AN ECONOMIC APPROACH TO THE HANDLING OF WAXY CRUDE OIL PIPELINES

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ABSTRACT

In order to optimize profitability in the handling of waxy crude oil pipelines, an optimum cost of handling or an optimum flowrate for a given handling budget must be worked out. Such optimum parameters are related to the operating temperature and rheology of the crude oil. A sensitivity study was conducted to identify those parameters which limit profitability. Based on the case study, it was found that the handling cost per foot is sensitive to profit margin, fraction of oil in flowing system, energy cost of transportation, cost of chemical and operations maintenance cost in decreasing order of elasticity.

Keywords: Waxy crude, Pour-point, Oil pipeline, Economics.

INTRODUCTION

Generally, all cases of organic deposition comprising paraffins and asphaltenes are referred to as waxy crude oils, Newberry, (1984). Waxy crudes poses serious flow assurance issues in the oil industry particular in deepwater and frontier environments which are associated with very low temperatures and rapid pressure drops from long tieback lines that connects subsea wellheads to production facility. These crudes are difficult to handle because of their high pour-points leading to unplanned shutdowns as well as restart events due to the complex rheological properties of the gelled crude, (Suppiah *et al*, 2012, Luthi, 2013). The pour-point is the temperature below which the oil ceases to flow (pour). The pour-point is usually about 10-20 ^oF lower than the cloud-point, the temperature at which paraffin particles begin to precipitate out of solution. The temperature at a waxy crude oil gels or wax precipitates is an important property that determines the initiation of the deposition process, Venkatesan *et al* (2002).

LITERATURE REVIEW

Available literatures discuss methods of handling the transportation of waxy crude oils in pipelines (Sarkar and Bhattacharya, 1991, Ells and Brown, 1971; Harvey et al, 1971; Smith, 1979; Uhde and Kopp, 1971, Ford et al, 1965). Ajienka and Ikoku (1990) have discussed the practices, problems and prospects of handling waxy crude oils in Nigeria. In another paper, Ajienka and Ikoku (1991) presented an economic model for comparing various methods of handling waxy crude oils to facilitate decision making. In this paper, the chosen handling method in a given pipeline diameter and length, is critically evaluated to optimize profitability and conduct sensitivity studies to determine those factors that limit profitability. Uhde and Kopp (1971) observed that the ideal method to handle waxy crude is that which changes the non-Newtonian flow behavior into a Newtonian one with a minimum of expenditure, minimum disturbance of the operation, without undesirable side effects and a resultant reduction in operational risks.

Ells and Brown (1971) compared various handling costs in a given 58 mile, 20 inch diameter pipeline. They did not consider mechanical methods. Most of these methods did not discuss optimization of the chosen handling method. The cost of chemicals, heating and other methods of handling can affect profitability as well as inefficient or excessive handling. To alleviate this problem, an optimum cost of handling waxy crude oil pipelines must be determined. On the alternative, an optimum flowrate for the available handling budget can be worked out. Such optimum parameters must be related to the operating temperature and rheology of the crude oil. It is also necessary to consider economic operations vis-a-vis maximum production or throughput. Optimization should not necessarily imply injection of chemicals or heating until maximum production is achieved. Thus the cost of handling must be taken together with the market value of the produced oil to determine the economic point of handling.

Yang and Luo (1987) optimized the handling of a heated flow line on the basis of minimum cost of transportation. They reported a hierarchical function:

$$C_{min} = C_f[T_o, C_p * (T_o)] + C_p[T_o, C_p * (T_o)] \quad (1)$$

It was observed that fuel, C_f and pumping C_p costs vary inversely with heating station inlet temperature. The higher the normal flowing temperature, the greater the pumpability of the crude oil thus lower, the cost of pumping, quantity and cost of fuel required to heat the pipeline.

DERIVATION OF ECONOMIC MODEL

In this study the annual energy cost of transportation is used to optimize the flow system. This helps in determining the economic flowrate for a given handling budget and expected profit regime. Such flowrate can then be compared with the design flowrate. It also helps in evaluating the effect of energy cost on the profitability of the handling method. Chemical injection is chosen as handling method to inhibit wax precipitation in the pipeline system. Thus the total handling cost C_{th} includes the energy cost of pumping and chemical injection as well as the cost of chemical used. The annual energy cost of pumping is given by Ajienka (1990) as:

$$C_1'(\$/yr) = (B) * (HP) \quad (2)$$

where:

$$B = 0.746 * 24 * 365 * C_a \quad (3)$$

$$HP = HP_1 + HP_2 \quad (4)$$

HP_1 = Horsepower from normal pumping operations

$$HP_1 = \frac{Q_{L(gpm)} \Delta P_t}{1714 E_{vl}} \quad (5)$$

Where $Q_{L(gpm)}$ is the flowrate in gallons per minute (GPM), ΔP_t is the total pressure in pounds per square inch (psi) and E_{vl} is the volumetric efficiency of the major pump, C_a is the energy cost, ($/KWh). HP_2 is the Horsepower from the chemical injection pump

$$HP_2 = \frac{Q_{L(gpm)}\Delta P_t}{1714E_{vl}} \quad (6)$$

where:

E_{vc} is the efficiency of the injection pump, $q_{c(gpm)}$ is chemical injection rate (GPM) and ΔP_{cp} is the total pressure drop in the injection pump (psi) . The ΔP_{cp} is taken as a fraction of the total pressure drop in the major pump in this investigation.

Assuming a power-law model, the total pressure drop for normal pumping operations at the worst condition of turbulent non-Newtonian flow is given by (Ajienka, 1990) as:

$$\Delta P_t = \Delta P_{el} + X_3 L Q^{\left(\frac{n+6}{4}\right)} D^{-(4+0.75n)} \quad (7)$$

$$\Delta P_{el} = \rho \frac{g}{g_c} \Delta z \sin\theta \quad (8)$$

$$X_3 = \frac{2.528\rho^{0.75}}{\pi(1.5 + 0.25n)g_c}\left[4^{2-n}\left(\frac{8}{k}\right)\left(\frac{n}{2+6n}\right)^n\right]^{-0.25} \quad (9)$$

Δz is the pipe elevation above the ground, ft and ρ is the density of oil, Ibm/ft^3, g_c is the conversion factor for acceleration due to gravity, Q is the flow rate, ft^3/sec, L is the length of the pipe (miles), D is the diameter of the pipe, (in), ΔP_{el} is the pressure drop due to elevation (psi), ΔP_t is total pressure drop in the major pump, (psi), θ is the angle the pipeline substends with the horizontal above the ground.

For restarted flow at some minimum flowrate Q_{min}, the total pressure drop is given by

$$\Delta P_t = \Delta P_{el} + \frac{4\tau_y L}{D} \quad (10)$$

τ_y is the yield stress in $Ibf/100ft^2$, L is the length of the pipe (miles), D is the diameter of the pipe, (in).

Here, the rheological parameters are defined as:

$$n, k, \tau_y = f(T_{NN}, API)$$

$$n = 1.103015 - 0.0158721T_{NN} - 0.0029286API \quad (11)$$

$$\tau_y = 0.55467\exp(0.12099T_{NN} + 0.02411API) \quad (12)$$

$$k = 0.017158\exp(0.1338021T_{NN}0.0247712\ API) \quad (13)$$

where

$$T_{NN} = T_p - T \quad (14)$$

T_{NN} is the non-Newtonian temperature, ^oF, T_p is the pour-point temperature, ^oF, T is the temperature, of the crude, n is the power law index, dimensionless, k is the power law consistency index, lbm/sec^n. The annual cost of chemical injection becomes:

$$C_i = 17.904 * 365 * q_c * C_{ai} * HP_2 \quad (15a)$$

The annual cost of chemical is given by:

$$C_2 = 365q_cC_{cPB} \quad (15b)$$

where q_c is chemical injection rate (bbl/D) and C_{cpB} is chemical cost (\$/bbl), C_{ai} is the energy cost due to injection, (\$/KWh).
Therefore, the total annual cost of handling chemical will be:

$$C_{cT} = (17.904C_{ai}HP_2 + C_{cPB})365q_c \tag{16a}$$

Assuming that the annual cost of injection is a fraction *(i)* of the annual chemical cost, then the total annual cost of handling chemical, C_{cT} will be:

$$C_{cT} = (1 + i)C_2 = (1 + i)365q_cC_{cPB} \tag{16b}$$

All other handling costs such as operations and maintenance costs can be expressed as a fraction of C_1' and defined as:

$$C_1 = (1 + i)C_1' \tag{17}$$

The cost of chemical injection can be related to the market value of the pumped oil and thus the average expected profit. In this, the concept of economic slope by Kanu et al (1981) was adapted to this work. The basis of this concept is that production should be at a point where the profit from incremental recovery of volume of oil equals or exceeds the increment in cost which was incurred as a result of additional chemical injection to effect that production or pumpability. Mathematically,

$$\Delta Q_Lf_oP \geq (17.904C_{ai}HP_2 + C_{cPB})\Delta q_c \tag{18a}$$

where Q_L is the total liquid produced, BPD; $f_o$is the fraction of oil produced, P is the profit in \$/bbl computed without cost of handling, Δq_c, is the chemical injection rate , bbl/day and C_{cT} is the total cost of handling (cost of chemical and cost of chemical injection) in \$/bbl
Equation 18a can be rewritten in this form

$$\Delta Q_Lf_oP \geq x(17.904C_{ai}HP_2 + C_{cPB})\Delta q_c \tag{18b}$$

Therefore,

$$x = \frac{\Delta Q_Lf_oP}{(17.904C_{ai}HP_2 + C_{cPB})\Delta q_c} \geq 1 \tag{19}$$

where $x \geq 1$
If $x < 1$, uneconomical handling. Cost of handling is greater than profit derived from production. Additional costs result in less profit.
$x > 1$, Production is economic but not at economic optimum.
$x = 1$, Increment in profit is equal to increment in cost of handling. This is economic limit.
Thus at economic limit,

$$x = \frac{\Delta Q_Lf_oP}{(17.904C_{ai}HP_2 + C_{cPB})\Delta q_c} = 1 \tag{20}$$

The optimum injection rate for a given flowrate to prevent wax precipitation can be determined experimentally. Thus

$$q_c = \frac{\Delta Q_Lf_oP}{(17.904C_{ai}HP_2 + C_{cPB})\Delta q_c} \tag{21}$$

Where ΔQ_L is the incremental rate; BPD; f_o is the fraction of oil produced, P is the profit in \$/bbl computed without cost of handling, Δq_c,is the incremental chemical injection rate, bbl/day and C_{cT} is the total cost of handling (cost of chemical and cost of chemical injection) in \$/bbl.

Solving equation 21 to calculate the optimum injection rate requires an iterative procedure since the procedure since the horsepower is a function of the injection flow as seen in equation 6; and this could easily be handled using Newton-Raphson method. An alternate method to boycott this iterative procedure is to use equation 16; which assumes that the cost of injection is a fraction of the cost of chemical since the cost of chemical is usually much higher than the injection cost.

Alternatively, since cost of chemical C_{cPB}, is usually much more than the cost of chemical injection, it is assumed that the annual cost of chemical, C_2, is approximately equal to the total annual cost of handling chemical, C_{cT}.
Equation (10) can then be rewritten as:

$$\Delta Q_L f_o P = x C_{cPB} \Delta q_c \tag{22}$$

Hence,

$$x = \frac{\Delta Q_L f_o P}{C_{cPB} \Delta q_c} \geq 1 \tag{23}$$

Thus at economic limit,

$$x = \frac{\Delta Q_L f_o P}{C_{cPB} \Delta q_c} = 1 \tag{24}$$

The optimum injection rate for a given flowrate to prevent wax precipitation assuming cost of chemical injection is negligible is given as:

$$q_c = \left(\frac{f_o P \Delta Q_L}{C_{cPB}}\right) \tag{25}$$

Substituting, equations (3, 5 &6) into eq (17) and adding eq (16) gives the total annual cost of handling (annual energy cost plus annual chemical cost) as:

$$C_{Th} = (1+j)\frac{B}{1714}\left(\frac{Q_{(gpm)\Delta P_t}}{E_{vl}} + \frac{q_{c(gpm)\Delta P_{cP}}}{E_{vc}}\right) + (1+i)365 q_c C_{cPB} \tag{26a}$$

If $C_1 \ll C_2$, then

$$C_{Th} = (1+j)\frac{B}{1714}\left(\frac{Q_{(gpm)\Delta P_t}}{E_{vl}} + \frac{q_{c(gpm)\Delta P_{cP}}}{E_{vc}}\right) + 365 q_c C_{cPB} \tag{26b}$$

METHOD OF APPLICATION

The method of application is to calculate cost per foot as a function of flowrate and chemical cost and interpolate to obtain the economic flowrate, Qec for a given handling budget per foot. Any flowrate greater or less than Qec will result in uneconomic handling. Matlab was used to solve the problem using the models as derived and generate the plots for the sensitivity analysis
The input data are given in the Table1 and the results presented in Figures 1-20.

RESULTS/DISCUSSIONS

The results of this study are evaluated using graphical approach and presented mainly in two folds: (i) plot of annual cost of handling per foot against temperature and (ii) plots of annual cost of handling against flow rate. Each fold is then subjected to sensitivity analysis to observe the effects of some essential parameters as input variables.

The annual cost of handling decreases with increasing temperature and flow rate as shown in Figures 1 to 10. This is expected and it is in conformance with fundamental principles of handling waxy crude oils. At higher temperatures, the pumpability of the crude increases and the flow behaviour changes from non-Newtonian to Newtonian flow.

Sensitivity analysis on the effect of oil fraction, the energy cost and profit margin was investigated. Figure 2 and 3 shows the effects of oil fraction from the base case of 100% to 80 and 70% while Figure 4 and 5 is for the effects of energy cost from base case of USD 0.238/kwh to 0.3 and USD 0.5/kwh respectively. The effect of the profit margin is shown in Figures 6 to 8 from USD10 to 5, 15 and USD 25 respectively. It is glaring to note that the most sensitive parameter is the profit margin followed by fraction oil; the least sensitive is the energy cost. The profit margin varies directly with the injection rate (see equation 22), thus at higher injection rates with the most suitable chemical, the profit margin increases.

The second fold of plots (Figures 11 to 20) are plots of annual handling cost against flow rate at different pour-point temperatures. Figure 10 is the base case and shows how the cost of handling increases with decreasing flow rate at different pour-points. Again this is expected as at higher pour-points, higher temperatures, more chemicals, etc. thus more cost, would be required to ensure continuous flow. Sensitivity analysis was also done in the range of data and variables as discussed in the first fold and the order of degree of sensitivity followed the same pattern with the profit margin being the most sensitive and the cost of chemical being the least sensitive.

CONCLUSIONS

An economic model is presented to optimize the handling of waxy crude oil pipelines. This model is dependent on the rheology of the crude, technical and economic parameters related to the chosen handling method. Optimization here should not necessarily imply injection of chemicals or heating until maximum production but operating at the economic point. The economic point being an interplay of operating and handling conditions and the market value of the produced oil. Both inefficient handling and excessive handling would affect profitability. From the study, the following conclusions are drawn:

1. The handling cost per foot decreases with increase in inlet temperature vis-a-vis the pour-point of the crude oil. This is expected because with heating, the crude oil temperature is raised above the pour-point, flow is Newtonian and pumpability is improved. In this instance where chemical injection is considered, crudes whose temperatures are close to the pour-point have a higher tendency of being prevented from gelation due to wax-up by chemical injection than those that are already gelled up and their temperature far below the pour-point of the crude.
2. An economic flowrate is that which corresponds to the available budget and prevailing economic parameters. Any flowrate greater or less than this does not make for optimization. The economic flowrate can be obtained from any of the Figures 12 by tracing the expected annual handling cost against the corresponding pour-point profile to determine the economic flow rate. If production due to chemical injection does not give a value close or equal to the value obtained from the figure, then the rate is not optimal.
3. The results of the sensitivity study show that the dependent parameter, cost per foot, C_{Th}/ft is sensitive to the following parameters in decreasing order of elasticity: profit margin, fraction of oil, energy cost. Assuming clean oil, the most sensitive parameter

is profit margin and the least sensitive parameter is operations and maintenance cost other than energy cost as a fraction of total cost, *j*.

4. This model is field specific and should be modified to account for changes in the rheological parameters as the flow condition changes over time.

Nomenclature

API	=	API gravity of crude oil
C_i	=	annual cost of chemical injection
C_1	=	Costs including operations and maintenance cost
C_2	=	Annual cost of chemicals
C_a	=	Energy cost, (USD/Kwh)
C_{ai}	=	Energy cost of injection
C_{min}	=	Minimum Cost, USD
C_f	=	Cost of Fuel, USD
C_{Th}	=	Handling budget, USD
C_p	=	Cost of pumping, USD
C_{cPB}	=	Cost of Chemical per harrel,USD
$D = d$	=	Pipe inside diameter, ft
E_{vl}	=	Major Pump efficiency, fraction
E_{vc}	=	Chemical pump efficiency, fraction
f_o	=	fraction of oil in well effluent
g	=	Acceleration due to gravity, ft/sec^2 (m/sec^2)
g_c	=	Conversion constant = 32.174 lbm ft/lbf sec^2
HP_1	=	Horsepower of major pump
HP_2	=	Horsepower of chemical pump
j	=	Operation and maintenance Cost (Other than energy cost) per annual chemical cost, fraction
i	=	Cost of chemical injection (a fraction of the annual chemical cost)
k	=	Power law consistency index, lbf/sec^n (Pa/sec^n)
L	=	Pipe length, ft or miles (M or km)
n	=	Power law index, dimensionless
P	=	Profit margin
ΔP_{cP}	=	Pressure drop in chemical pump (psi)
ΔP_{el}	=	Pressure drop due to elevation, (psi)
ΔP_t	=	Total pressure drop in major pump, (psi)
Q_L	=	Flowrate, BPD
$Q_{(gpm)}$	=	flowrate, gallon per minute (GPM)
ΔQ_L	=	Incremental flowrate, BPD
q_c	=	Chemical injection rate BPD
$q_{c(gpm)}$	=	Chemical injection rate, gallon per minute
Δq_c	=	Incremental injection rate
T	=	Temperature, ^{o}F
T_{cp}	=	Cloud-point, ^{o}F
T_p	=	Pour-point, ^{o}F
$T_1 = T_o$	=	Inlet temperature, ^{o}F
x	=	Fraction
ρ	=	Crude oil density lbm/ft^3
π	=	pie, 3.1416 or 22/7
τ_y	=	Yield stress lbf/100ft^2

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Table 1: Data for modelling economic handling of waxy crude oil pipeline (base case)

Pipeline diameter	= 16 inches
Pipe length, L	= 30 miles
Cost of chemical per barrel, C_{cPB},	= USD400/bbl
Operations and maintenance cost as a fraction of annual cost, j	= 10%
Beta, fraction of ΔP_t that is ΔP_{cp}	= 0.001
Energy cost, C_{cPB},	= USD 0.07/kwh
Pump Efficiency, E_v	= 90%
Profit, P	= USD10/bbl
Fraction of oil, f_o	= 1 (water-less oil)

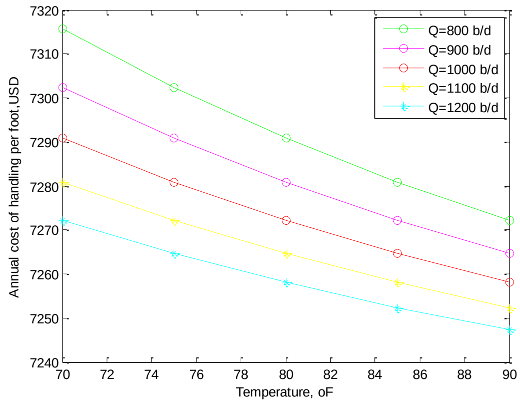

Figure 1: Temp against cost of handling (Base case)

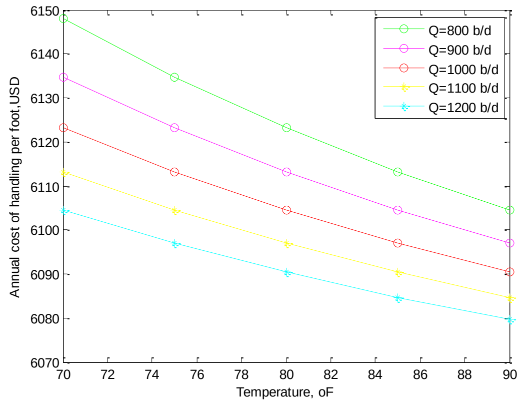

Fig 3: Temp against cost of handling (f_o= 0.7)

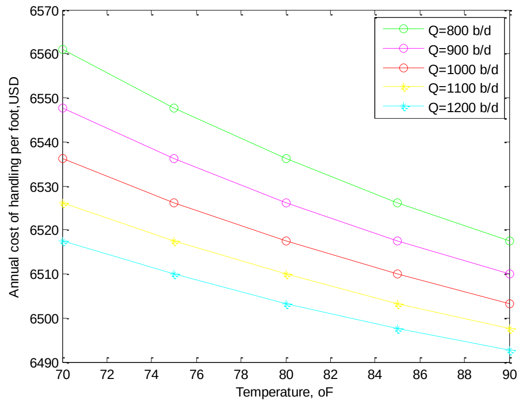

Fig 2: Temp. against cost of handling (f_o= 0.8)

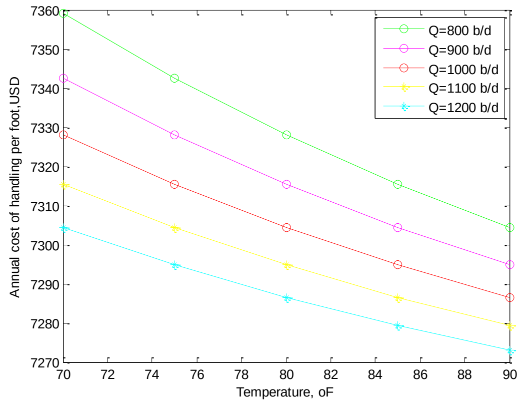

Fig 4: Temp against cost of handling (Ca = 0.3)

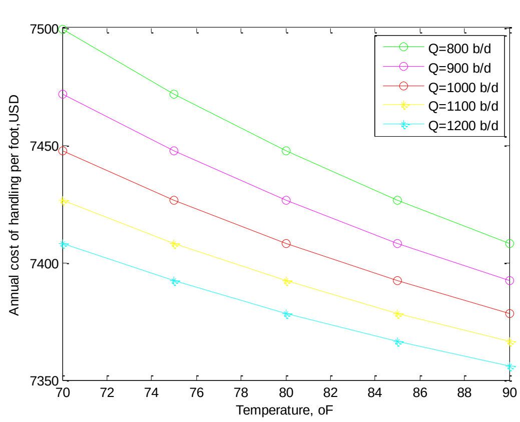

Fig 5: Temp against cost of handling (Ca=0.5)

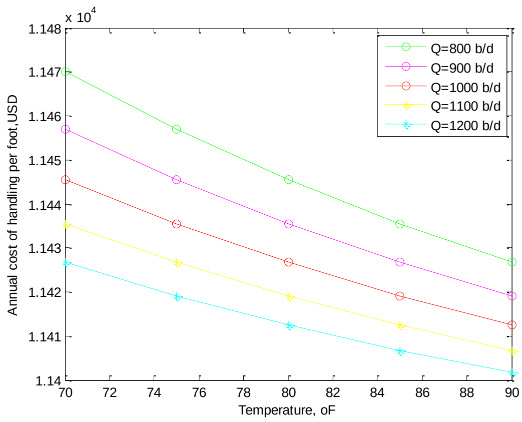

Fig 8: Temp against cost of handling (P=25)

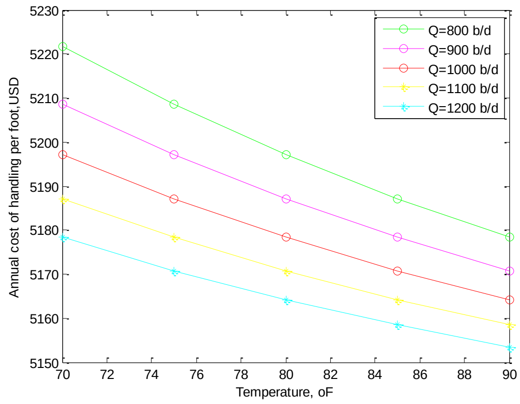

Fig 6: Temp against cost of handling (P=5)

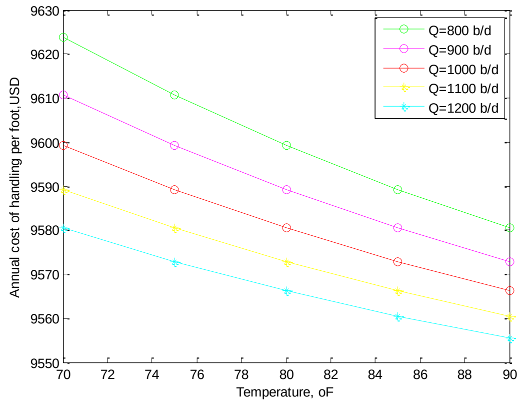

Fig 9: Temp against cost of handling (C_{cPB} =700)

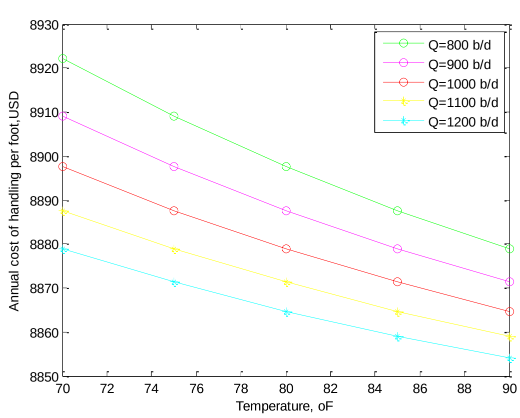

Fig 7: Temp against cost of handling (P=15)

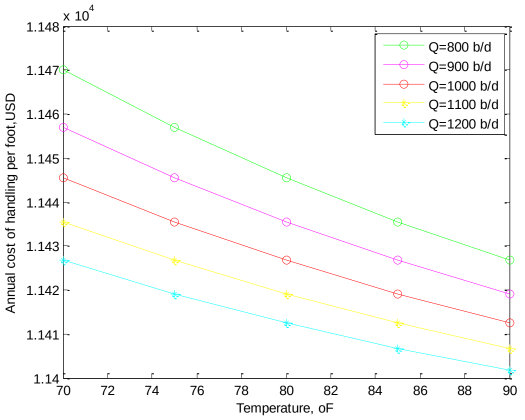

Fig 10: Temp against cost of handling (C_{cPB} =1000)

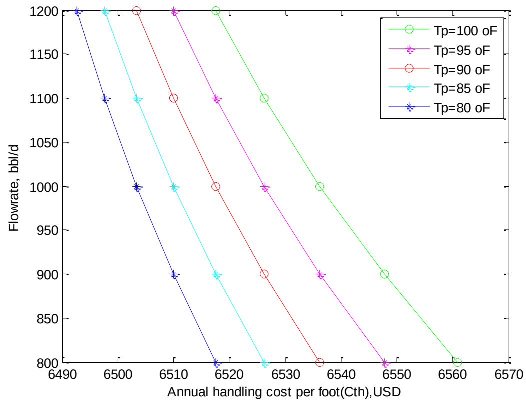

Fig 11: Cost of handling against flowrate (f_o=0.8)

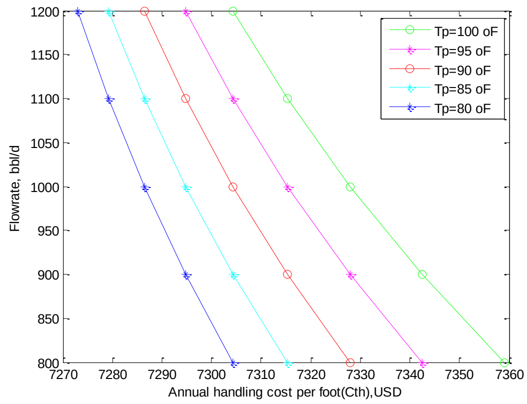

Fig14: Cost of handling against flowrate (Ca = 0.3)

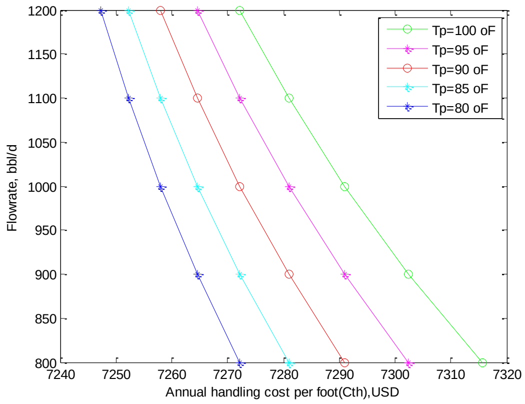

Fig12: Cost of handling against flowrate (Base case)

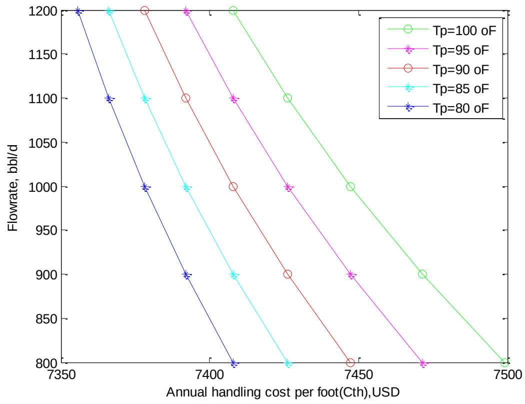

Fig 15: cost of handling against flowrate (Ca = 0.5)

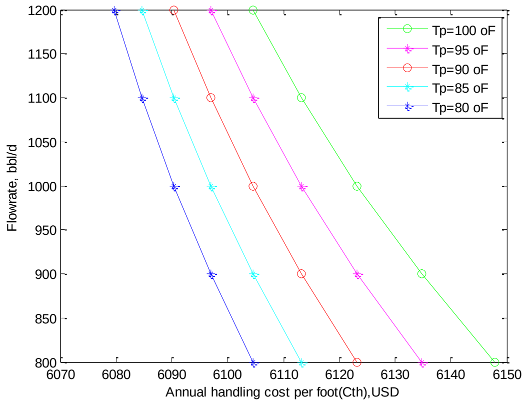

Fig 13: Cost of handling against flowrate (f_o=0.7)

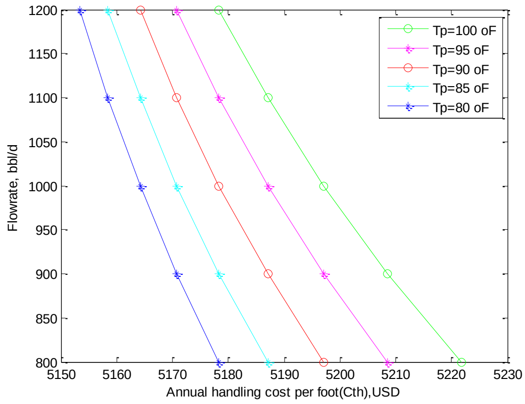

Fig 16: cost of handling against flowrate (P = 5)

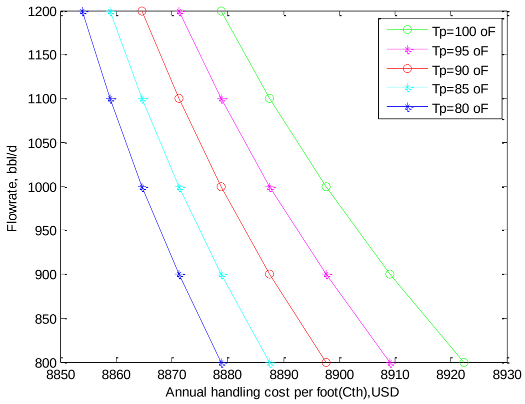

Fig17: cost of handling against flowrate (P = 15)

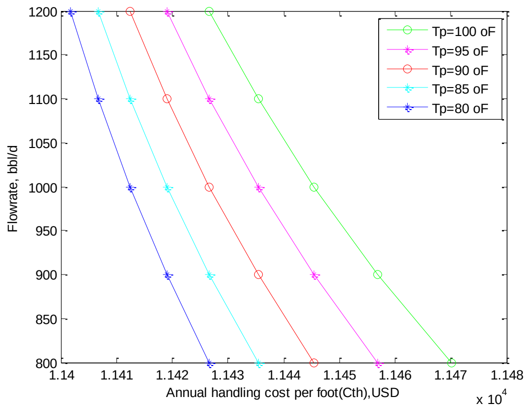

Fig 20: Temp against cost of handling (C_{cPB} =1000)

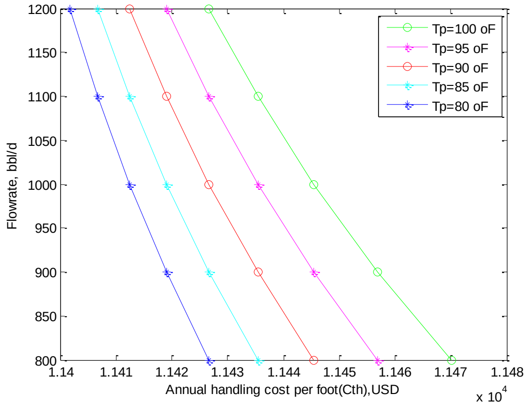

Fig18: cost of handling against flowrate (P = 25)

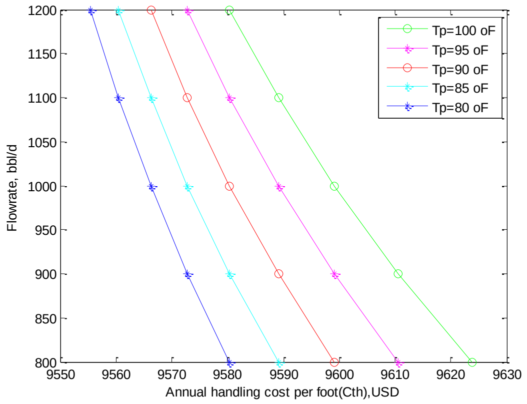

Fig 19: Temp against cost of handling (C_{cPB} =700)