Journal of Petroleum and Gas Exploration Research (ISSN 2276-6510) Vol. 2(2) pp. 033-043, February, 2011
Available online http://www.interesjournals.org/JPGER

Review

A predictive tool for thermal/hydraulic calculations of Fula pipeline

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Accepted 11 January, 2012

A multi-function predictive tool has been developed for Fula pipeline thermal and hydraulic prediction and simulation during its operation. The predictive tool has been developed utilizing published mathematical models applied to thermal/hydraulic calculations in pipeline operation. Real field data has been entered into the tool and the outputs have been validated with the Stoner Pipeline simulator (SPS) using the same entered parameters. It has been found that the predictive tool and the Stoner software outputs are virtually alike. More accurate results of the effect of pipeline elevation profile (potential pressure) on the remaining pressure along the pipeline are gained from the predictive tool. This accuracy is indicated by zigzagged hydraulic gradient lines resemble to the pipeline route between every two pump stations. The predictive tool also has the capability of predicting the transient temperature and friction pressure distribution along the pipeline under shutdown conditions.

Keyword: Fula pipeline, operation, shutdown

INTRODUCTION

Fula pipeline is a spiral Seam Submerged-Arc Welded (API Spec 5L) 24 in diameter, 715.44 km length pipeline constructed in 2003 and commissioned by the first quarter of 2004 to transport the Fula field crude oil from CPF located in the south-west of Sudan to Khartoum refinery.

To achieve the ultimate throughput pipeline capacity of 200,000 BOPD in phase IV, five booster pump stations have been designed; details as in table (1).

Table (1) illustrates the elevations of the pumps stations along the pipeline and their distance from the pipeline inlet. The table shows that the target of phase II is achieved by operating three pumps stations (PS#01, PS#03, and PS#04). Figure (1) illustrates the pipeline profile. Figure (2) illustrates the types and ratings of pumps contained in the three pumps stations running during phase II operation.

Fula pipeline has successfully achieved phase I throughput of 12,000 BOPD in 2004 and phase II throughput of 40,000 BOPD in 2007.

This paper discusses a predictive tool developed for analysis of thermal/hydraulic parameters of Fula pipeline at different flow conditions for a selected phase (phase I through phase IV)

Literature review

Computer simulation now a day is of great importance in engineering educations and applications. For petroleum engineering discipline, in particular, computer simulation plays an important role in assessment and evaluation of many processes that associated with high degree of difficulty and/or high cost to evaluate them experimentally.

We can divide the roles that computer simulation plays in petroleum engineering into two parts. The first one is the education-related role (e-learning) in which the usefulness of computer simulation is not far differing from other engineering disciplines. Examples of such usefulness are simulating of labs that are impractical, expensive, impossible, or too dangerous to run (Strauss

Table 1. Fula pipeline pump stations arrangement

PS No.	Mileage Km	Elevation m	Remarks
PS#01	0	550.5	Phase I, Initial
PS#02	165.5	584.3	Phase III
PS#03	280.5	576	Phase II
PS#04	468	412.5	Phase II
PS#05	618.2	441.7	Phase III
PS#06	715.42	404.88	Phase I, Terminal

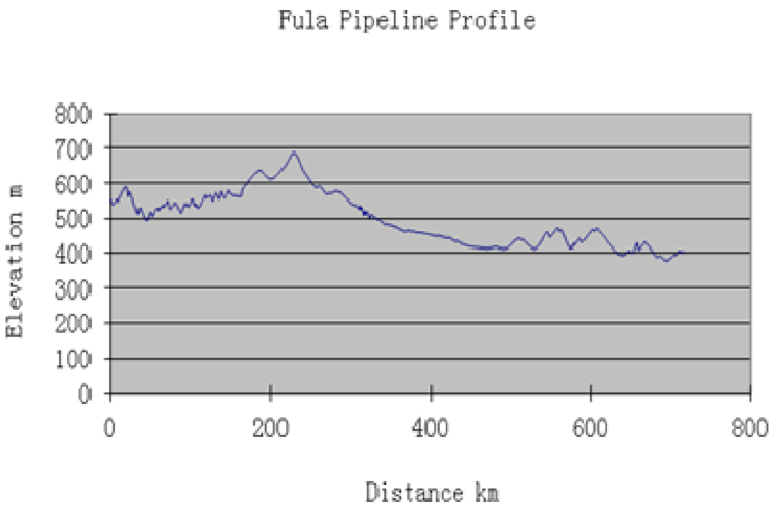


Figure 1. Pipeline Profile

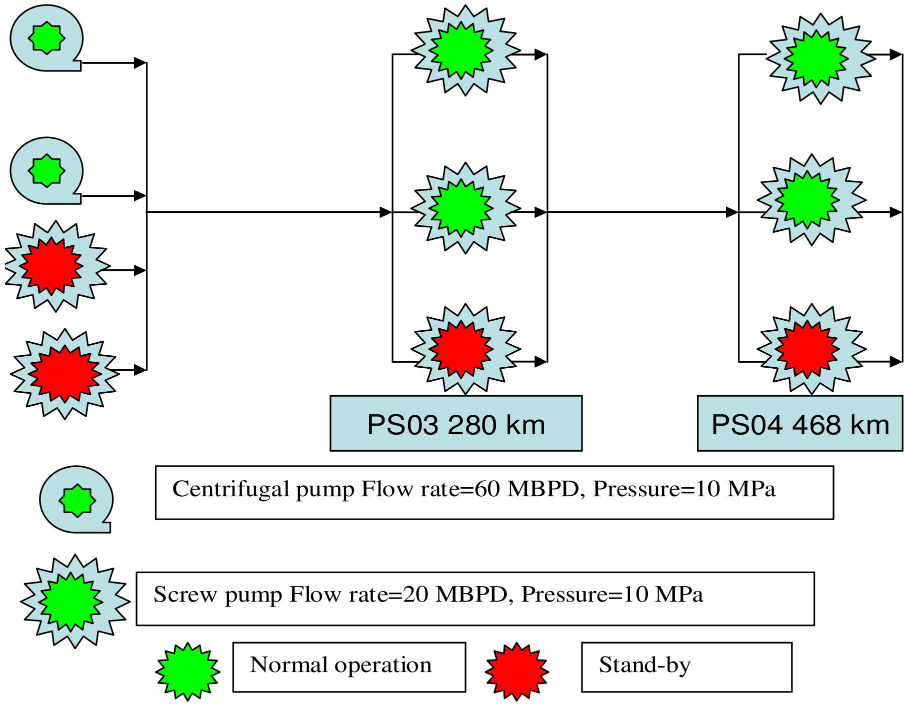


Figure 2. Fula pipeline phase II pumps types and ratings

Table 2. Fula crude properties (Phase II)

NO	Item	Result
1	Density, (kg/m^3)	940.9
2	Dynamic Viscosity, (mPa.s)	
	29□	1600
	35□	910
	40□	620
	60□	210
	80□	100
3	Solidifying point, (□)	-5
4	Saturation hydrocarbon, (m%)	38.5
5	Aromaticity hydrocarbon, (m%)	28.1
6	gummy matter,（m%）	13.69
7	Asphalt matter, (m%)	0.6
8	Acid number,（mgKOH/g）	6.1
9	Wax Content, (m%)	13.5
10	Flash point（OPEN）, (□)	168
11	Ash, (m%)	0.4
12	Remnant charcoal, (m%)	7.54
13	C, (m%)	86.59
14	H, (m%)	11.86
15	S, (m%)	0.16
16	N, (m%)	0.28
17	Sand Content, (m%)	0.1
18	Salt Content,（mgNaCl/L）	683
19	Ni,（mg/kg）	18.3
20	V,（mg/kg）	0.9
21	Ca,（mg/kg）	1652
22	Distillation range,（□）	
	Initial point	245
	5%	301
	10%	366
	30%	496
	34.6%	518
23	Invariability, grade	1

and Kinzie, 1994), Contribution to conceptual changes (Zietsman, 1986; Stieff, 2003), source of open-ended experiences for students (Sadler et al. 1999), provider of tools for scientific inquiry (Mintz, 1993; White and Frederiksen, 2000; Windschitl, 2000; Dwyer and Lopez, 2001) and problem solving experiences (Woodward et al., 1988; Howse, 1998), and contribution in distance education (Lara and Alfonseca, 200; McIsaac and Gunawardena, 1996).

The second role of computer simulations in petroleum engineering is their use as tools for controlling real field processes. Computer simulations are the only way to evaluate, assess, and control processes in far-to-reach spots such as reservoirs and deep-water pipelines.

A good reference of reviewing computer application in petroleum engineering is a paper written by Dougherty and Ershaghi (Dougherty and Ershaghi, 1986) in which the authors have reviewed historical trends and attitudes of petroleum engineering schools toward computer applications, discussed the state of the art, and suggested a syllabus to take advantage of the potential benefits of computer-aided instruction (CAI) and computer-aided design (CAD) in petroleum engineering education.

Calculations procedure

The calculations are performed using mathematical models regularly applied to pipelines thermal and hydraulic calculations. To include the variation of the rheological properties (viscosity, fluid consistency, and flow index) with temperature, empirical equations are formulated describing these variations before entering the input data.

The following are the main equations used for normal operation calculations:

$$T_l = T_0 + (T_{i0} - T_0)\exp\left(-\frac{k_t \pi D l}{G c_o}\right) \quad \text{....(1)}$$

Equation (1) calculates the temperature at any distance L along the pipeline. The calculated temperature is then used to calculate Newtonian viscosity or non-Newtonian fluid consistency and flow index using the empirical equations created before. Experiments carried out during the Fula pipeline design and commissioning provide evidence that Fula crude always exhibits Newtonian flow above 29 C, which is the minimum environmental temperature along the pipeline. Thus the non-Newtonian fluid consistency and flow index need not be considered and only one viscosity-temperature equation need to be formulated. This relationship is most probably linear [1] following the equation $\log \mu = A - BT$. To formulate the viscosity-temperature equation we dealt with the data contained in table 2 to attain the curve and associated equation contained in figure 3. The constants A and B are introduced to the program as input data instead of input a single value of viscosity because temperature markedly affects viscosity which in turn affects friction losses along the pipeline. The friction pressure is calculated using equation (2).

$$\Delta P_f(T) = f_i(T)\frac{\rho(T)\,\Delta L V^2}{2 D_1} \quad \text{.......(2)}$$

The viscosity-temperature experiments shall be re-carried out whenever there are changes in operation conditions to update the rheology constants.

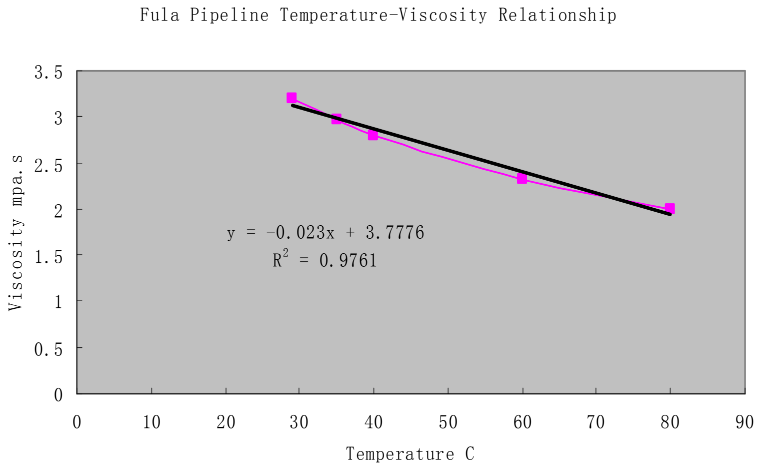


Figure 3. Fula Crude Viscosity Variation with Temperature

Fula Crude Export Pipeline Shutdown and Restarting

Designed by:Mysara Eissa

Figure 4. The Software GUI

The software

The software is an appropriate quick-prediction tool for Fula pipeline thermal/hydraulic prediction. The main graphical user interface (GUI) of the software is illustrated in figure (4). Actual field data can be introduced into the operation condition input form figure (5).

These input data will be processed in accordance to the mathematical models.

The software capabilities

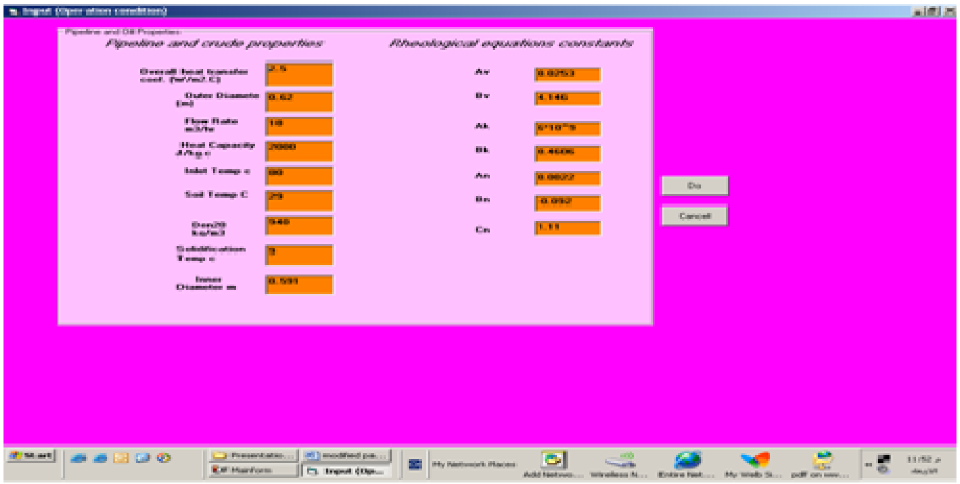
Different output can be obtained in tabular or graphical forms. These outputs include the following:

Operation Condition Output

1- One-km friction pressure distribution and temperature distribution along the pipeline as in figure (6).

This output emphasizes the scientific fact that friction pressure increases with temperature reduction.

2- Hydraulic gradient: the hydraulic gradient line is the line which shows the distribution of the available pressure (pumping pressure head plus the elevation difference head minus pressure losses due to friction) downstream to pump station. To obtain this output the separate form shown in figure (7) is to be filled. The of running pumps is selected then the remaining input data are entered accordingly. Pressing Fula



Pipeline and crude properties

Overall heat transfer coef. (w/m2.C): 2.5
Outer Diameter (m): 0.62
Flow Rate m3/hr: 118
Heat Capacity J/kg.c: 2000
Inlet Temp c: 80
Soil Temp C: 29
Den20 kg/m3: 940
Solidification Temp c: 3
Inner Diameter m: 0.591

Rheological equations constants

Av: 0.0253
Bv: 4.146
Ak: 5*10^-5
Bk: 0.4606
An: 0.0022
Bn: -0.092
Cn: 1.11

Figure 5. Operation Condition Input Form

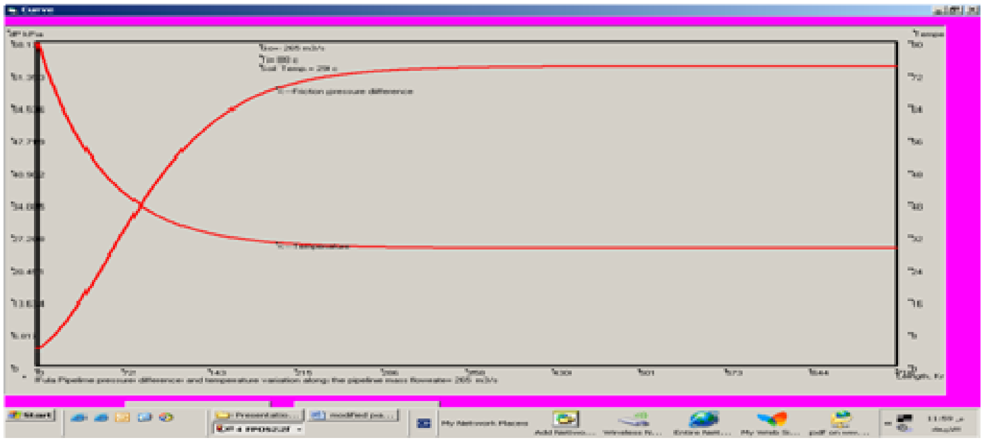


Figure 6. Fula Pipeline Temperature and one-km Friction Pressure Distribution

Pipeline button automatically introduces the default Fula pipeline data for the selected case.

Figure (8) is the output hydraulic gradient line of Fula pipeline in phase I (only PS01 is running with discharge pressure=9.2 MPa, flow rate=60 m^3/h) . Whereas figure (9) is the same output in phase II (PS01 9 MPa, PS03 8.7 MPa and PS04 9.2 MPa are running, flow rate=265 m^3/hr).

The software also output the operation results in tabular format as in figure (10). In this table the first column is the temperature distribution along the pipeline every kilometer. The second column illustrates the accumulated pressure losses for the segment from the pipeline inlet. The third column illustrates the pressure losses within every km along the pipeline. The fourth column identifies whether the flow within the current kilometer length is Newtonian or non-Newtonian. For Fula pipeline up to now the flow is always Newtonian because the crude pour point is very low when compared with the soil temperature.

Shutdown condition output

Figure (11) is the input form of the shutdown condition. The key input parameters of shutdown calculations are shutdown time, the calculations time interval, and the flow rate before shutdown and after start-up. The input data shown in figure (11) result the output shown in figures (12)~(15), which are tabular and curves out put of temperature and friction pressure distribution along the pipeline after every time interval.

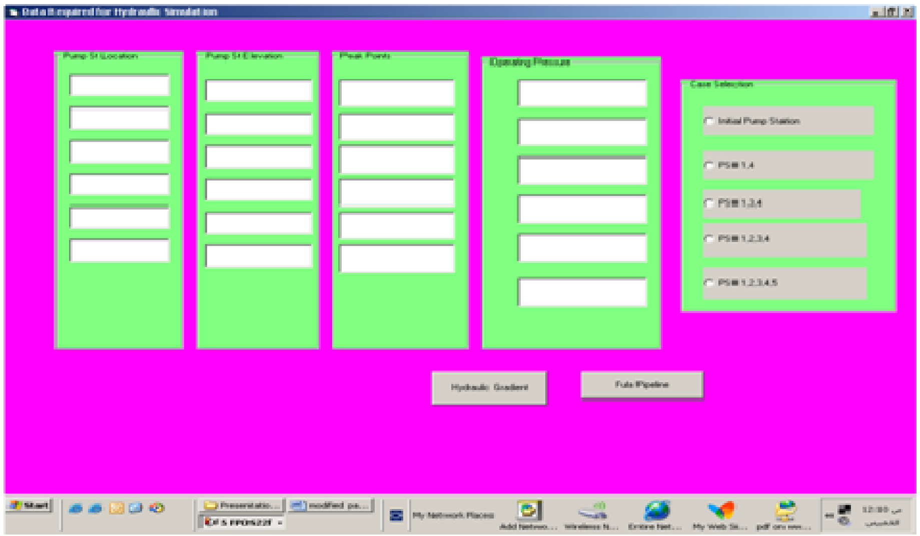


Figure 7. Hydraulic Gradient Input Form

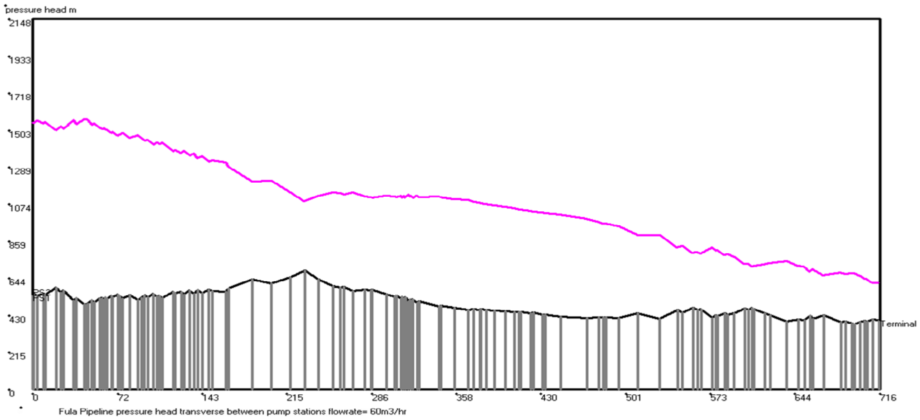


Figure 8. Fula Pipeline Hydraulic Gradient Line (Phase I)

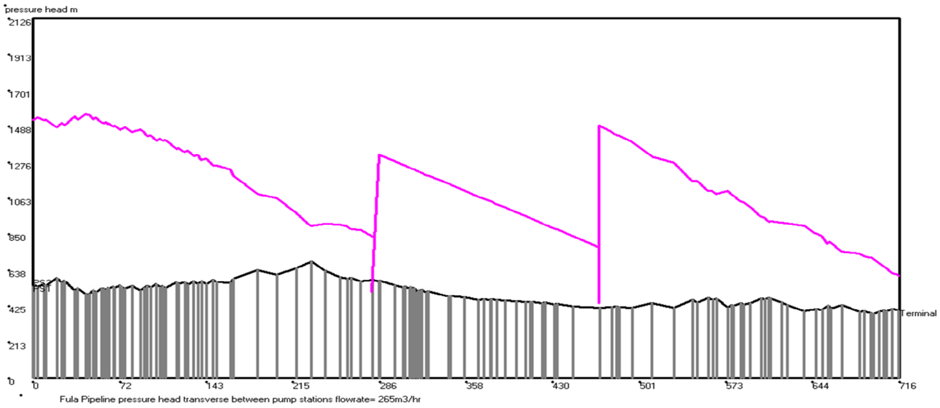
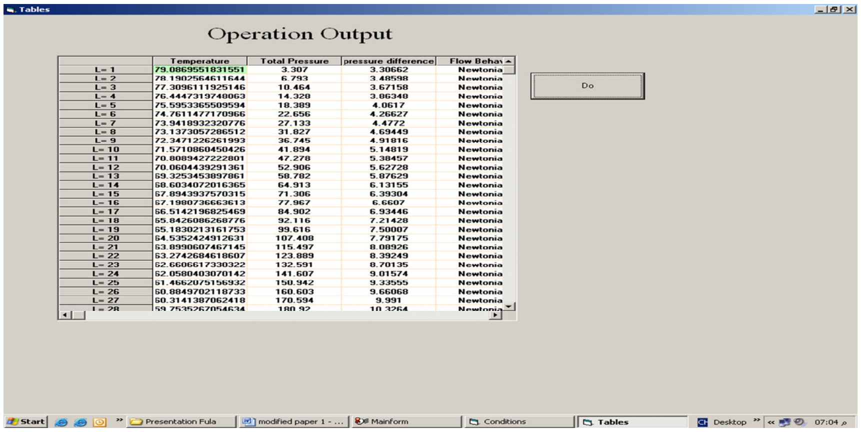
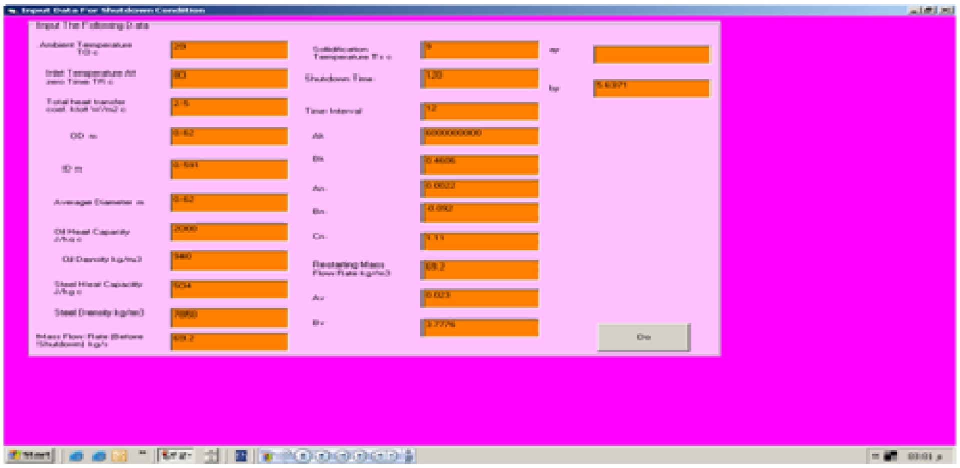


Figure 9. Fula Pipeline Hydraulic Gradient Line (Phase II)



	Temperature	Total Pressure	pressure difference	Flow Behav
L= 1	79.0869551831551	3.307	3.30662	Newtonia
L= 2	78.1902564611644	6.793	3.48598	Newtonia
L= 3	77.3096111925146	10.464	3.67158	Newtonia
L= 4	76.4447319748063	14.328	3.86348	Newtonia
L= 5	75.5953365509594	18.389	4.0617	Newtonia
L= 6	74.7611477170966	22.656	4.26627	Newtonia
L= 7	73.9418932320776	27.133	4.4772	Newtonia
L= 8	73.1373057286512	31.827	4.69449	Newtonia
L= 9	72.3471226261993	36.745	4.91816	Newtonia
L= 10	71.5710860450426	41.894	5.14819	Newtonia
L= 11	70.8089427222801	47.278	5.38457	Newtonia
L= 12	70.0604439291361	52.906	5.62728	Newtonia
L= 13	69.3253453897861	58.782	5.87629	Newtonia
L= 14	68.6034072016365	64.913	6.13155	Newtonia
L= 15	67.8943937570315	71.306	6.39304	Newtonia
L= 16	67.1980736663613	77.967	6.6607	Newtonia
L= 17	66.5142196825469	84.902	6.93446	Newtonia
L= 18	65.8426086268776	92.116	7.21428	Newtonia
L= 19	65.1830213161753	99.616	7.50007	Newtonia
L= 20	64.5352424912631	107.408	7.79175	Newtonia
L= 21	63.8990607467145	115.497	8.08926	Newtonia
L= 22	63.2742684618607	123.889	8.39249	Newtonia
L= 23	62.6606617330322	132.591	8.70135	Newtonia
L= 24	62.0580403070142	141.607	9.01574	Newtonia
L= 25	61.4662075156932	150.942	9.33555	Newtonia
L= 26	60.8849702118733	160.603	9.66068	Newtonia
L= 27	60.3141387062418	170.594	9.991	Newtonia
L= 28	59.7535267054634	180.92	10.3264	Newtonia

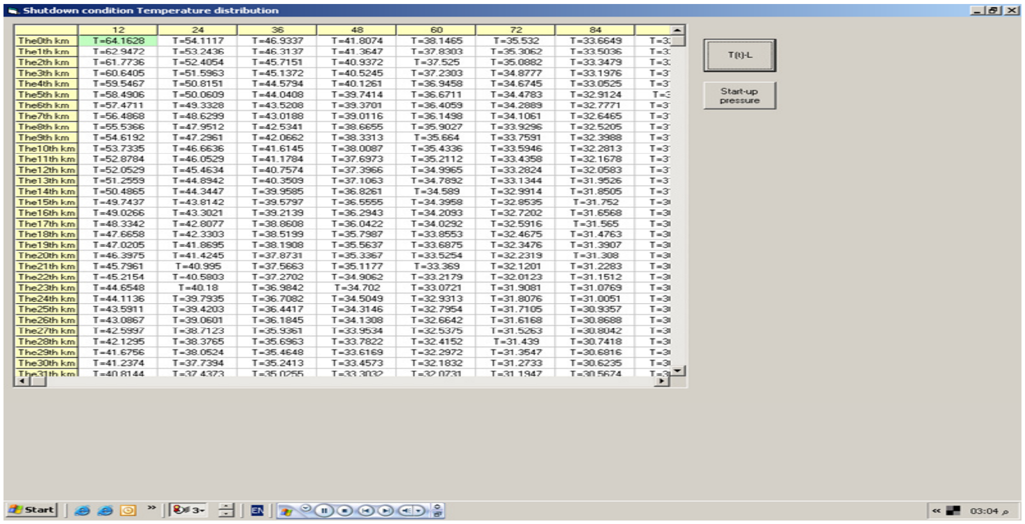
Figure 10. Operation Tabular Output



Input The Following Data

Ambient Temperature T(0) c	29	Solidification Temperature T(s) c	9	ay	
Inlet Temperature At zero Time T(R) c	80	Shutdown Time	120	by	5.6371
Total heat transfer coef. k(w/m2 c)	2.5	Time Interval	12		
OD m	0.62	Ak	6000000000		
ID m	0.591	Bk	0.4606		
Average Diameter m	0.62	An	0.0022		
Oil Heat Capacity J/kg c	2000	Bn	-0.092		
Oil Density kg/m3	940	Cn	1.11		
Steel Heat Capacity J/kg c	504	Restarting Mass Flow Rate kg/m3	69.2		
Steel Density kg/m3	7850	Av	0.023		
Mass Flow Rate (Before Shutdown) kg/s	69.2	Bv	3.7776		

Figure 11. Shutdown Condition Input Form



	12	24	36	48	60	72	84	
The0th km	T=64.1628	T=54.1117	T=46.9337	T=41.8074	T=38.1465	T=35.532	T=33.6649	T=3
The1th km	T=62.9472	T=53.2436	T=46.3137	T=41.3647	T=37.8303	T=35.3062	T=33.5036	T=3
The2th km	T=61.7736	T=52.4054	T=45.7151	T=40.9372	T=37.525	T=35.0882	T=33.3479	T=3
The3th km	T=60.6405	T=51.5963	T=45.1372	T=40.5245	T=37.2303	T=34.8777	T=33.1976	T=3
The4th km	T=59.5467	T=50.8151	T=44.5794	T=40.1261	T=36.9458	T=34.6745	T=33.0525	T=3
The5th km	T=58.4906	T=50.0609	T=44.0408	T=39.7414	T=36.6711	T=34.4783	T=32.9124	T=3
The6th km	T=57.4711	T=49.3328	T=43.5208	T=39.3701	T=36.4059	T=34.2889	T=32.7771	T=3
The7th km	T=56.4868	T=48.6299	T=43.0188	T=39.0116	T=36.1498	T=34.1061	T=32.6465	T=3
The8th km	T=55.5366	T=47.9512	T=42.5341	T=38.6655	T=35.9027	T=33.9296	T=32.5205	T=3
The9th km	T=54.6192	T=47.2961	T=42.0662	T=38.3313	T=35.664	T=33.7591	T=32.3988	T=3
The10th km	T=53.7335	T=46.6636	T=41.6145	T=38.0087	T=35.4336	T=33.5946	T=32.2813	T=3
The11th km	T=52.8784	T=46.0529	T=41.1784	T=37.6973	T=35.2112	T=33.4358	T=32.1678	T=3
The12th km	T=52.0529	T=45.4634	T=40.7574	T=37.3966	T=34.9965	T=33.2824	T=32.0583	T=3
The13th km	T=51.2559	T=44.8942	T=40.3509	T=37.1063	T=34.7892	T=33.1344	T=31.9526	T=3
The14th km	T=50.4865	T=44.3447	T=39.9585	T=36.8261	T=34.589	T=32.9914	T=31.8505	T=3
The15th km	T=49.7437	T=43.8142	T=39.5797	T=36.5555	T=34.3958	T=32.8535	T=31.752	T=3
The16th km	T=49.0266	T=43.3021	T=39.2139	T=36.2943	T=34.2093	T=32.7202	T=31.6568	T=3
The17th km	T=48.3342	T=42.8077	T=38.8608	T=36.0422	T=34.0292	T=32.5916	T=31.565	T=3
The18th km	T=47.6658	T=42.3303	T=38.5199	T=35.7987	T=33.8553	T=32.4675	T=31.4763	T=3
The19th km	T=47.0205	T=41.8695	T=38.1908	T=35.5637	T=33.6875	T=32.3476	T=31.3907	T=3
The20th km	T=46.3975	T=41.4245	T=37.8731	T=35.3367	T=33.5254	T=32.2319	T=31.308	T=3
The21th km	T=45.7961	T=40.995	T=37.5663	T=35.1177	T=33.369	T=32.1201	T=31.2283	T=3
The22th km	T=45.2154	T=40.5803	T=37.2702	T=34.9062	T=33.2179	T=32.0123	T=31.1512	T=3
The23th km	T=44.6548	T=40.18	T=36.9842	T=34.702	T=33.0721	T=31.9081	T=31.0769	T=3
The24th km	T=44.1136	T=39.7935	T=36.7082	T=34.5049	T=32.9313	T=31.8076	T=31.0051	T=3
The25th km	T=43.5911	T=39.4203	T=36.4417	T=34.3146	T=32.7954	T=31.7105	T=30.9357	T=3
The26th km	T=43.0867	T=39.0601	T=36.1845	T=34.1308	T=32.6642	T=31.6168	T=30.8688	T=3
The27th km	T=42.5997	T=38.7123	T=35.9361	T=33.9534	T=32.5375	T=31.5263	T=30.8042	T=3
The28th km	T=42.1295	T=38.3765	T=35.6963	T=33.7822	T=32.4152	T=31.439	T=30.7418	T=3
The29th km	T=41.6756	T=38.0524	T=35.4648	T=33.6169	T=32.2972	T=31.3547	T=30.6816	T=3
The30th km	T=41.2374	T=37.7394	T=35.2413	T=33.4573	T=32.1832	T=31.2733	T=30.6235	T=3
The31th km	T=40.8144	T=37.4373	T=35.0255	T=33.3032	T=32.0731	T=31.1947	T=30.5674	T=3

Figure 12. Fula Pipeline Transient Temperature Distribution Table (Unsteady State)

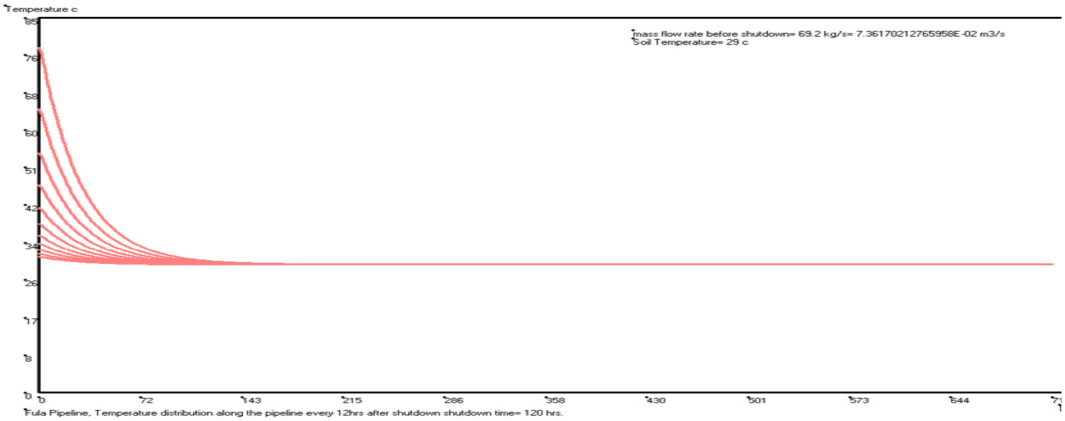
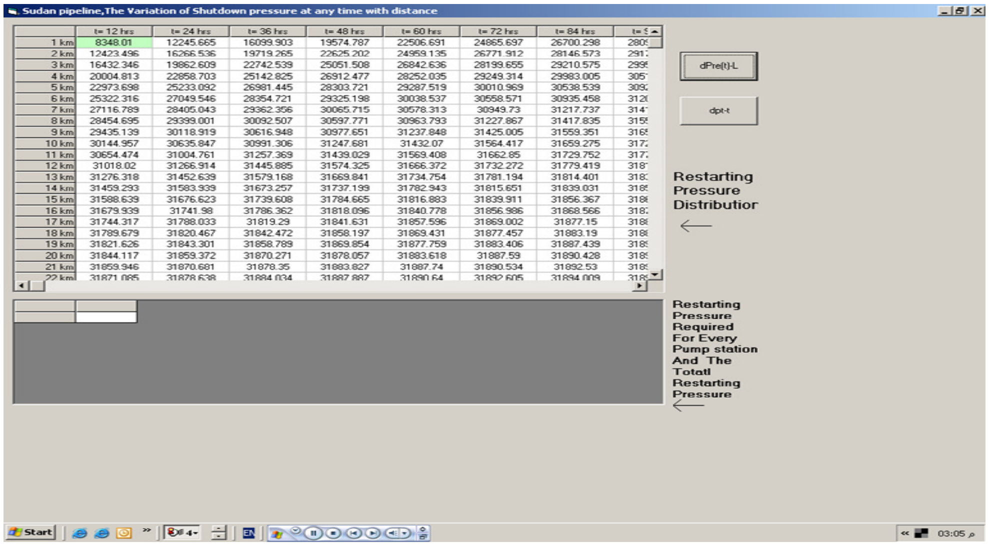


Figure 13. Fula Pipeline Transient Temperature Distribution Curve (Unsteady State)



Sudan pipeline,The Variation of Shutdown pressure at any time with distance

	t= 12 hrs	t= 24 hrs	t= 36 hrs	t= 48 hrs	t= 60 hrs	t= 72 hrs	t= 84 hrs	t=
1 km	8348.01	12245.665	16099.903	19574.787	22506.691	24865.697	26700.298	280
2 km	12423.496	16266.536	19719.265	22625.202	24959.135	26771.912	28146.573	291
3 km	16432.346	19862.609	22742.539	25051.508	26842.636	28199.655	29210.575	299
4 km	20004.813	22858.703	25142.825	26912.477	28252.035	29249.314	29983.005	305
5 km	22973.698	25233.092	26981.445	28303.721	29287.519	30010.969	30538.539	309
6 km	25322.316	27049.546	28354.721	29325.198	30038.537	30558.571	30935.458	312
7 km	27116.789	28405.043	29362.356	30065.715	30578.313	30949.73	31217.737	314
8 km	28454.695	29399.001	30092.507	30597.771	30963.793	31227.867	31417.835	315
9 km	29435.139	30118.919	30616.948	30977.651	31237.848	31425.005	31559.351	316
10 km	30144.957	30635.847	30991.306	31247.681	31432.07	31564.417	31659.275	317
11 km	30654.474	31004.761	31257.369	31439.029	31569.408	31662.85	31729.752	317
12 km	31018.02	31266.914	31445.885	31574.325	31666.372	31732.272	31779.419	318
13 km	31276.318	31452.639	31579.168	31669.841	31734.754	31781.194	31814.401	318
14 km	31459.293	31583.939	31673.257	31737.199	31782.943	31815.651	31839.031	318
15 km	31588.639	31676.623	31739.608	31784.665	31816.883	31839.911	31856.367	318
16 km	31679.939	31741.98	31786.362	31818.096	31840.778	31856.986	31868.566	318
17 km	31744.317	31788.033	31819.29	31841.631	31857.596	31869.002	31877.15	318
18 km	31789.679	31820.467	31842.472	31858.197	31869.431	31877.457	31883.19	318
19 km	31821.626	31843.301	31858.789	31869.854	31877.759	31883.406	31887.439	318
20 km	31844.117	31859.372	31870.271	31878.057	31883.618	31887.59	31890.428	318
21 km	31859.946	31870.681	31878.35	31883.827	31887.74	31890.534	31892.53	318
22 km	31871.085	31878.638	31884.034	31887.887	31890.64	31892.605	31894.009	318

Figure 14. Fula Pipeline one-km Friction Pressure Distribution Table (Unsteady State)

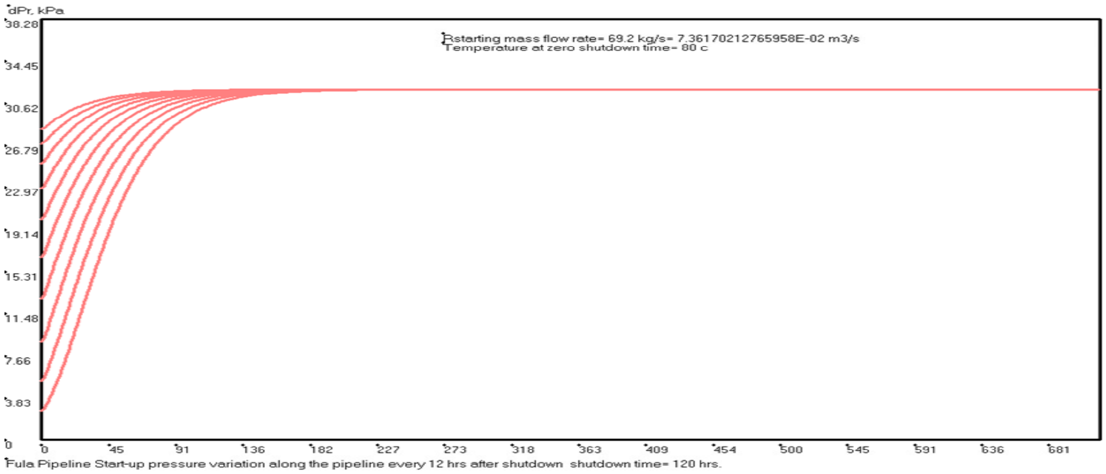


Figure 15. Fula Pipeline one-km Friction Pressure Distribution Curve (Unsteady State)

Table 3. The Studied Case Input Data

category	Input parameter	Unit	Remarks
Pipeline system input data	Overall heat transfer coefficient	w/m^2.C^o	Assumed=2.5 (a little change has no significant effects on calculation)
	Outer , inner diameter	m	6.1, 5.92
	Flow rate	M^3/hr	265
	Heat capacity	j/kg.C^o	2000
	Inlet temperature	C^o	80
	Soil temperature	C^o	29
	Solidification temperature	C^o	9
Fluid Rheological constants *These constants relate the variation of crude rheological properties with temperature.	Av, Bv	When flow is Newtonian (viscosity variation with temperature)	Av=0.023, Bv=3.7776
	Ak, Bk, Not considered for Fula crude as the flow is Newtonian at all	Non-Newtonian flow (fluid consistency variation with temperature)	K=Ak*e^{-Bk*T} Not considered
	An, Bn, Cn Not considered for Fula crude as the flow is Newtonian at all	Non-Newtonian Flow index variation with temperature	N=An^2*T+Bn*T+Cn Not considered

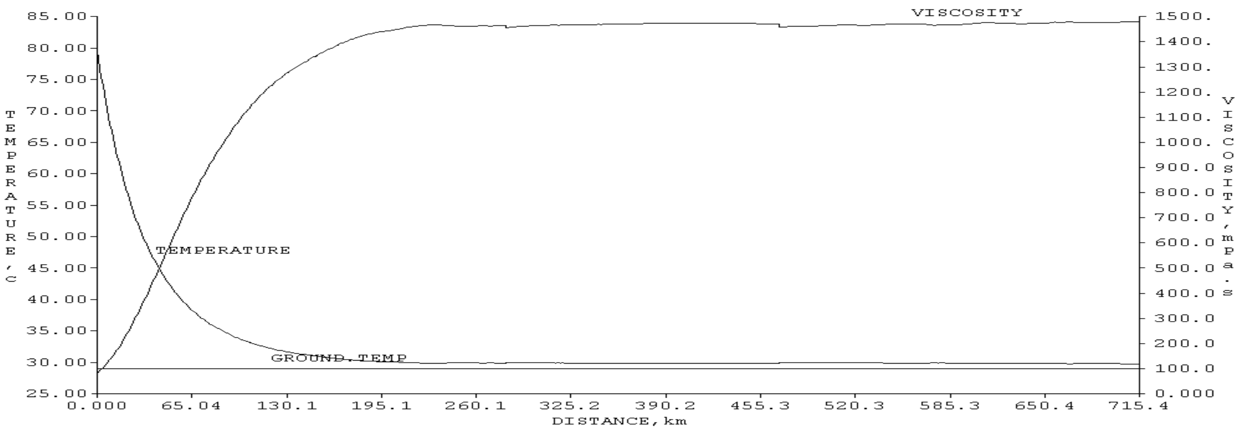


Figure 16. Temperature and Viscosity Distributions along Fula Pipeline, SPS Results (Fula pipeline phase II detailed design, CPPE)

The software results validation

Table (3) shows the data that input to the software. The same data are used for the pipeline phase II detailed design hydraulic calculations and simulation that conducted by the China Petroleum Pipeline Engineering Company (CPPE) using the Stoner pipeline software package (SPS). Figures (16)~(19) show a comparison of the results obtained from the software with that obtained using the Stoner software package. Figure (16) and (17) show identical thermal calculation results in form of temperature distribution along Fula pipeline. The viscosity-temperature dependency is clearly illustrated in figure (16). The same dependency is illustrated in figure (16) as friction pressure-temperature dependency which is obviously logical as friction pressure is markedly dependant on viscosity. Figure (18) and (19) show similar results of hydraulic gradient lines between pump stations. By comparing the curves' shapes of these two figures, more zigzag is noted on

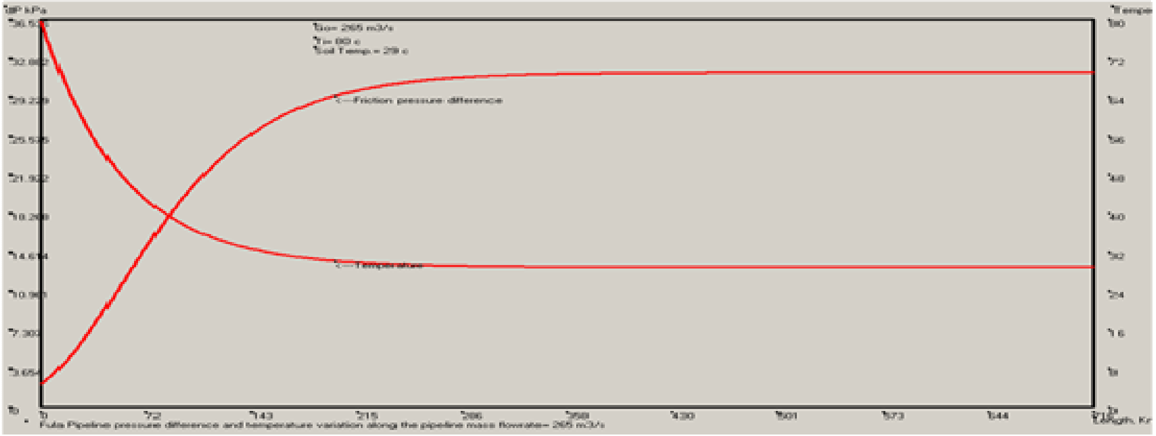


Figure 17. Temperature and one-km Friction Pressure Distribution along Fula Pipeline

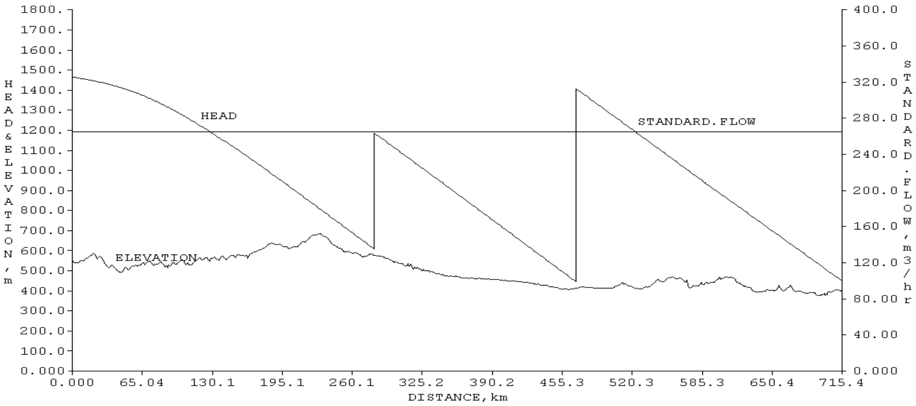


Figure 18. Hydraulic Gradient of Fula Pipeline, SPS Output (Fula Pipeline Phase II Detailed Design, CPPE)

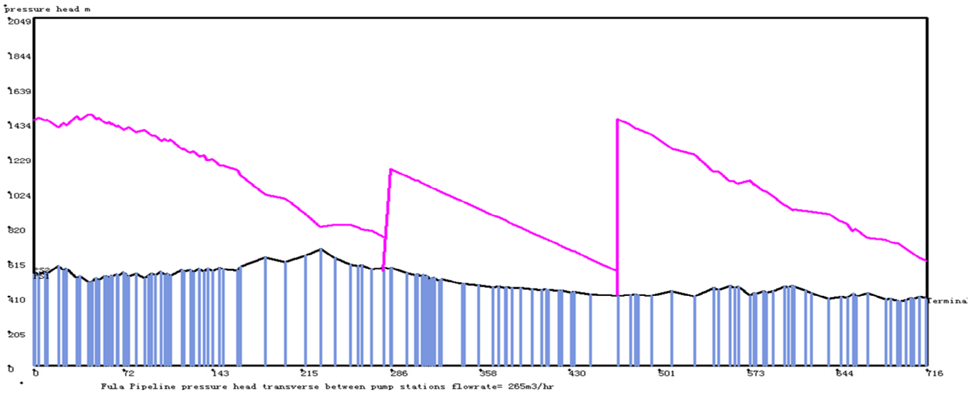


Figure 19. Hydraulic Gradient of Fula Pipeline, (the Software Output)

our software curves. These zigzags represents the pipeline profile, hence our software shows real potential pressure distribution between pump stations.

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