5.4 HEAT TRANSFER CALCULATIONS

To determine the heat transfer and fluid dynamic effects on the fluids flowing through the Trans-Alaska Pipeline System (TAPS), a computer program has been developed in Microsoft Visual Basic 6.0, giving links to Microsoft Access (for storing database) and Excel (spreadsheets) as the back ends providing a user friendly interface.

The design requirement of this algorithm is to calculate the required heat transfer and fluid dynamic parameters for different types of fluids (crude oil, pure GTL, commingled flow with various blends). This design is based on the concept that, some portion of TAPS is above ground and other is below ground. The total length of TAPS is 800.302 miles of which 420 miles of the pipe is above ground and 380 miles of the pipe is buried.

The program basically works on Microsoft Access and Excel, and works continuously unless the user manually quits the program and deletes the required files. The back end automatically opens the file and reads the data coming from the front end and the received data is stored as records in the form of tables in the memory of the program. The received data before storing in the records is converted into required data formats. The back end program keeps working till the front end quits.

The front end MS Visual Basic is a user friendly interface and works only on the commands of the user. The program stops working when there is no user entry or by any quit commands from the users. Depending upon the commands of the user it performs various operations and gives the required results.

5.5 RESULTS AND DISCUSSION

The heat transfer and fluid dynamic parameters are found by using the equations in Sections 5.1 and 5.2 for crude oil, GTL and commingled mixture . The results of these computations are summarized as follows.

5.5.1 Heat Transfer Parameters

The heat transfer parameters for unit length of the pipe are shown below. Three different types of fluids are considered, namely:

i) 100% Crude oil
ii) 100% GTL
iii) Crude oil + GTL blend in 3:1 ratio

The results shown below are determined by assuming that 10 miles length of the pipe as buried and the adjacent 10 miles as above ground.

TABLE 5.3
Heat Transfer Parameters for Below Ground Pipeline

PARAMETERS	CRUDEOIL	GTL	COMMINGLED FLOW
Re_d (fluid)	350422	$1.6*10^6$	$4.12*10^5$
Pr (fluid)	68.75	13.95	57.42
Nu_d (fluid)	4326.16	8610.59	4632.45
h_i (W/m^2 k)	521.35	953.12	548.21
U_i (W/m^2 k)	0.91153	0.9122	0.91161
T_e (°C)	45.236	45.020	45.188
q" (W/m^2)	68.14	68.09	68.12
q (kW) for 16.09 km	4119	4110	4115
q_l (W/m)	255.95	255.39	255.70

TABLE 5.4
Air Parameters for below ground pipe

PARAMETERS	CRUDEOIL	GTL	COMMINGLED FLOW
Re_H (air)	$7.397*10^6$	$7.397*10^6$	$7.397*10^6$
Pr (air)	0.7271	0.7271	0.7271
Nu_H (air)	10430	10430	10430
h_o (W/m^2 k)	12.51	12.51	12.51

TABLE 5.5
Heat Transfer Parameters for above ground Pipeline

PARAMETERS	CRUDEOIL	GTL	COMMINGLED FLOW
U_i (W/m^2 k)	0.5543	0.5555	0.5544
T_e (°C)	44.366	44.00	44.286
q" (W/m^2)	40.18	40.04	40.15
q (kW) for 16.09 km	2427.58	2419.19	2423.32
q_l (W/m)	150.84	150.32	150.58

TABLE 5.6
Air Parameters for above ground Pipe

PARAMETERS	CRUDEOIL	GTL	COMMINGLED FLOW
Re_D (air)	$5.654*10^5$	$5.654*10^5$	$5.654*10^5$
Pr (air)	0.7314	0.7314	0.7314
Nu_D (air)	778.599	778.599	778.599
h_o (W/m^2 k)	12.217	12.217	12.217

5.5.2 Heat Loss from TAPS

The total heat loss from Trans-Alaska Pipeline System (TAPS) while transporting the three different types of fluid as mentioned above is determined for January, the coldest month of the year, and the results are tabulated as follows.

TABLE 5.7
Heat Loss from TAPS

Type of Fluid	Total Heat Loss from TAPS (kW)
Crude Oil	141793.51
GTL	132356.87
Commingled Mixture	141111.03

The above results are obtained for January with the temperature varying from –20°F to 10°F along the 800 miles length of the pipe. The wind velocity is taken as 10mph with a snow depth of 1ft on the ground. The variations in properties of the fluid and air are considered due to the changes in temperature along the length of the pipe. The results for all the three types of fluids are shown in a graphical form in Figure 5.12.

From Figure 5.12, it can be seen that for 100% Crude oil the cumulative heat loss from the pipeline is much more pronounced than in other cases. The density of GTL is much less than the density of Crude oil as the result of which the mass flow rate of GTL is less than that of Crude oil. The lower mass flow rate of GTL accounts for lesser heat loss from the fluid to the atmosphere. The commingled mixture is the combination of 75% of Crude oil and 25% GTL. The addition of 25% GTL to the Crude oil reduces the density of the mixture so results in the lower mass flow rate than Crude oil, which accounts for a relatively less heat loss from TAPS.

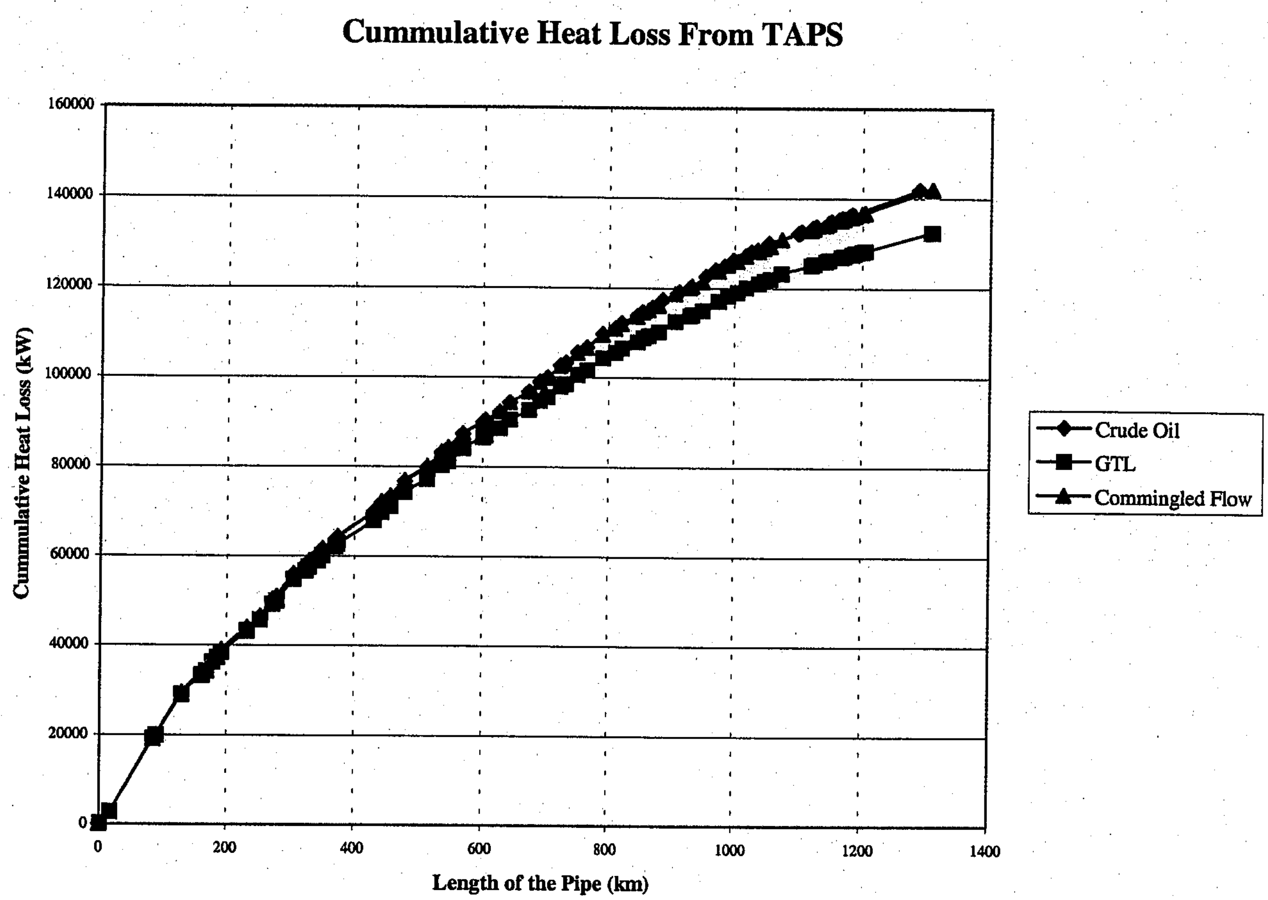

FIGURE 5.12 The Cumulative Heat Loss from TAPS from different fluids in January

The heat transfer from or to the body is given by

$$Q = \dot{m} c_p \Delta T$$

Where $\dot{m}$ is the mass flow rate

c_p is the specific heat of the medium

ΔT is the difference in temperature between two mediums

From the above equation it is clear that the mass flow rate is directly proportional to the heat transfer rate. The lower mass flow rate yields lower heat transfer rate and vice versa.
The specific heat is assumed to be same for the all the three fluids. So the lower heat loss from GTL is mainly because of lower mass flow rate.

5.5.3 Exit Temperature of the Fluid from TAPS

The exit temperature of the fluid at the terminal Valdez is determined for the all the three types of fluid and are tabulated below

TABLE 5.8 Exit Temperature of the Fluid from TAPS

Type of Fluid	Exit Temperature in °C
Crude Oil	0.877
GTL	-2.05
Commingled Mixture	-0.5

The above results are calculated for January with wind velocity of 10 mph and snow depth of 1ft. The exit temperature of the fluid leaving TAPS in the month of January is shown graphically in Figure 5.13.

Figure 5.13 shows that the exit temperature of GTL is less than that of the other two fluids. The lower temperature of GTL is because of its lower mass flow rate. Lower mass flow rate has lower heat content and cools down further. Lower mass flow rate is due to the lower density of GTL because of which the exit temperature of GTL is lower than the other two fluids. Since the density of crude oil is higher, the mass flow rate is higher and hence it has higher exit temperature than GTL and commingled mixture.

The mass flow rate is given by:

$$\dot{m} = volumertricflowrate * densityoffluid$$

Volumetric flow rate is taken as 1.1 Million barrels per day for all the fluids. As density of GTL is the minimum the mass flow rate is less for GTL.

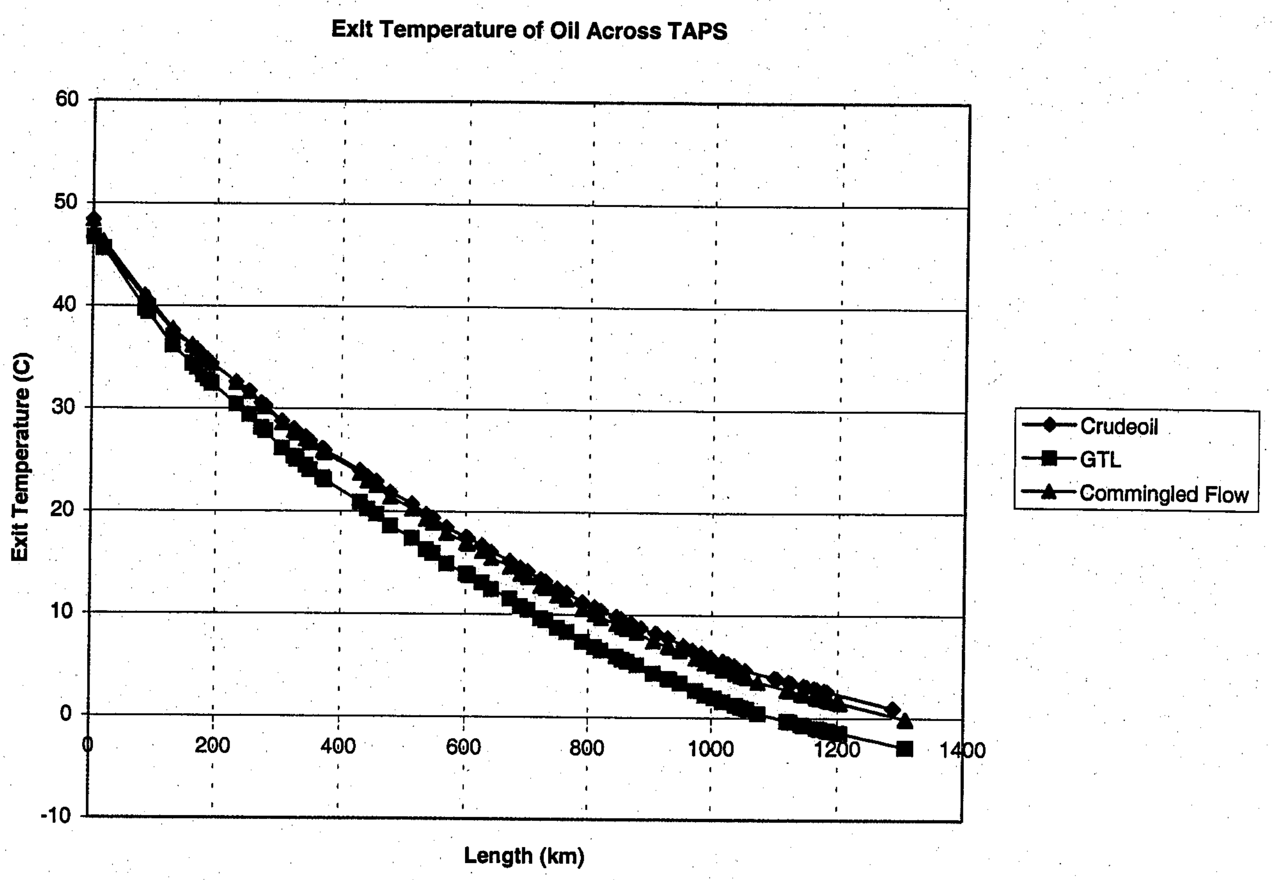

FIGURE 5.13 Exit Temperature of the fluid leaving TAPS in January

5.5.4 Exit Temperature of Fluid in Various Months

The exit temperature of the fluid leaving the TAPS is different in different months due to the variations in ambient temperatures. The exit temperatures of GTL and crude oil are calculated and shown in Table 5.9 for the four months of winter.

TABLE 5.9
The Exit Temperature of Fluid in Various Months

Month of the Year	Exit Temperature (°C)	
	Crude Oil	GTL
December	2.1	-1.4
January	0.877	-2.05
February	3.5	0.5
March	7.1	4.2

The above results are based on 10 MPH wind velocity and snow depth of 1ft. The exit temperatures of crude oil and GTL in the winter months are shown in Figures 5.14 and 5.15. Heat loss is maximum in January, which is due to the minimum air temperatures. Thus, because of the maximum temperature difference between the pipeline fluid and air in January, the exit temperature of the fluid from TAPS is minimum in January and increases towards March.

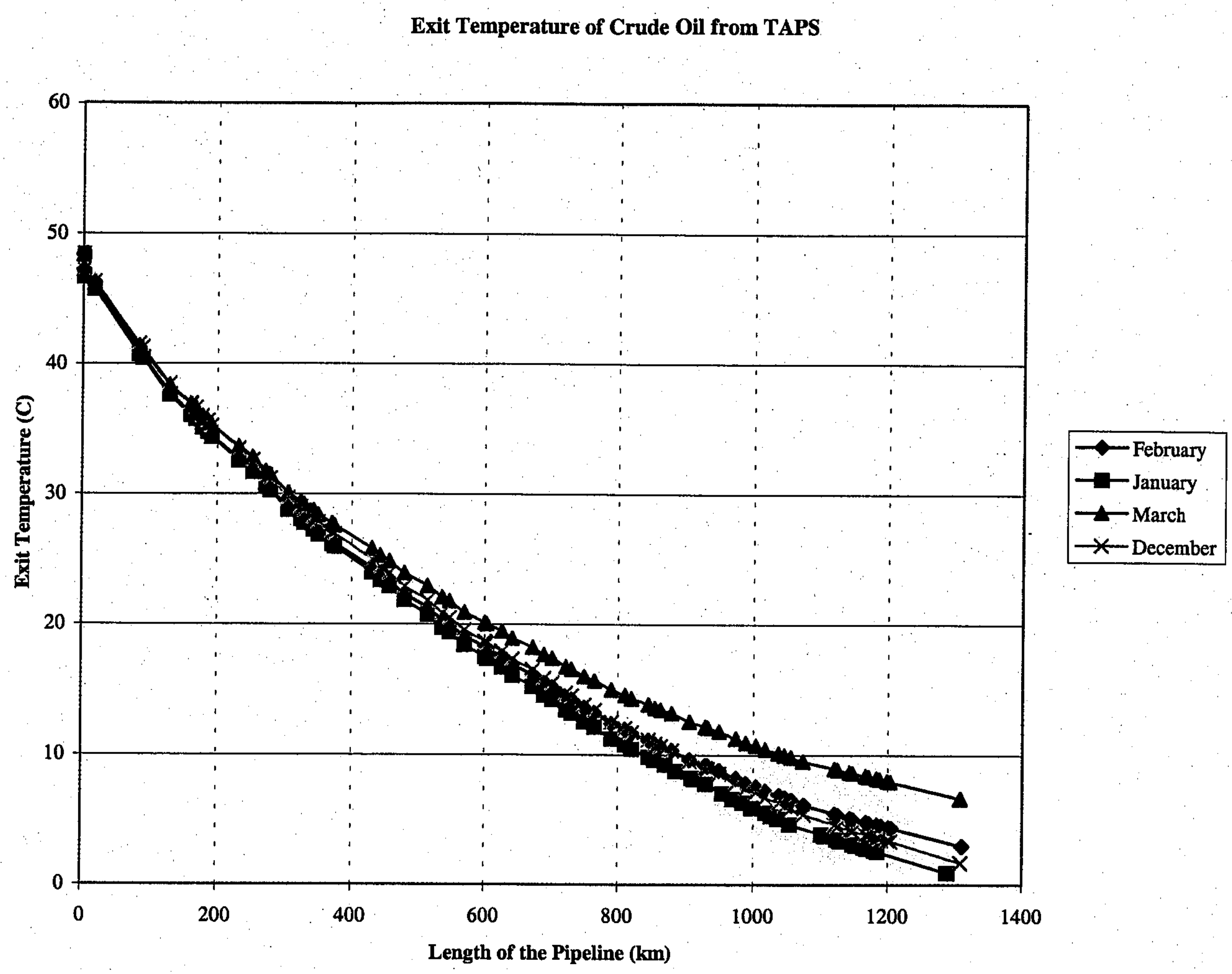

FIGURE 5.14 The exit temperature of the crude oil leaving TAPS in various months

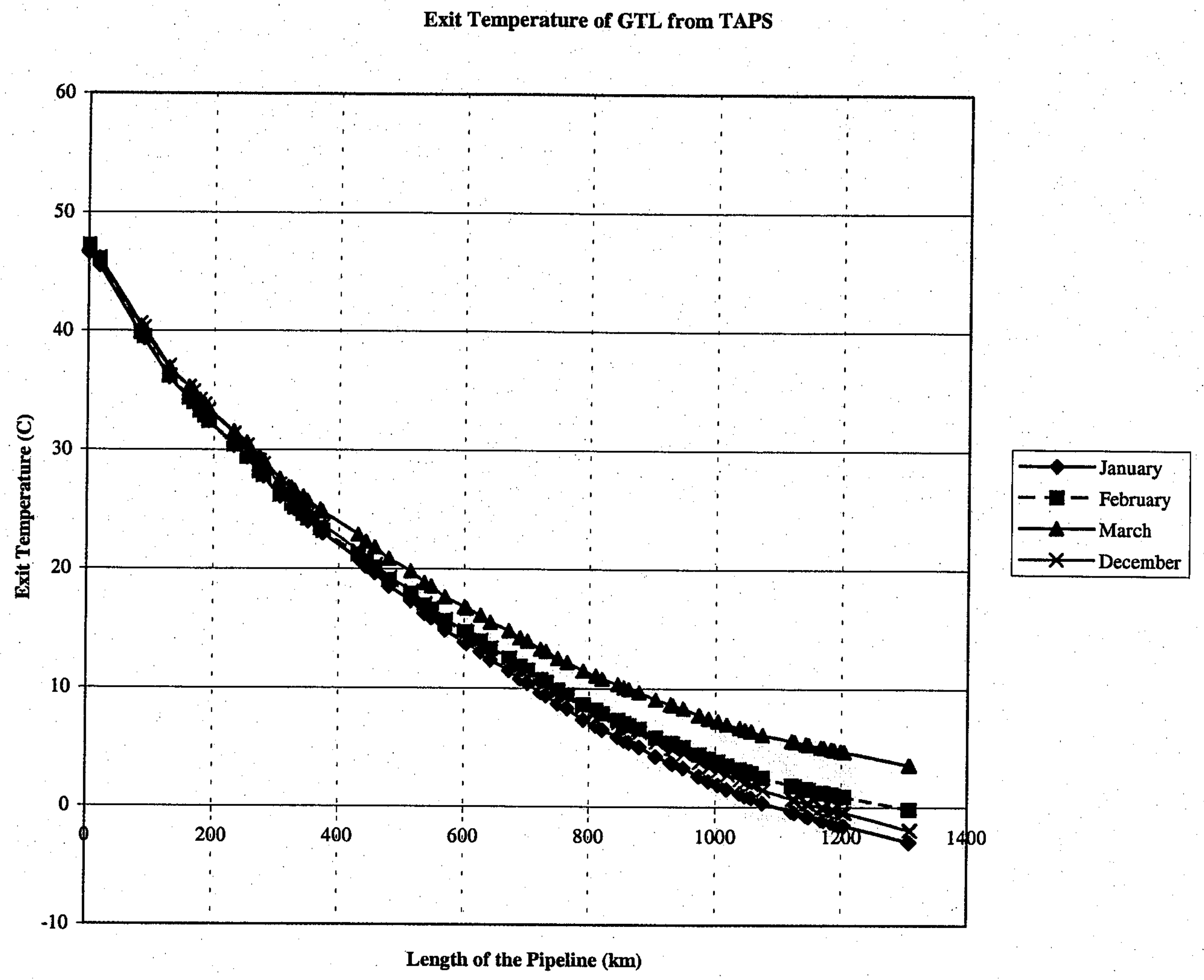

FIGURE 5.15 The exit temperature of GTL leaving TAPS in various months

5.5.5 Heat Loss from Aboveground and Belowground Sections of the Pipeline

The heat loss from the fluid to the ambient air for belowground sections of the pipe is given by

$$q = \frac{T_{iav} - T_{\infty}}{[1/(h_i 2\pi R_1 L)] + [\ln(R_2 / R_1)/(2\pi k_p L)] + [1/(k_s S)] + [d_2 /(k_{sn} LH)] + [1/(h_o LH)]}$$

The heat loss from the fluid to the ambient air for aboveground sections of the pipe is given by

$$q = \frac{T_{iav} - T_{\infty}}{[1/(h_i 2\pi R_1 L)] + [\ln(R_2/R_1)/(2\pi k_p L)] + [\ln(R_3/R_2)/(2\pi k_i L)] + [1/(h_0 2\pi R_3 L)]}$$

From the above equations we can see that the total resistance offered to the heat flow from belowground and aboveground sections of the pipe is different. Therefore the heat loss from belowground and aboveground sections will be different. The total resistance offered for the unit length of the pipe both for belowground and aboveground sections is calculated and shown in Table 5.10.

TABLE 5.10
Resistance Offered in Below Ground and Above Ground Section of the Pipe

Section of Pipe	Total Resistance Offered (m^2*k/W)
Belowground Pipe	1.1622
Aboveground Pipe	1.8316

The resistances are obtained for unit area and unit length of the pipe.

The resistance for the belowground pipe is less than the resistance for the aboveground pipe. So Heat Loss from the belowground pipe should be more than the heat loss from the above ground pipeline. The heat loss is determined for the unit length of the pipe for belowground and aboveground sections of the pipe for the month of January using wind velocity of 10 mph and is shown graphically in Figures 5.16 and Figure 5.17.

The heat loss from the entire 800 miles of the pipe of which 380 miles of the pipe is buried and 420 miles of pipe is elevated is determined. The amount of heat loss from the elevated and buried sections for the whole length of the pipe is determined and is shown in a tabular form in Table 5.11

TABLE 5.11
Heat Loss in Below Ground and Above Section of the Pipe

Section of Pipe	Heat Loss in kW
Belowground Pipeline	84292.74
Aboveground Pipeline	57500.76

The results in the above table are obtained with 10 MPH wind velocity, snow depth of 1ft and for January month. The heat loss in both the sections of the pipe is shown graphically in Figure 5.18.

Table 5.10 shows that the resistance offered to the heat flow for belowground section is much less than the resistance offered to the heat flow for aboveground pipeline. The resistance offered for the aboveground pipeline is nearly 36% more than that for the belowground section. The aboveground section of the pipe is 40 miles more than the belowground section. Due to the large difference in the resistance offered to the heat flow, the heat loss from the belowground section is higher than the heat loss from the aboveground section.

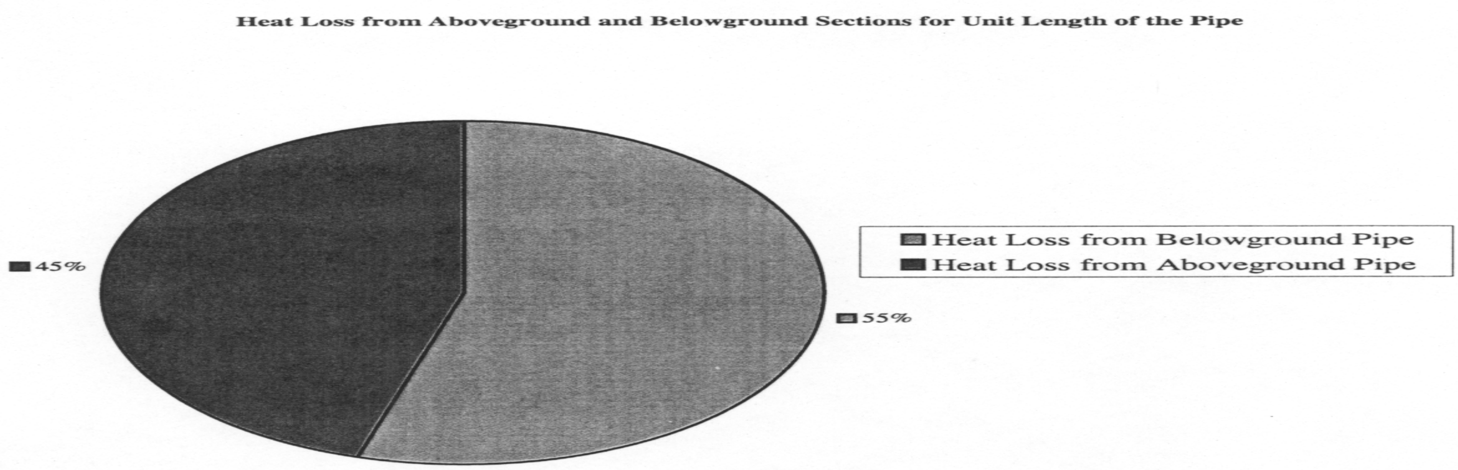

FIGURE 5.16 Heat Loss from Different Sections of the Pipe per Unit Length

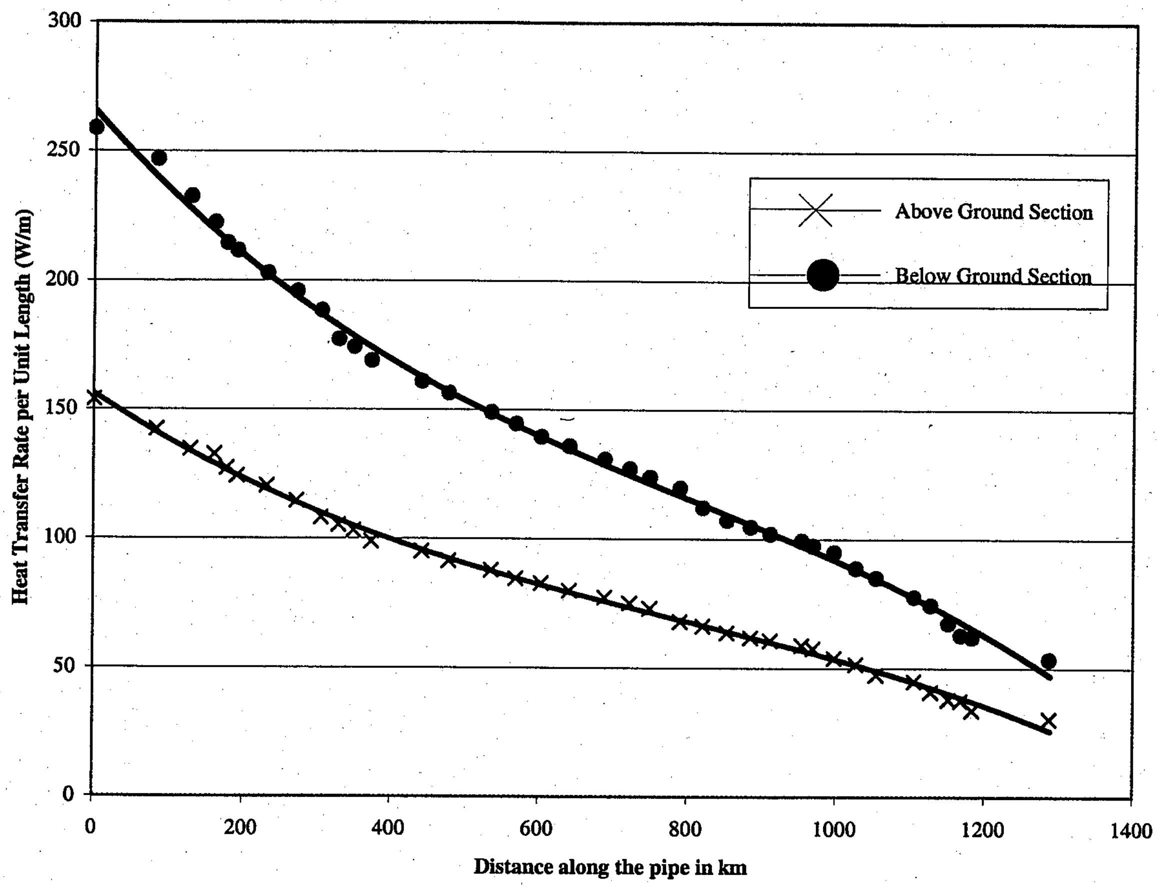

FIGURE 5.17 Heat Loss Rate from Above and Below Ground Sections of the Pipeline in January.

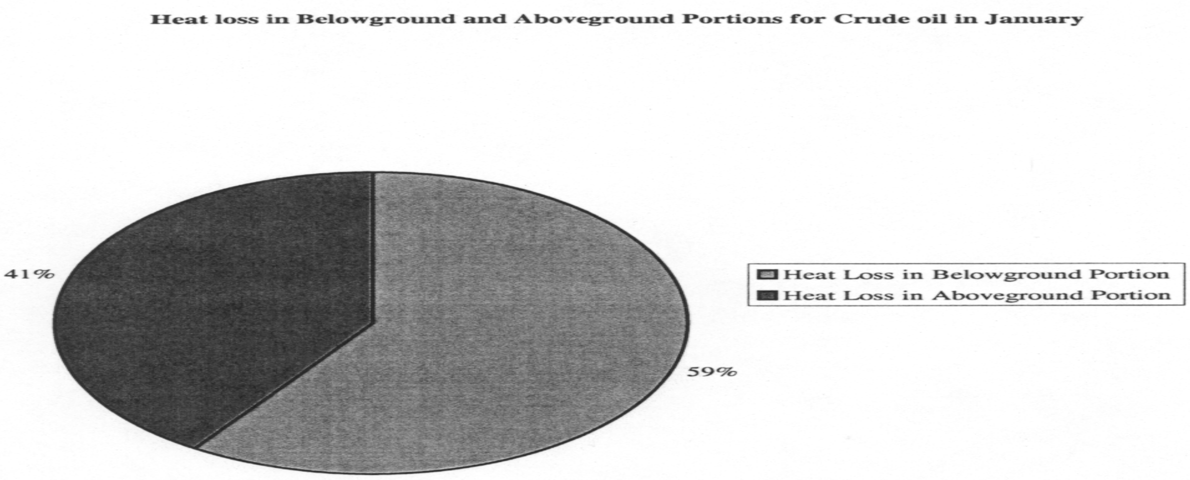

FIGURE 5.18
Heat Loss from Different Sections of the Pipe While Transporting Crude Oil

5.5.6 Comparison of Actual Data and Calculated Results

The 800 miles Trans Alaska Pipeline is currently under operation transporting crude oil from Prudhoe Bay to Valdez. The operating inlet and exit temperatures of the crude oil at different pump stations are known.

The inlet and exit temperatures of the crude oil at working pump stations are shown in the Table 5.12 (Chrisman, 2000)

TABLE 5.12
Actual Temperature of Crude Oil at Various Pump Stations

Pump Station	Inlet Temperature	Exit Temperature
PS1		115.7
PS3	83.8	86.4
PS4	81.3	84.1
PS5	71.4	
PS7	66.5	70.3
PS9	72	74.9
PS12	64.4	64.7
Valdez	64.7	

The above temperatures are for a flow rate of 1.1 MBPD for the month of April.

By using the equations in Sections 5.1 and 5.2, and the Visual Basic program, the temperatures are determined and they are compared with the actual data. The comparison between the actual data and simulated data is shown graphically in Figure 5.19.

The simulated data are calculated for:

i) 1.1 Million Barrels per Day flow rate
ii) 10 MPH wind velocity
iii) Snow depth of 1 ft
iv) For the month April

The actual data graph shows an increase in the temperature of the fluid at around 400 miles, which is at pump station 7. The abrupt increase in the temperature of the fluid is due to the pumping problems in the pump station 7.

The simulated inlet and exit temperatures of the crude oil are shown in Table 5.13.

TABLE 5.13

Calculated Temperatures of the Crude Oil at Various Pump Stations

Pump Station	Temperature
PS1	115.7
PS3	98.99
PS4	94.32
PS5	80.99
PS7	71.99
PS9	64.78
PS12	57.16
Valdez	54.91

The differences in the actual and the simulated temperatures are due to:

i) It is assumed that wind is blowing at a velocity of 10 MPH through the pipeline.

ii) Snow depth of 1ft is taken as constant through the pipeline.

iii) The actual belowground and aboveground sections of the pipe are different from the simulated sections.

iv) The variation in specific heat of crude oil is neglected with the change in temperature.

v) Difference in the actual ambient temperatures and the simulated temperatures.

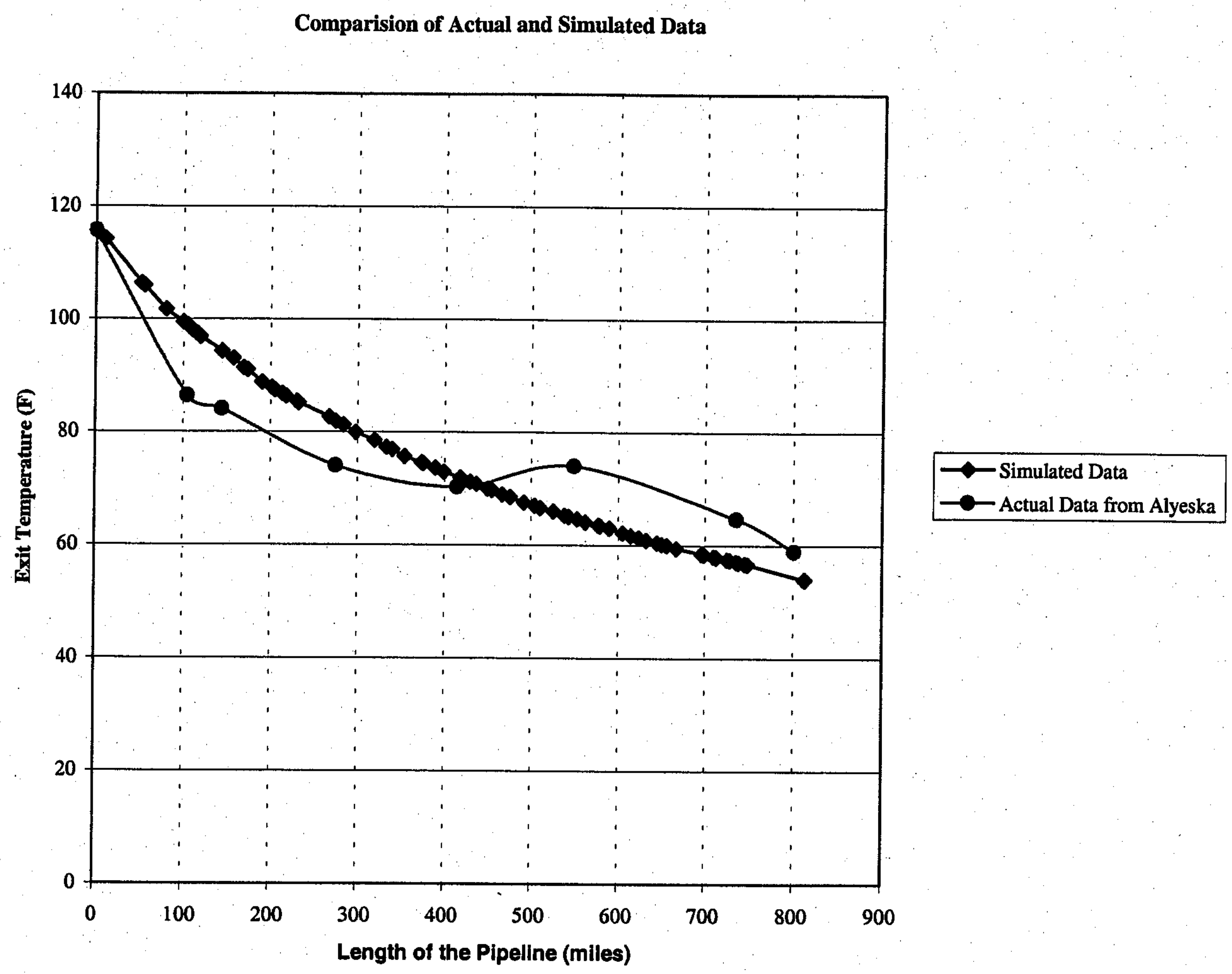

FIGURE 5.19 Comparison of Actual Temperatures with Calculated Results

5.6 CONCLUSIONS

The following conclusions are made based on this study.

1. Good agreement between calculated and measured oil temperatures is observed, proving the validity of our model.

2. Heat loss in below ground section is higher than heat loss in above ground section which is because of the absence of insulation in the below ground section.

3. Heat loss from GTL flow is less than heat loss from crude oil flow for both below ground and above ground pipeline. This is due to a reduction in mass flow rate for GTL.

4. Exit temperature of the GTL is slightly lower than the exit temperature of the crude oil. Lower mass flow rate has lower heat content and cools down further.

5. The heat loss is more in January than in March both for crude oil and GTL. The increased heat loss in January is because of the low ambient temperatures. The temperature difference between the fluid and the ambient air is greater which results in more heat loss.

6. The temperature of oil arriving at Valdez is 57°F for crude oil from the calculations. Temperature reported by Alyeska Pipeline Service Comapny is 60°F (Chrisman, 2001). Difference may be due to many assumptions made in the calculations, which may deviate from actual conditions.

NOMENCLATURE

A_i	Inside surface area of the pipe, m^2
c_p	Specific heat of the fluid, J/kg K
d	Buried depth of the pipeline below the ground, m
d_1	Inner diameter of the pipe, m
d_2	Thickness of the snow layer, m
f	Friction factor
h_f	Frictional head loss, m
h_i	Inside convective heat transfer coefficient, W/m^2 K
h_m	Head loss in fittings, m
h_o	Outside convective heat transfer coefficient, W/m^2 K
H	Width over which the heat is transmitted, m
k_a	Thermal conductivity of air, W/m k
k_f	Thermal conductivity of fluid, W/m K
k_i	Thermal conductivity of insulation, W/m K
k_p	Thermal conductivity of pipe, W/m K
k_s	Thermal conductivity of soil, W/m K
k_{sn}	Thermal conductivity of snow, W/m K
L	Length of the pipe segment. m
$\dot{m}$	mass flow rate of the fluid, kg/s
Nu_d	Nusselt number based on inner diameter
Nu_D	Nusselt number based on outside diamter
Nu_H	Nusselt number based on width
P	Power, kW (hp)
Pr	Prandtl number
Δp	Pressure drop due to friction, Pa
Δp_h	Pressure difference due to hydrostatic head, Pa
Δp_m	Pressure loss in fittings, Pa

q	Heat flow rate, W
q_l	Heat flow rate per meter, W/m
q''	Heat flux, W/m^2
Re_d	Reynolds number based on the inner diameter
Re_D	Reynolds number based on the outside diameter
Re_H	Reynolds number based on the width
R_1	Inner radius of the pipe, m
R_2	Outer radius of the pipe, m
R_3	Radius of the pipe with the insulation, m
S	Conduction shape factor for ground, m
T_{iav}	Average of inlet and outlet temperatures of fluid, °C
T_{s1}	Inside temperature of pipe wall below ground, °C
T_{s2}	Outside temperature of the pipe wall below ground, °C
T_{s3}	Temperature of the ground surface, °C
T_{s4}	Temperature of the snow surface
T_{s1}'	Inside temperature of pipe wall above ground, °C
T_{s2}'	Outside temperature of pipe wall above ground, °C
T_{s3}'	Outside temperature of the insulation above ground, °C
T_i	Inlet temperature of the fluid, °C
T_e	Outlet temperature of the fluid, °C
T_∞	Ambient air temperature, °C
U_i	Overall heat transfer coefficient with respect to pipe inner surface, W/m^2 K
V	Velocity of fluid flowing through the pipe, m/s
V_∞	Wind velocity across the pipeline, m/s
z_1	Elevation of the pump station 1, m
z_2	Elevation of the pump station 3, m
μ	Coefficient of dynamic viscosity of the fluid, kg/m s
ν	Coefficient of dynamic viscosity of the fluid, m^2/s
ρ	Density of the fluid, kg/m^3
ρ_a	Density of air, kg/m^3
ε	Roughness of the pipe, mm

REFERENCES

Andersland, O.B., & Anderson, D.M., 1978, *Geotechnical Engineering for Cold Regions,* McGraw-Hill Book Company, New York.

Akwukwaegbu, C.F., 2001, "Evaluation of the Modes of Transporting GTL Products through the Trans-Alaska Pipeline System (TAPS)," M.S. Thesis, Univesity of Alaska Fairbanks, Alaska.

Chrisman, K.A., 2001, E-mail Communication, Alyeska Pipeline Service Company, Fairbanks, Alaska.

Chukwu, G.A., Kamath, S., Patil, S., Liu, C., Akwukwaegbu, H., Ramakrishnan, H., & Driscoll. D., 2000, "An Overview of Gas-To-Liquids (GTL) Transport Issues in Pipes", Society of Petroleum Engineers, pp. 212-214.

Chukwu, F.A., 2001, E-mail Communication, Alyeska Pipeline Service Company, Fairbanks, Alaska.

Dandekar, A.Y., 2001, E-mail Communication, University of Alaska, Fairbanks, Alaska.

Govier, G.W., & Aziz,K., 1972, *The Flow of Complex Mixtures in Pipes*, Van Nostrand Reinhold Company, Newyork.

Haaland, S.E., 1983, "Simple and Explicit Formulas for the Friction Factor in Turbulent Pipe Flow," Journal of Fluids Engineering, pp. 89-90.

Holman, J.P., 1997, *Heat Transfer*, Mcgraw-Hill Inc., Newyork.

McQuiston, F.C., & Parker, J.D., 1994, Heating, Ventilating and Air Conditioning, John Wiley & Sons, New York.

Ramakrishnan, H., 2000, Experimental and Economic Evaluation of GTL Fluid Flow Properties and Effect on TAPS." M.S Thesis, University of Alaska, Fairbanks, Alaska.

Sachdeva, R.C., 1999, *Fundamentals of Engineering Heat and Mass Transfer*, New Age International Publishers, New Delhi, India.

Suryanarayana, N.V., 1995, *Engineering Heat Transfer*, West Publishing Company, Minneapolis.

Spirey, J.J., Iglesia, E. and Fleish, T.H., 2001, "Studies in Surface Science and Catalysis", Elsevier Science B.V. Publication.

Thomas, L.C., 1993, *Heat Transfer*, Prentice Hall, New Jersery.