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Heat Transfer Model of Above and Underground Insulated Piping Systems

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ABSTRACT

A simplified heat transfer model of above and underground insulated piping systems was developed to perform iterative calculations for fluid temperatures along the entire pipe length. It is applicable to gas, liquid, fluid flow with no phase change. Spreadsheet computer programs of the model have been developed and used extensively to perform the above calculations for thermal resistance, heat loss and core fluid temperature.

NOMENCLATURE

A, Ai = surface area (sf)
Ain = inner surface area of hollow cylinders, pipes, or insulation (sf)
Aou = outer surface area of hollow cylinders, pipes, or insulation (sf)
Am = logarithmic mean area of heat transfer (sf)
Ç = specific heat of the core pipe fluid (Btu/lbF)
Ch = pipe constant (use 1.016 for horizontal and 1.235 for vertical pipe)
d, di = diameter (ft)
do = pipe covering or insulation OD (ft)
dn = ID of of hollow cylinder pipes or insulation (ft)
dt = OD of hollow cylinder pipes or insulation (ft)
dh = burial depth of pipe centerline (ft)
e = surface emittance of pipe covering or insulation
H = total thermal transmittance (Btu/ hr F)=1/R
h, hi = film coefficient (Btu/hr sf F)
i = subscripts 1,2,3,4,5,6,7,8 or a,b,c,d
Examples, i of Ti,Ri,Ai,hi,ki
k, ki = conductivity (Btu/hr ft F)
ks = soil conductivity (Btu/hr ft F)
L = pipe length of one interval or one element (ft)
La = starting fluid location, Example, La = 0 ft
Le = ending fluid location, Example, Le= 9100 ft
Lt = total pipe length (ft)
Lk = conduction wall thickness of pipes, insulation and soil (ft)
M = mass of core fluid per one interval pipe length (lbs)
n = number of pipe elements or intervals
Example, n = 100
Q = heat flow (Btu/hr)
R, Ri = resistance (hr F / Btu)
r, ri = radius (ft)
ro = do/2 = outer radius of pipe covering or insulation (ft)
t = time for moving fluid to travel the distance of pipe interval L (hr)
tc = time interval for stagnant fluid to cool a given temperature drop (hr)

T, Ti = temperature (F or C)
T1 = Tf = core pipe fluid temperature (F or C)
T2 = average temperature of ambient air film (F or C)
T3 = core pipe id temperature (F or C)
T4 = core pipe OD temperature (F or C)
T5 = jacket pipe ID temperature (F or C)
T6 = jacket pipe OD temperature (F or C)
T7 = pipe covering or insulation OD temp (F or C)
T8 = Ts = soil or ambient air temperature (F or C)
To = initial or starting interval temperature (F or C)
Te = ending interval temperature (F or C)
Tend = end temperature of travel (F or C)
Ts = soil or ambient air temperature (F or C)
U = overall heat transfer coefficients (Btu/hr sf F)
Xi = fluid location at the start of interval (ft)
Xe = fluid location at the end of interval (ft)
wind = wind velocity (mph)

BASIC EQUATIONS

(1) inner surface area of heat transfer for pipes or insulation (sf) = Ain = (π) (dn) (L)

(2) outer surface area of heat transfer for pipes or insulation (sf) = Aou = (π) (dt) (L)

(3) logarithmic mean area of heat transfer for pipes or insulation (sf)= Am = (Aou - Ain) / Logn (Aou / Ain)

(4) aboveground ambient air convective film coefficient (Btu/hr sf F) per Ref. [1].
ha=(Ch)*(1/dc)^0.2*(1/T2)^0.181*(1+1.277*wind)^0.5
where Ch=1.016 for horizontal cylinders or pipes
Ch = 1.235 for longer vertical pipes

(5) aboveground radiation surface coefficient (Btu/hr sf F) per Ref. [1].
hb = (e)*(0.1713)*10^(-8)*[(Ts+459.6)^4 - (T7+459.6)^4] / (Ts-T7)

(6) total aboveground thermal coeff. (Btu/hr sf F) per Ref. [3] = h7 = ha +hb

(7) thermal resistance of film convection (hr F / Btu) per Ref. [3].
Ri = 1/(hi*Ai) for core fluid and air
R1 = 1/(h1*A1) = core fluid resistance (hr F/Btu)
R4 = 1/(h4*A4) = annular air resistance (hr F/Btu)
R7 = 1/(h7*A7) = ambient air resistance (hr F/Btu)

(8) thermal resistance of wall conduction (hr F/Btu) per Ref. [3].
Ri = Lk/(ki*Am) for pipes and insulation
R2 = Lk2/(k2*Am2) = core pipe inner fouling
R3 = Lk3/(k3*Am3) = core pipe wall resistance
R5 = Lk5/(k5*Am5)= outer pipe wall resistance
R6 = Lk6/(k6*Am6)= external insulation resistance

(9) resistance of soil for underground pipe (hr F / Btu) per Ref. [1]. R7 = Lk7 / (k7*Am7) or
R7 = Logn { (dh/ro) + [(dh/ro)^2 - 1]^0.5 } / (2*πi*ks*L)

(10) total or resultant resistance (hr F / Btu).
R = R1+R2+R3+R4+R5+R6+R7

(11) ending fluid temperature of pipe interval (F)
Te = To - (Tf-Ts)(t) / (M)(C)(R)

(12) mean fluid temperature of typical interval (F)
Tf = (To+Te)/2
Tf = (2*M*C*R*To + Ts*t) / (2*M*C*R + t)

(13) core pipe mean or average temperature (F)
Ta = 0.5 [2T1- (1/R) (2R1 + 2R2 + R3) (T1-T8)]

(14) annulus air mean or average temperature (F).
Tb = 0.5 [2T1- (1/R) (2R1 + 2R2 + 2R3 + R4) *(T1-T8)]

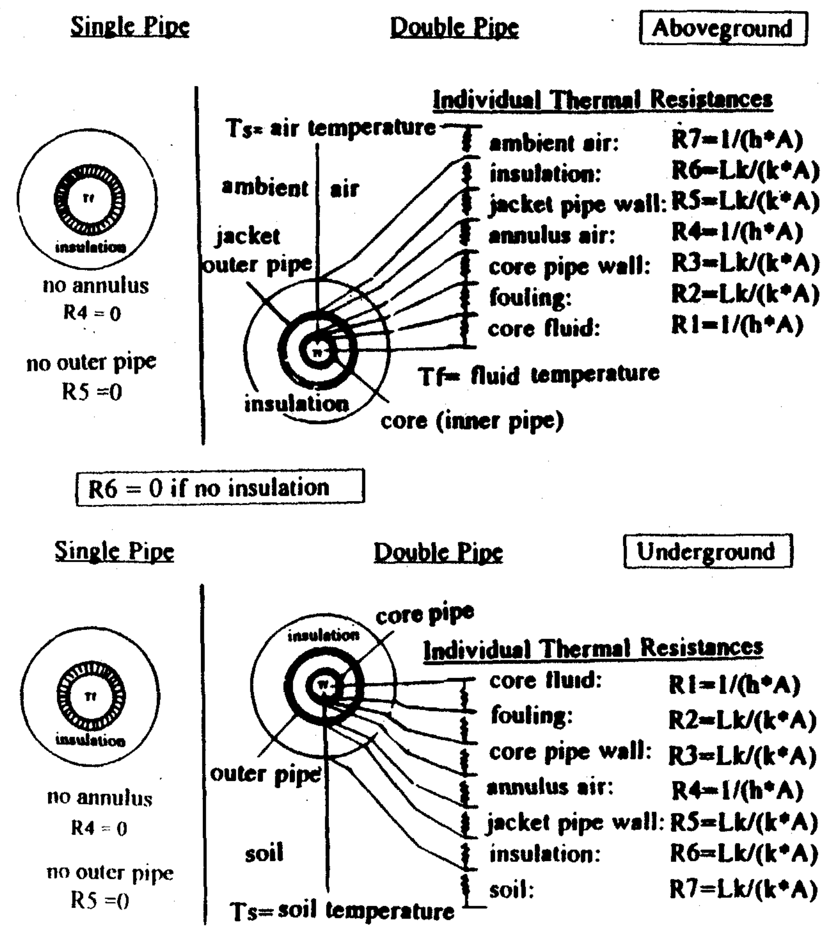
(15) outer-jacket pipe mean temperature (F)
Tc = 0.5 [2T1- (1/R) (2R1 + 2R2 + 2R3 + 2R4 + R5) (T1-T8)]

(16) external insulation mean temperature (F)
Td = 0.5 [2T1- (1/R) (2R1+2R2+2R3+2R4 +2R5+R6) (T1-T8)]

INTRODUCTION

Heat gain, heat loss and temperature change of transfer pipe lines are significantly influenced by (a) insulation, (b) surrounding environment - ambient air for above-ground pipe or soil for underground pipe and (c) pipe structure - single pipe or double pipe. A heat transfer model of above and underground insulated piping systems are shown in Figure 1.

Fig. 1 Above and Underground Insulated Piping System Model



Overall Resistance (hr F/Btu):

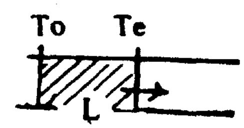
R = R1+R2+R3+R4+R5+R6+R7

Heat Flow / dT (Btu/hr F):

Q/dT = Q/(Tf-Ts)= 1/R = (U)(A)

Equation of Heat Balance of Pipe Interval Element (Btu/hr):

Tf = To to Te



one of 100 intervals

(M) (C) (To-Te) / t = (Tf-Ts) / R

= (U) (A) (Tf-Ts)

Table 1. Steady State Pipe Flow - Heat Loss (9100 ft, 93.3 gpm, starting 107C at 0 ft)

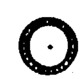
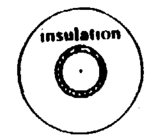
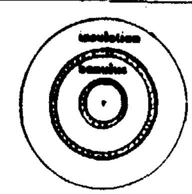
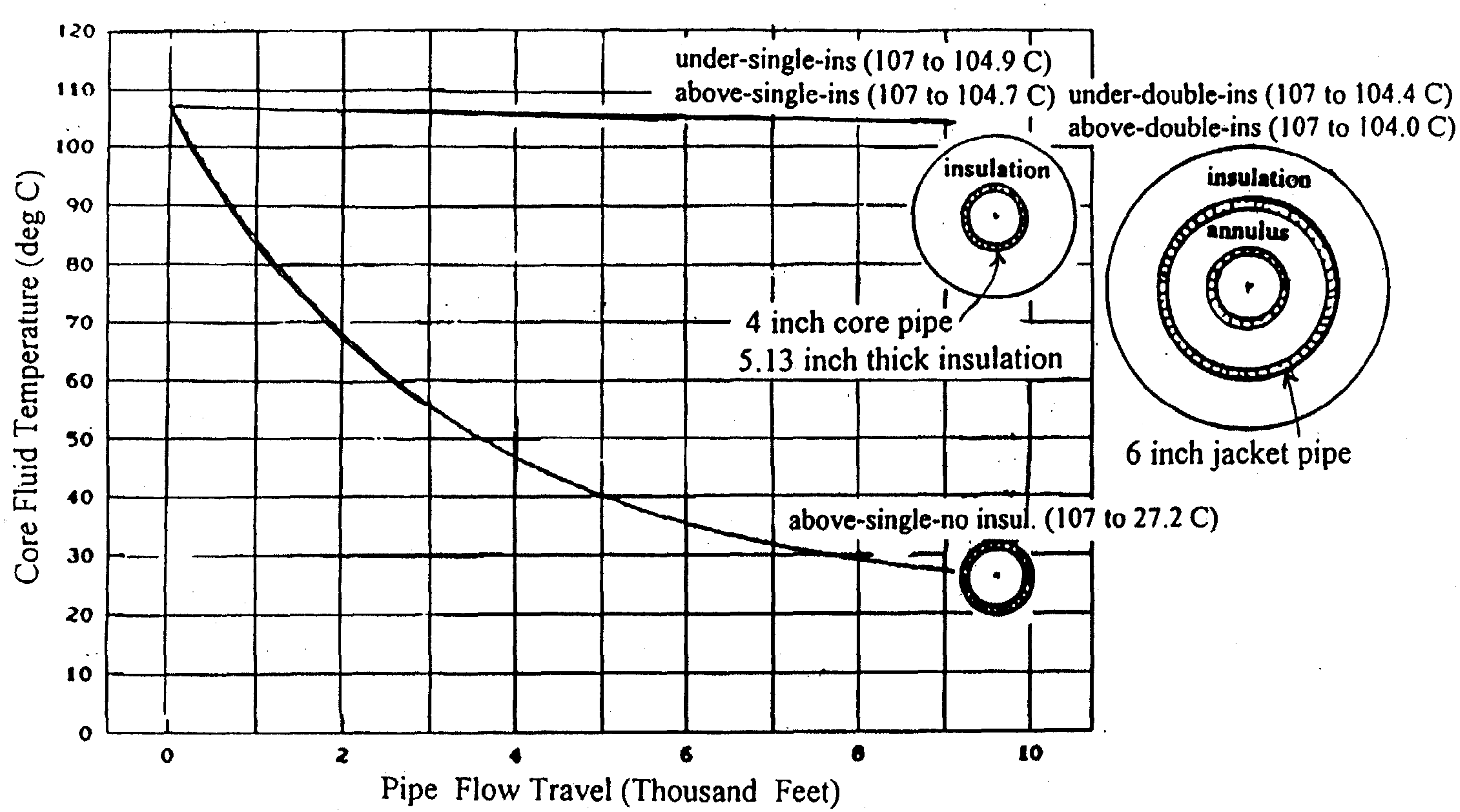
single or double	single pipe			double	pipe
above or underground	above	above	under	above	under
unisulated or insulated	uninsul.	insul.	insul.	insul.	insul.
core fluid (hr F/Btu): **R1=1/(h*A)**	0.000029	0.000029	0.000029	0.000029	0.000029
core fouling (hr F/Btu): **R2=Lk/(k*A)**	0.000031	0.000031	0.000031	0.000031	0.000031
4" core pipe (hr F/Btu): **R3=Lk/(k*A)**	0.000023	0.000023	0.000023	0.000023	0.000023
annular air space (hr F/Btu): **R4=1/(h*A)**	0	0	0	0.002211	0.002211
6" outer pipe (hr F/Btu): **R5=Lk/(k*A)**	0	0	0	0.000005	0.000005
5.13" insulation (hr F/Btu): R6 = Lk/(k*A)	0	0.077905	0.077905	0.058178	0.061372
Ambient Air, Soil (hr F/Btu): R7=1/(h*A), Lk/(k*A)	0.000705	0.000705	0.007930	0.000607	0.007447
total resistance (hr F/Btu): R	0.000788	0.078693	0.085918	0.061084	0.071118
heat flow=U*A=1/R (Btu/hr F): Q/dT	1269.0	12.7	11.6	16.4	14.1
fluid temp. at 9100 ft (C): Tend	27.2	104.7	104.9	104.0	104.4
avg. fluid temp. (C)= Tf = (107+Tend) / 2	67.1	105.8	105.9	105.5	105.7
ambient (25C), soil (22C): Ts	25.0	25.0	22.0	25.0	22.0
avg.temp.diff.= Tf-Ts (F): dT	75.7	145.5	151.1	144.9	150.7
average heat loss (Btu/hr) Q	96,112	1,849	1,758	2,372	2,118
order of effective insulation	5th	2nd	1st	4th	3rd
The most effective insulation can be obtained by maximizing R6=Lk/(k*A): **a) maximum insulation thickness (Lk)** **b) minimum conductivity (k)** **c) minimum conduction area (A)**					

Fig. 2 Steady State Pipe Flow - Core Fluid Temperature Changes



As shown in Fig. 1 the heat transfer of aboveground pipe is very similar to that of the underground pipe. The only difference in heat transfer between the above and underground pipes is thermal resistance, R7. Thermal resistance (R7) of aboveground pipe is mainly affected by radiation and convection by ambient air. It can be calculated by using the preceding Basic Equations (4), (5), (6), and (7) or R7 = 1/(h7*A7).

Thermal resistance (R7) of underground pipe is affected by conduction of soil. It can be calculated by using the preceding Basic Equation (9) which is a form of
R7 = Lk7 / (k7*Am7) or
R7 = Logn { (dh/ro) + [(dh/ro)^2 - 1]^0.5 } / (2*πi*ks*L)

Other thermal resistances such as R1, R2, R3, R4, R5, R6 of Basic Equations. (7) and (8) are the same between above and underground pipes.

For hot temperature service such as superheated steam or hot water transfer, the outer surface temperatures of aboveground pipes should be at or below a predetermined value for personnel safety and equipment protection. For cold temperature service such as coolant or chilled water transfer, insulation outer surface temperature should be above the dew point temperature of the surrounding air to prevent condensation.

Most of city water, sewage and liquid waste are usually transferred through single or double underground pipe lines.

The important variables of the underground pipe heat transfer are:

1) Type of fluid flow affecting the inner-most core pipe film coefficient
2) Pipe material affecting the pipe wall conduction.
3) Type of soil affecting dissipation of heat away from the pipeline.
4) Moisture content of the soil affecting dissipation of heat through soil
5) Wind velocity and ground soil surface characteristics around pipeline

The basic pipe flow data used in the heat transfer model calculation are:

a) 4" stainless steel single or inner core pipe, sch.40
b) 6" carbon steel jacket outer pipe, schedule 40
c) 5.13" thick insulation with thermal conductivity of 0.0267 Btu/hr ft F
d) 6 ft deep of buried pipe soil with thermal conductivity of 0.5 Btu/hr ft F
e) 93.3 gal/min core pipe fluid flow with film coefficient of 1182 Btu/hr ft2 F
f) starting fluid temperature at 107 C
g) average core fluid specific gravity is 0.98
h) total pipe flow travel is 9100 feet

Figure 2 shows steady state pipe flow-fluid temperature change during the total pipe flow travel of 9100 feet. The heat loss from the moving fluid to the surrounding ambient air or underground soil varies as it travels along the whole pipe length. The greater temperature difference between the fluid and surrounding, the more heat loss occurs. The calculation results of steady state pipe flow heat loss of various pipes is shown in Table 1.

The average heat loss (Q: Btu/hr) shown in Table 1 is based on the difference between average core fluid (Tf) temperature and surrounding ambient air or soil temperature Ts).

1) <u>aboveground uninsulated single pipe</u>
   core fluid temperature = 107 to 27.2 C
   heat loss = Q = 96,112 Btu/hr

2) <u>aboveground insulated single pipe</u>
   core fluid temperature = 107 to 104.7 C
   heat loss = Q = 1,849 Btu/hr

3) <u>underground insulated single pipe</u>
   core fluid temperature = 107 to 104.9 C
   heat loss = Q = 1,758 Btu/hr

4) <u>aboveground insulated double pipe</u>
   core fluid temperature = 107 to 104.0 C
   heat loss = Q = 2,372 Btu/hr

5) <u>underground insulated double pipe</u>
   core fluid temperature = 107 to 104.4 C
   heat loss = Q = 2,118 Btu/hr

UNDERGROUND DOUBLE PIPE MODEL

In a steady state condition when the environment condition is constant, we can assume that the soil or ambient air temperature (Ts) remains constant.

Consider a underground horizontal insulated double pipe as shown in the lower right position of Figure 1. It is 9100 feet long and its 4" core pipe carries a hot fluid starting 107C from one end and moving toward the other end. As the fluid moves inside the core pipe, the fluid temperature (Tf) will gradually decreases. The changing temperatures of core fluid can be calculated in the following procedure.

(A) Moving Fluid Calculation Procedure

1. Subdivide the entire pipe length into many intervals or elements. If the number of intervals or pipe elements selected is n = 100, we have a length of each pipe interval (L) = 9100 ft / 100 = 91 ft.
   The initial temperature (To) of the first interval at Xi=0 ft is known but the unknown ending temperature (Te) at Xe=91 ft is to be calculated.

2. Calculate individual thermal resistance (R1,R2,R3,R4,R5,R6 and R7) and total resistance (R) by using the previously shown Basic Equations (1) through (10).

2. From the heat balance equation,
   (M)(C)(To-Te) / t = (Tf - Ts) / R
   the ending temperature (Te) of the first interval (Te) can be calculated.
   Te = To - (Tf-Ts)(t)/(M)(C)(R) ----- Eq. (11).

   Average or mean fluid temperature of the first or typical interval be
   Tf = (To+Te)/2
   2 Tf = To + [To - (Tf-Ts)(t)/(M)(C)(R)]
   Tf = (2*M*C*R*To + Ts*t) / (2*M*C*R + t)

3. The second interval starting temperature (To2) is the same as the ending temperature of the first interval (Te).

   Average or mean fluid temperature of the second interval becomes
   Tf2 = (To2+Te2)/2
   2 Tf2 = To2 + [To2 - (Tf2-Ts)(t)/(M)(C)(R)]
   Tf2 = (2*M*C*R*To2 + Ts*t) / (2*M*C*R + t)

4. The third interval starting temperature (To3) is the same as the ending temperature of the second interval (Te2).

   Average or mean fluid temperature of the third interval becomes
   Tf3 = (To3+Te3)/2
   2 Tf3 = To3 + [To3 - (Tf3-Ts)(t)/(M)(C)(R)]
   Tf3 = (2*M*C*R*To3 + Ts*t) / (2*M*C*R + t)

5. Continuing this way we can calculate the fluid temperature from the first interval to the last 100th interval from Xi=9009 ft to Xe=9100 ft.

6. The last interval starting temperature (To100) is the same as the ending temperature of the 99th interval (Te99).

   Average or mean fluid temperature of the 100th interval becomes
   Tf100 = (To100+Te100)/2
   2 Tf100 = To100 + [To100 - (Tf100-Ts)(t)/(M)(C)(R)]
   Tf100 = (2*M*C*R*To100 + Ts*t) / (2*M*C*R + t)

SINGLE PIPE MODEL

The heat transfer modeling of single pipe can be made in the same method and procedure as that of double or core-jacket pipe.

The following individual thermal resistances are zeros for single pipes:

annular air thermal resistance, R4 = 0
jacket or outer pipe wall resistance, R5 = 0

Total resistance of a single pipe system is
R = R1 + R2 + R3 + R6 + R7

The heat balance equation of a single pipe is
(M)(C)(To-Te) / t = (Tf - Ts) / R

(B) Stagnant Fluid Calculation Procedure

Most of above and underground transfer pipe lines are almost fully or partially filled with fluid during the time of valve closing or pump-off. If the ambient air or surrounding soil temperature is lower than the core fluid temperature, the natural pipe cooling will continue with stagnant fluid. The pipe and insulation will be also cooled down in the stagnant flow. It is important to analyze the significance of pipe cooling during the stop.

Consider the previous underground horizontal double pipe containing a horizontal double pipe containing hot fluid with initial temperature of 107 C.

1. Complete a previous calculation procedure for steady state moving fluid before the fluid stops.
   The total thermal resistance (hr F/Btu) = R
   The total thermal transmittance (Btu/hr F) = H = 1/R

2. Estimate the percent of stagnant fluid filling the core pipe inner space.
   (% fill) = 100%, 50%, or 0 % as needed.

   Note: 100% was used in the calculation for Fig.4.

3. Calculate the heat to be removed for 1 deg C drop of core fluid temperature per pipe interval.

   Fluid heat content (Btu/C) per interval
   = (M) (C) (1.8 degF) = (1.8*M*C)

4. Select a temperature drop increment (dT) as needed (0.1, 0.25, 0.5 or 1): For Example, dT= 1 C.

   The smaller dT selected, the higher accuracy can be achieved.

   Calculate the cooling Btu to drop dT of fluid (Btu)
   = 1.8*M*C*dT

5. Calculate the first temperature difference between fluid and soil.

   Tf1 = (107+106)/2 = 106.5 C
   (Tf1-Ts) = 106.5 C - 22 C = 84.5 C = 152.1 F

   Heat Loss (Btu/hr) = (H)*(Tf1-Ts) = (Tf1-Ts) / R

   Time interval for stagnant fluid to cool dT or 1 C temperature drop (hr)
   tc1 = (1.8*M*C*dT) / [H*(Tf1-Ts)]

6. Calculate the second temperature difference between fluid and soil.

   Tf2 = (106+105)/2 = 105.5 C
   (Tf2-Ts) = 105.5 C - 22 C = 83.5 C = 150.3 F

   Heat Loss (Btu/hr) = (H)*(Tf2-Ts) = (Tf2-Ts) / R

   Time interval for stagnant fluid to cool dT or 1 C temperature drop (hr)
   tc2 = (1.8*M*C*dT) / [H*(Tf2-Ts)]

7. Continuing this way we can calculate the time interval for stagnant fluid to cool continuing gradual temperature drop dT.

8. Calculate the last temperature difference between the fluid (Tend) and soil (Ts) = (Tend - Ts)

   Heat Loss (Btu/hr) = (H)*(Tend-Ts) = (Tend-Ts) / R

   Time interval for stagnant fluid to cool dT temperature drop (hr)
   tc end = (1.8*M*C*dT) / [H*(Tend-Ts)]

9. Total time to cool down the fluid temperature from 107 to Tend.

   Total tc time (hr)
   = tc1 + tc2 + tc3 + -----------+ tc end

10. By using Basic Equations (13) through (16) and spreadsheet computer calculations, we can calculate the mean temperatures of core pipe, annular air, outer jacket pipe, and insulation or pipe covering.

Figure 3 shows the calculation results of 168 hour cooling analysis of above underground double pipe.

In the calculation for Figure 3, we selected dT= ~0.25C to achieve a higher degree of accuracy instead of 1C as shown in step 4.

Fig. 3

168 Hour Cooling Analysis Of Underground Double Pipe

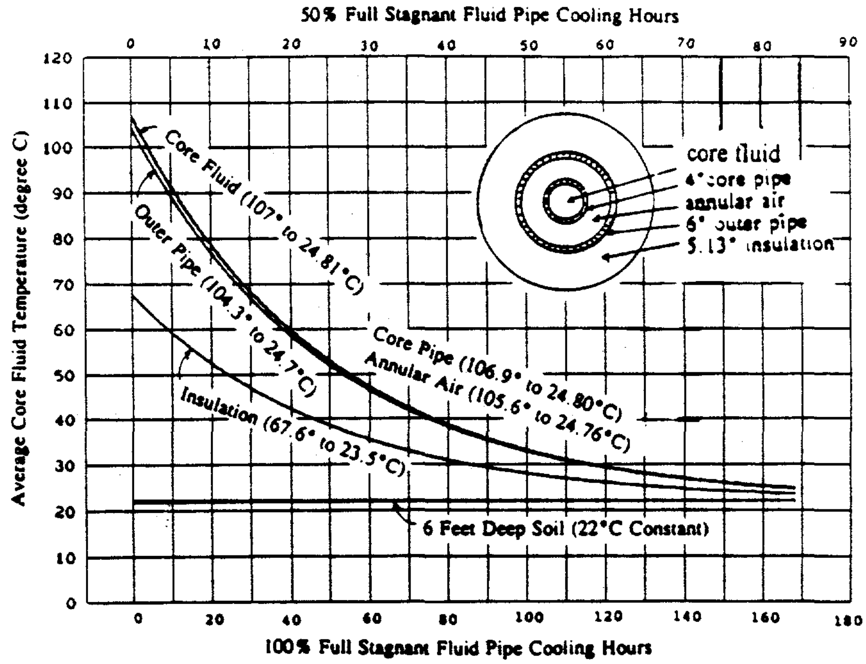
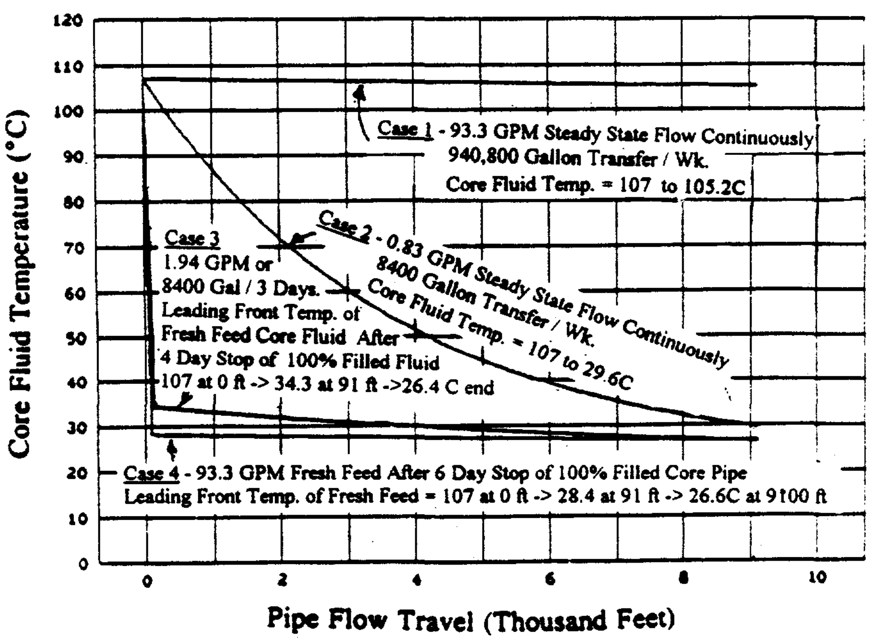


Fig. 4

Thermal Analysis of Underground Double Pipe (9100 Feet)



COMBINED MOVING AND STAGNANT FLUID MODELING

The following actual case of batch flow condition was analyzed by using two previous calculation procedures for moving fluid and stagnant fluid (see Figure 4).

Actual Batch Flow Condition:
Stop 4 days and subsequent Intermittent Flow

1400 gallon for 15 minutes (93.3 GPM) Every 12 Hours for 3 days / week.

(a) Cumulative Stop (stagnant fluid)
= 4 days + 11.75 hours x 6
= 166.5 hours /week
= 6.9375 days / week
= almost 7 days / week

(b) Cumulative Flow (moving fluid)
= 93.3 GPM for 90 minutes / wk
= 8,400 gallon transfer / wk

(c) Actual Batch Flow Case is close to Cases 2, 3, or 4
Case 2 is a quick steady state approximation method.
Case 3 or Case 4 is more accurate calculation method including unsteady cooling of stagnant fluid.

DISCUSSION

Case 1 is steady state full flow 93.3 gpm for 7 days and results in 104.4 C at the end of 9100 ft travel.

Case 2 is steady state flow of 0.83 gpm for 7 days and results in 29.6 C at the end of 9100 ft travel.

Case 3 is a combined stagnant fluid (4 days) and moving fluid (3 days) at 1.94 gpm and results in 26.4 C at the end of 9100 ft travel.

Case 4 is also a combined stagnant fluid (6 days) and moving fluid (1 day) at 93.3 gpm and results in 26.6 C at the end of 9100 ft travel.

For simplicity, the transition effect of mixing existing old fluid and new fluid is excluded in Case 3 and Case 4.

CONCLUSION

The most common pipe flow is unsteady batch type flow or combination of moving fluid and stagnant fluid.
The calculation method shown in Case 4 is most likely the most accurate. Calculating core fluid temperature changes and pipe heat loss by using Case 2 steady state condition formula is probably good enough to most plant engineers who need quick approximation.

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