the equations of mass and energy conservation and the second law of thermodynamics applied to each one of the main control volumes in Figure 1:

- the power system represented by the thermal engine (E),
- the combustion chamber (CC),
- the heat exchanger (HE),
- the crude oil pump (P) and
- the crude oil flowing pipeline.

The mathematical problem consisted of computing the petroleum temperature and pressure loss distribution along the pipeline, entropy generation or exergy destruction during the petroleum flow throughout the pipeline, the crude oil consumption for fueling the power systems along the pipeline and the carbon dioxide emissions from the combustion chambers. The model also considers the following hypothesis:

- steady-state operation of all the pipeline components,
- kinetic and potential energy effects are ignored,

- laminar steady-state oil flowing regime,
- stoichiometric reaction into the combustion chamber produces only carbon dioxide, water and SO_2,
- ideal gas principles applies for the air and the combustion products,
- Dalton model is assumed for calculating thermodynamic properties of the combustion gas components.

By considering an infinitesimal control volume along the pipeline, the thermodynamic model represented by the energy conservation equation and the second law of thermodynamics can be written for an irreversible flowing process as shown below:

$$\delta\dot{Q} - \dot{m} \cdot dh = 0 \tag{1}$$

$$\frac{\delta\dot{Q}}{T^*} - \dot{m} \cdot ds + \delta\dot{S}_{ger} = 0 \tag{2}$$

where $\delta\dot{Q} = -\pi DU(T - T_\infty)dL < 0$ represents the heat transfer interaction between the flowing crude oil at temperature T and the permafrost whose temperature is $T_\infty = 269.15\ K$, $\dot{m}$ is the petroleum mass flow rate, $dh \cong cdT$ is the crude oil specific enthalpy variation with $c(T)$ the crude oil specific heat, $T_\infty < T^* < T$ is the thermal interaction characteristic temperature, $ds = dh/T - vdP/T$ calculates the crude oil specific entropy variation and $\delta\dot{S}_{ger}$ is the rate of entropy generation.

First derivatives dT/dL and $d\dot{S}_{ger}/dL$ can be expressed now based on the Eqs. (1) and (2)

$$\frac{dT}{dL} = -\frac{\pi DU}{\dot{m}c}(T - T_\infty) \tag{3}$$

$$\frac{d\dot{S}_{ger}}{dL} = -\dot{m}c\frac{T - T^*}{TT^*}\frac{dT}{dL} - \frac{\dot{m}}{T\rho}\frac{dP}{dL} \tag{4}$$

It is worth noting into the last equation that the rate of entropy generation can be calculated by adding the two terms accounting for the entropy generation by irreversibility related to the finite temperature difference thermal interaction $\dot{S}_{ger,T}$ and irreversibility related to the internal dissipation mechanism associated to the oil viscosity $\dot{S}_{ger,P}$

$$\frac{d\dot{S}_{ger,T}}{dL} = -\dot{m}c\frac{T - T^*}{TT^*}\frac{dT}{dL} \tag{5}$$

$$\frac{d\dot{S}_{ger,P}}{dL} = -\frac{\dot{m}}{T\rho}\frac{dP}{dL} \tag{6}$$

Distribution of the crude oil pressure losses along the pipeline can be calculated with the well known relation

$$d(\Delta P) = f\frac{p}{A}\left(\frac{1}{2}\rho V^2\right)dL \tag{7}$$

where $p = \pi D$, $A = \pi D^2/4$, $\rho = \rho(T)$ and V represent respectively the perimeter and area of the cross section of the pipeline, the crude oil density and the bulk flow axial velocity. Based on the Reynolds Number, the coefficient f may be calculated for laminar regime with $f = 16/Re = 16\upsilon/(VD)$ and by substituting dT/dL from Eq. (3) and dP/dL from Eq. (7) into Eqs. (5) and (6) is possible to check that $\dot{S}_{ger,T} \geq 0$ and $\dot{S}_{ger,P} \geq 0$

$$\frac{d\dot{S}_{ger,T}}{dL} = \pi DU\frac{(T - T^*)(T - T_\infty)}{TT^*} \geq 0 \tag{8}$$

$$\frac{d\dot{S}_{ger,P}}{dL} = \frac{128\dot{m}^2}{\pi\rho D^4}\frac{\upsilon}{T} \geq 0 \tag{9}$$

where $\upsilon = \upsilon(T)$ represents the kinematic viscosity of crude oil and $\dot{m} = \rho VA$.

Then, the mathematical model to solve the problem is represented for the following ordinary differential equations

$$\frac{dT}{dL} = -\frac{\pi DU}{\dot{m}c(T)}(T - T_\infty) \tag{10}$$

$$\frac{dP}{dL} = -\frac{128\dot{m}}{\pi D^4}\upsilon(T) \tag{11}$$

$$\frac{d\dot{S}_{ger,T}}{dL} = \pi DU\frac{(T - T^*)(T - T_\infty)}{TT^*} \geq 0 \tag{12}$$

$$\frac{d\dot{S}_{ger,P}}{dL} = \frac{128\dot{m}^2}{\pi D^4 T}\frac{\upsilon(T)}{\rho(T)} \geq 0 \tag{13}$$

3. NUMERICAL METHOD

3.1 Numerical procedure

The main condition that should be imposed for this project to comply with the ambient legislation is to keep the temperature of the pipeline external surface T_{ext} below 0 ^{0}C. Then, calculation of petroleum maximum temperature can be developed based on these followings equations to express the thermal interaction between the bulk oil flow into the pipeline and the surroundings $\delta\dot{Q} = -\pi DU(T - T_\infty)dL$ and $\delta\dot{Q} = -\pi DU_{ext}(T - T_{ext})dL$, where the overall heat transfer coefficients U and U_{ext} are calculated based on the already published by Stoecker (1989) formulae

$$\frac{1}{U} = \frac{1}{113} + \frac{2\delta A_{int}}{(A_{int} + A_{ext})k} + \frac{A_{int}}{7.2A_{ext}} \tag{14}$$

$$\frac{1}{U_{ext}} = \frac{1}{113} + \frac{2\delta A_{int}}{(A_{int} + A_{ext})k} \tag{15}$$

with $A_{int} = \pi DL$ and $A_{ext} = \pi(D + 2\delta)L$ representing respectively the internal and external area of the pipeline cross section, and δ and k the thermal insulation's thickness and thermal conductivity.

When combining Eqs. (14) and (15) and imposing the condition $T_{ext} = T - (T - T_\infty)(U / U_{ext}) < 273.15\ K$, the maximum value for the crude oil temperature at the entrance of each module of length L is given by

$$T_{max} \leq \frac{273.15 - UT_\infty / U_{ext}}{1 - U / U_{ext}} \tag{16}$$

Numerical procedure employed in this paper to calculate energy costs and carbon dioxide emissions firstly solves the algebraic equations system represented by Eqs. (17) – (19) for the unknowns $\Delta\dot{m}^i$, $\dot{m}^i_{CO_2}$ and $T_{DewPoint}$, to calculate the energy costs for heating-up and pumping the oil, and the carbon dioxide emissions along the L_i transportation module

$$\frac{\Delta\dot{m}^i}{M}\left[\bar{h}^{T_2^{i-1}}_{C_xH_yO_zN_wS_v} - x\bar{h}^{T_{DewPoint}}_{CO_2} - \frac{y}{2}\bar{h}^{T_{DewPoint}}_{H_2O_{vap}} - v\bar{h}^{T_{DewPoint}}_{SO_2} - 3.76\left(x + \frac{y}{4} + v - \frac{z}{2}\right)\bar{h}^{T_{DewPoint}}_{N_2}\right] =$$

$$= \left(\dot{m}^{i-1} - \Delta\dot{m}^i\right)c\left(T_1^i - T_2^{i-1}\right) + \frac{\dot{m}^{i-1} - \Delta\dot{m}^i}{\rho}(P_{max} - P_{min}) \tag{17}$$

$$\dot{m}^{i}_{CO_2} = x \Delta \dot{m}^{i} \left(M_{CO_2} / M \right) \tag{18}$$

$$(y / 2) P_0 = P_{sat} \left(T_{DewPoint} \right) \tag{19}$$

where $\Delta \dot{m}^{i}$ gives the oil consumption to power the i-th transportation module's pumping and heating systems. Eq. (17) represents the 1st Law of Thermodynamics written down for the combustion chamber (CC). Since the energy source for all processes (pumping and heating) is represented by the oil chemical energy, the left side term calculates the energy extracted from the oil during the combustion process while the right side terms represent the energy needed for heating and pumping the oil along the L_i module.

Then we integrate the ordinary differential equation system represented by Eqs. (10) – (13) starting with the same initial conditions for each module $\left[T \quad P \quad \dot{S}_{ger,T} \quad \dot{S}_{ger,P} \right]_0^T = \left[T_{max} \quad P_{max} \quad 0 \quad 0 \right]^T$, where T_{max} is the maximum allowed oil temperature to avoid the melting of the permafrost surrounding the pipeline. Integration for each module ends when $P = P_{min}$.

3.2 Numerical results and discussion

Numerical simulations were performed for a pipeline project that is being developed for the initial mass flow rate of $\dot{m}^0$ = 44 kg/s of crude (Stoecker, 1989). Design of the pipeline assumes the internal pipeline diameter D = 600 mm and the maximum and minimum pumping pressures P_{max} = 2400 kPa and P_{min} = 2400 kPa. To easy the oil flow along the pipeline, a heater (HE) is mounted at the entrance of each pumping station as showed in the Fig. 1. Since the pipeline is supposed to be buried in the permafrost layer, and the most important restriction is to keep the permafrost frozen, temperature of the pipeline external surface should be kept under 0ºC. Technical features of the available materials for the pipeline building and the required parameters for the evaluation of the transferred thermal flux from the oil to the permafrost are as follows:

- zero thermal resistance of the pipeline material,
- thermal conductivity of the insulation k = 0.036 W/(m·K),
- coefficient of heat transfer between the surface and permafrost equal to 7.2 W/(m^2·K),
- convection heat transfer coefficient from oil to the pipeline equal to 113 W/(m^2·K),
- available thicknesses of the insulation for the pipeline external surface are 0.050, 0.075 or 0.100 m.

Table 1. Maximum allowed oil temperatures to avoid permafrost melting.

Insulation Thickness	$T_{max} \le \left(273.15 - UT_\infty / U_{ext} \right) / \left(1 - U / U_{ext} \right)$
δ = 50 mm	$T_{max} \le 46.46\ ^0C$
δ = 75 mm	$T_{max} \le 73.57\ ^0C$
δ = 100 mm	$T_{max} \le 102.9\ ^0C$

Substituting these values initially in Equation (14) - (16) are calculated the maximum allowed values for the oil temperature at the entrance of each transportation module to avoid melting of the permafrost (Table 1). Considering also that the maximum temperature of petroleum should be lower than the dew point temperature of the combustion gas ($T_{DewPoint} = 69.18^0C$) calculated based on Eq (19) to enable the thermal interaction into the heat exchanger (HE), we define the input temperature for each transportation module equal to T_1 = 30^{0}C.

Table 2. Crude oil composition by weight.

Element	Percent range	Average composition
Carbon	83 to 87%	84%
Hydrogen	10 to 14%	11%
Nitrogen	0.1 to 2%	1%
Oxygen	0.1 to 1.5%	1%
Sulfur	0.5 to 6%	3%
Metals	less than 1000 ppm	-

The content of hydrocarbons in crude oil generally varies widely but the proportion of chemical elements belongs to a fairly narrow limit (Speight, 1999). To develop our numerical computation, we considered a certain type of petroleum $C_xH_yO_zN_wS_v$ with $x = 0.384$, $y = 0.603$, $z = 0.003$, $w = 0.004$, $v = 0.005$, the apparent molecular weight $M = 5.486$ kg/kmol and the heat of combustion $\overline{h}^{T_2^{i-1}}_{C_xH_yO_zN_wS_v} = 253530\ \text{kJ/kmol}$ evaluated based on the average values shown in Table 2. Now, the equation for the oil complete combustion into the combustion chamber might be written as follows

$$C_{0.384}H_{0.603}O_{0.003}N_{0.003}S_{0.005} + 0.538\left(O_2 + 3.76N_2\right) \rightarrow 0.384CO_2 + 0.301H_2O + 0.005SO_2 + 2.0245N_2 \tag{20}$$

and based on numerical coefficients in Eq. (20) and on the previously calculated value of $T_{DewPoint}=69.18^0C$ the Eq. (17) rewrites as

$$\frac{\Delta\dot{m}^i}{\dot{m}^{i-1}} = \left\{ \frac{4.752\times10^8}{M\left[c\left(T_1 - T_2^{i-1}\right) + (P_{max} - P_{min})/\rho\right]} + 1 \right\}^{-1} \tag{21}$$

allowing, for $i \geq 1$, the computation of the energy costs for heating-up and pumping the oil through the i-th transportation module of length L_i.

Table 3. Properties of the crude oil.

Temperature	Dynamic viscosity (1)	Kinematic viscosity (1)	Density (2)	Specific heat (1)
T (^{0}C)	μ (kg/m·s)	ν (cm^2/s)	ρ (kg/m^3)	c (kJ/kg·K)
0	1.760	20.70	850.24	1.8329
5	1.240	14.70	843.54	1.8513
10	0.903	10.71	843.14	1.8698
15	0.643	7.65	840.52	1.8882
10	0.498	5.96	835.57	1.8698
25	0.422	5.08	830.71	1.9252

(1) (Bobra and Callaghan, 1990); (2) calculated based on μ=ρν.

The integration of the ODE system represented by Eqs. (10) – (13) has been performed by the fourth order Runge-Kutta technique for different adjacent transportation modules until the total length represented a certain distance of the order of magnitude $\sum L_i = 4000\ km$. The initial conditions for each transportation module were $\left[30^0C \quad 2400\ kPa \quad 0 \quad 0\right]^T$ and integration ended when $P = 100\ kPa$. Temperature variation of the crude oil properties are calculated by interpolation in Table 3 based on the already published data. The final values of oil temperature and pressure calculated for the i-th transportation module were then considered as the initial values to calculate the (i+1)-th module.

Numerical procedure has been applied for different values of the thickness of the insulation layer of the pipeline external surface $\delta \in \{0.050$ m; 0.075 m; 0.100 m$\}$ and then different lengths for the first transportation module have been determined $L_1 \in \{154.65$ km; 173.86 km; 188.01 km$\}$.

To certify that the mathematical model reproduces well the main features of the real phenomenon, Figure 2 shows the variations of petroleum temperature and pressure along the first transportation module. It can be clearly seen in Fig. 2 the results of numerical simulation showing realistically the accentuated pressure loss when viscosity of petroleum increases while its temperature decreases.

The numerical results of the three numerical simulations considering thicknesses of the insulating layer equal to 0.050 m, 0.075 m e 0.100 m, respectively are shown in Table 4 for a 4000 km long pipeline. The calculus performed to assess energetic costs for heating and pumping of petroleum in this type of transportation has determined the consumption of pumped petroleum for heating and power supply by

$$\sum_i \frac{\Delta\dot{m}^i}{\dot{m}^0} = \frac{\dot{m}^0 - \dot{m}^i}{\dot{m}^0} \tag{22}$$

Based on the values shown in Table 4 it is worth noting that that consumption of petroleum for the operation of the pipeline decreases 21.62%, from 1.85% to 1.45%, when insulation thickness increases from 0.050 m to 0.100 m. Since the insulation volume increases 2.154 times when insulation thickness increases, this also yields an increase of the fixed-capital investment. Optimization of the pipeline design is then necessary in order to balance investments to reduce or at least maintain a certain payback period.

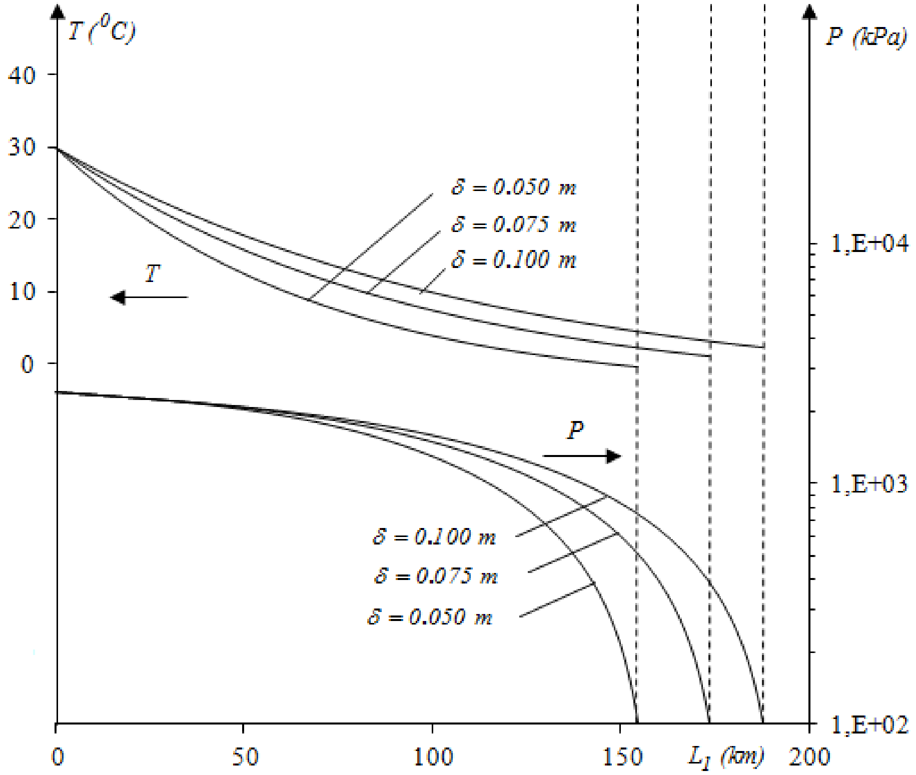

Figure 2 – Variations of petroleum temperature and pressure along the first transportation module.

Table 4. Energy costs, CO_2 emissions and entropy generation/ exergy destruction.

δ	i	L_i	$\dot{m}^i$	$\dot{S}_{ger,T}$	$\dot{S}_{ger,P}$	$\sum_i \frac{\Delta \dot{m}^i}{\dot{m}^0}$	$\frac{1}{\dot{m}^i}\sum_i \dot{m}^i_{CO_2}$	Taxes/ CO_2 Emission	$\frac{\dot{E}_{lost}}{\dot{m}^i}$
(m)		(km)	(kg/s)	(W/K)	(W/K)	(%)	(kg CO_2/BBL)	(A$/BBL)	(MJ/BBL)
0.050	5	773.47	43.83	2352.13	2142.25	0.40	1,66	0,04	4,13
	10	1547.50	43.67	4695.98	4277.15	0.74	3,12	0,08	8,28
	15	2322.07	43.52	7031.49	6404.74	1.09	4,60	0,12	12,43
	20	3097.30	43.37	9358.72	8525.47	1.43	6,07	0,16	16,61
	25	3873.07	43.22	11677.72	10638.85	1.78	7,56	0,20	20,80
	26	4028.28	43.19	12140.52	11060.58	1.85	7,86	0,20	21,64
0.075	5	869.48	43.83	2350.81	2130.55	0.38	1,58	0,04	4,12
	10	1739.46	43.69	4694.00	4254.13	0.71	2,98	0,08	8,25
	15	2610.04	43.54	7029.56	6371.17	1.04	4,38	0,11	12,39
	20	3481.12	43.40	9357.52	8481.25	1.37	5,78	0,15	16,56
	23	4004.04	43.31	10750.63	9744.10	1.57	6,63	0,17	19,06
0.100	5	940.28	43.84	2341.40	2122.65	0.37	1,53	0,04	4,10
	10	1881.12	43.70	4675.76	4238.84	0.69	2,87	0,07	8,22
	15	2822.45	43.56	7003.07	6348.36	1.00	4,22	0,11	12,34
	20	3764.34	43.42	9323.35	8451.42	1.32	5,58	0,14	16,49
	22	4141.25	43.36	10249.50	9290.86	1.45	6,12	0,16	18,15

Numerical results in Table 4 indicate the emission of CO_2 - related only with the pipeline operation - in the range 6.12 to 7.86 kg CO_2/ oil barrel (BBL). Carbon dioxide emissions along the pipeline are evaluated by adding the emitted CO_2 on each transportation module and dividing by the mass flow rate of petroleum which continuously diminishes. The longer the distance the petroleum has to reach the larger are the specific CO_2 emissions.

$$\frac{1}{\dot{m}^i}\sum_i \dot{m}^i_{CO_2} = x\frac{M_{CO_2}}{M}\left(\frac{\dot{m}^0}{\dot{m}^i}-1\right) \tag{23}$$

It is very important to point out that the CO_2 emissions decrease when insulation thickness increases. This is a very interesting finding since there are countries that are concerned with this question and already charging CO_2 emissions taxes. For instance Australia where the biggest polluters will initially pay A$23 per tonne of carbon dioxide emitted, more than twice the cost of carbon pollution in the European Union, currently trading around $10 a tonne (Grubel and Reklev, 2012). The CO_2 emission taxes in Table 4 shows that if applied according to Australian regulations, the CO_2 emission taxes should add from 16 to 20 cents of Australian dollar (A$) to the petroleum cost. Then, investing in the insulation cost to reduce CO_2 emission makes sense since it would reduce payments with the taxes.

Entropy generation by irreversibility related to the finite temperature difference thermal interaction between the petroleum flowing through the pipeline and the surrounding permafrost, $\dot{S}_{ger,T}$, and irreversibility related to the frictional dissipation mechanism associated with the oil internal viscosity, $\dot{S}_{ger,P}$, are evaluated in Table 4 for $T^* = 273.15\ K$ and then the specific exergy destruction is evaluated for $T_0 = 298\ K$ with

$$\frac{\dot{E}_{lost}}{\dot{m}^i} = \frac{\dot{S}_{ger,T}+\dot{S}_{ger,P}}{\dot{m}^i}T_0 \tag{24}$$

Based on the numerical values in Table 4 we learned that it would be possible to reduce up to 16.12% the exergy destruction during the oil transportation by increasing from 0.05 m to 0.10 m the insulation thickness.

4. CONCLUSIONS

Energy efficiency of oil pumping along an Arctic pipeline is evaluated when considering the losses generated by thermal and frictional mechanisms of irreversibility. Entropy generation was evaluated and we learned that it would be possible to avoid up to 16.12% of the exergy destruction by increasing from 0.05 m to 0.10 m the insulation thickness.

Energy costs for pumping and heating during pipeline transportation decreases 21.62% when pipeline insulation thickness increases from 0.05 m to 0.10 m.

Environmental issues are considered in connection with the permafrost layer conservation, where the pipeline is buried at temperatures below 0 ^{0}C. Assuming the energy for oil heating and pumping to be extracted from the pumped petroleum, we calculated 6.12 to 7.86 kg CO_2/BBL of oil transported through a 4000 km long pipeline.

CO_2 emission cost, if taxes applied according to Australian regulations, should add from 16 to 20 cents of Australian dollar (A$) to the petroleum cost. Therefore investing in the insulation cost to reduce CO_2 emission makes sense since it would reduce payments with the taxes.

5. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of this work by the Interdisciplinary Program in Engineering of Oil and Natural Gas/ PRH-24 at the Federal University of Paraná, PR Brazil.

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