Applied Engineering
2018; 2(2): 33-38
http://www.sciencepublishinggroup.com/j/ae
doi: 10.11648/j.ae.20180202.12

Methods of Heat Transfer Analysis of Buried Pipes in District Heating and Cooling Systems

Jianguang Yi

East China Architecture Design & Research Institute Co., Ltd, Shanghai, China

Email address:
jianguang_yi@ecadi.com

To cite this article:
Jianguang Yi. Methods of Heat Transfer Analysis of Buried Pipes in District Heating and Cooling Systems. *Applied Engineering*. Vol. 2, No. 2, 2018, pp. 33-38. doi: 10.11648/j.ae.20180202.12

Received: September 28, 2018; **Accepted**: October 17, 2018; **Published**: November 21, 2018

Abstract: District heating and cooling system is an energy-efficient and environment-friendly way of energy supply. Transmission and distribution pipeline system is an essential part of district heating and cooling system. Underground buried laying is the prevailing way of transmission and distribution pipeline system in district heating and cooling systems. Heat transfer calculation of pipeline is very important to determine the thickness of the insulation layer, accessory load of central plant, and the possibility of thermal damage. There are some factors that influence the heat transfer calculation of underground buried pipeline, including: temperature difference between fluid and soil, pipe insulation properties, burial depth, soil thermal conductivity and distance between adjacent pipes. Numerical methods to compute transient heat gains or losses in underground piping systems, is complicated and time consuming. To simplify the calculations, this paper introduces the steady-state thermal calculation method based on thermal resistance formulations that, that avoids the complex calculation process, and greatly simplifies the computational effort, and the calculated results can meet project needs. This method is suitable for the majority types of buried pipeline, so it can be used as reference for engineering design.

Keywords: Distribution System, Underground Buried, Thermal Resistance, Steady-State Calculations

1. Preface

District heating and cooling systems consist of three components: the central plant, the distribution pipeline system, and consumer systems (heat exchange plants). The transmission and distribution pipeline system is the link between the central plant and consumer systems. In general, there are three types of pipeline laying: overhead pipeline laying, direct-buried pipeline laying and comprehensive trench pipeline laying. Direct-buried pipeline laying and comprehensive trench pipeline laying are more common. Overhead pipeline laying is used in industrial enterprises or district heating and cooling systems with specific conditions. Direct-buried pipeline laying is generally the first choice, which is convenient to construction and low investment. But inconvenience to maintenance and repair is its main shortcoming.

The heat loss of transmission and distribution pipeline system is independent of the simultaneous coefficient of district cooling/heating load and the simultaneous coefficient of transmission and distribution pipeline system. But heat loss of transmission and distribution pipeline system is a part of the total load of the central plant.

2. Method and Influence Factors of Heat Transfer Calculation for Underground Transmission and Distribution Pipeline System

2.1. Classification of Heat Transfer Calculation

The heat transfer calculation of underground transmission and distribution pipeline system can be divided into the following three categories:

(1) Calculation of insulation thickness

The reasonable insulation thickness should be determined by the life-cycle cost analysis method under the design condition. The main influencing factors include the average soil temperature, the burial depth and the thermal property of the material. Appropriate allowance should be taken into account in the design, if the thermal performance of the thermal insulation material attenuates during the life cycle.

(2) Calculation of additional load of central plant

Additional load of the central plant caused by the transmission and distribution pipeline system is determined by the maximum heat loss of the transmission and distribution pipeline system. At the same time, the maximum heat loss of the transmission and distribution pipeline system determines the temperature rise/drop of the transmission and distribution pipeline system, thus affecting the supply water temperature to consumers. In the calculation, the maximum thermal conductivity of the material, the extreme environmental temperature, the maximum temperature difference between the fluid and the soil, and the minimum burial depth are generally considered.

(3) Calculation of thermal damage

During the operation of the pipeline system, it is necessary to ensure that any component materials of the pipeline system do not exceed the thermal performance under design conditions, so do any other materials affected by pipeline system in the buried pipes area. Therefore, heat transfer analysis should be carried out to check the possibility of heat damage in each component materials of pipeline system and other materials in buried pipes area.

2.2. Methods of Heat Transfer Calculation

The heat transfer calculation of underground pipeline system is carried out according to the basic principle of heat transfer. There are two main methods: numerical method and steady-state method.

The numerical method is used to calculate the instantaneous heat loss of underground pipeline system. This method can solve the heat transfer problem of any pipe approximately, and the influence of temperature change on the thermal performance of materials should be considered at the same time. Except for the thermal failure of the objects around the pipeline system and the complex section shape, the numerical method is not necessary in most engineering applications.

Steady-state calculations are appropriate for determining the annual heat loss from a buried pipeline system when average annual earth temperatures are used. Steady-state method may also be appropriate for worst-case analyses of thermal effects on materials. Steady-state method for a one-pipe system may be done without a computer, but it becomes increasingly difficult for a two-pipe, three-pipe, or four-pipe system.

The simplified steady-state method using resistance formulations are developed by Phetteplace and Meyer (1990) [1]. The resistances are on a unit length basis so that heat flows per unit length result directly when the temperature difference is divided by the resistance.

2.3. Influence Factors of Heat Transfer Calculation

The primary factors influencing the heat loss of underground pipeline system include the temperature difference between fluid and soil, the thermal insulation performance of pipeline. Other factors include burial depth, thermal conductivity of soil and the distance between adjacent pipes. Especially when the thermal resistance of the thermal insulation layer is lower, thermal conductivity of soil and burial depth have greater influence on the heat loss of the pipeline system. The thermal conductivity of soil is greatly affected by its composition and water content. The typical soil thermal conductivity can be referred to reference [2].

The conditions of heat transfer calculation must be chosen to represent the worst-case scenario from the perspective of the component being examined. For example, in assessing the suitability of a coating material for a metallic conduit, the thermal insulation is assumed to be saturated, the soil moisture is at its lowest probable level, and the burial depth is the maximum. These conditions, combined with the highest anticipated temperatures of pipe and soil, can give the highest temperature of pipe surface which the coating could be exposed.

3. Selection Principle and Calculation Method of Soil Temperature

Before any heat transfer calculation may be conducted, the undisturbed soil temperature at the site must be determined. The choice of soil temperature is guided primarily by the type of calculation. The appropriate choice of undisturbed soil temperature also depends on the location of the site, time of year, burial depth, and thermal properties of the soil. Some methods for determining undisturbed soil temperatures and suggestions to use them on appropriate circumstances are as follows:

(1) When the objective of the calculation is to yield average heat loss over the yearly weather cycle, the average annual air or groundwater temperature is used to approximate the average annual soil temperature. The annual average temperature in different zones of China can be selected in Appendix A of reference [3].

(2) When checking the temperatures to determine if the temperature limits of any of materials proposed to use will be exceeded, the maximum/minimum air temperature is used to estimate the maximum/minimum undisturbed soil temperature for pipes buried at a shallow depth, which burial depth of pipe center is less than twice the diameter of pipes (including thickness of insulation layer). Maximum and minimum expected air temperatures in different zones of China can be selected in Appendix A of reference [3].

(3) For pipes that are buried more deeply, which burial depth of pipe center is greater than twice the diameter of pipes (including thickness of insulation layer), maximum/minimum undisturbed soil temperatures may be estimated as a function of depth, soil thermal properties, and prevailing climate. This estimate is appropriate when checking temperatures in pipeline system to determine whether the temperature limits of any of the materials proposed to use will be exceeded. The following formulas may be used to estimate the minimum and maximum expected undisturbed soil temperatures[4]:

$$t_{s,z,max} = t_{ms} + A_s e^{-z\sqrt{\pi/\alpha\tau}} \quad (1)$$

$$t_{s,z,min} = t_{ms} - A_s e^{-z\sqrt{\pi/\alpha\tau}} \quad (2)$$

Where

$t_{s,z,\,max}$– the maximum temperature of soil, °C

$t_{s,z,\,min}$– the minimum temperature of soil, °C

Z–burial depth, m

τ–annual period, 365 days

α–thermal diffusivity of the ground, m^2/day

t_{ms}–mean annual surface temperature, °C

A_s–surface temperature amplitude, °C

The influence of convection heat transfer, precipitation and radiation should be taken into account in the calculation of soil surface temperature. The thermal balance of soil surface is very complex, so it is not necessary to calculate in detail in the design of underground pipeline system. In the estimation, an effective thickness of a fictitious soil layer may be added to the burial depth to account for the effect of the convective heat transfer resistance at the ground surface. The effective thickness is calculated as formula (3). In order to simplify the calculation, the soil surface temperature can be approximately taken as air temperature, which is acceptable for most projects.

$$\delta = k_s/h \quad (3)$$

Where

δ –effective thickness of fictitious soil layer, m

ks –thermal conductivity of soil, W/(m·K)

h –convective heat transfer coefficient at ground surface, W/(m^2·K)

Thermal diffusivity of soil may be calculated as formula (4):

$$\alpha = \frac{24\times3600k_s}{1000\rho_s[c_s+c_w(w/1000)]} = \frac{86.4k_s}{\rho_s[c_s+4.18(w/1000)]} \quad (4)$$

Where

ρ_s –soil density, kg/m^3

c_s –dry soil specific heat, kJ/(kg·K), taken as 0.73 kJ/(kg·K)

c_w –specific heat of water, 4.18 kJ/(kg·K)

w –moisture content of soil, % (dry basis)

k_s –soil thermal conductivity, W/(m·K)

When heat loss of the buried pipeline system is calculated, the undisturbed soil temperature may be estimated for any time of the year as a function of depth, soil thermal properties, and prevailing climate. This temperature may be used in lieu of the soil surface temperature normally called for by the steady-state heat transfer equations. The formula (5) may be used to estimate the undisturbed soil temperature at any depth at any point during the yearly weather cycle [4].

$$t_{s,z} = t_{ms} - A_s e^{-z\sqrt{\pi/\alpha\tau}} \sin\left[\frac{2\pi(\theta-\theta_{lag})}{\tau} - z\sqrt{\frac{\pi}{\alpha\tau}}\right] \quad (5)$$

Where

$t_{s,z}$ –the temperature of soil, °C

θ –Julian date, days

θ_{lag} –phase lag of soil surface temperature, days

θ_{lag} for various regions of the United States can be selected in the relative references. There is no basis for the selection of this variable in China.

Formula (5) does not account for latent heat effects from freezing, thawing, or evaporation. However, for soil adjacent to a buried hot-water pipe, the formula (5) provides a good estimate, because heat loss from a pipe tend to prevent the adjacent ground from freezing. For a buried chilled-water pipe, freezing may be a consideration. Therefore, chilled-water pipe that is not used or drained during the winter months should be buried below the seasonal frost depth.

4. Calculation Method of Heat Transfer of Single Direct-buried Pipe

The single direct-buried pipeline system includes single direct-buried uninsulated pipe (Figure. 1) and single direct-buried insulated pipe (Figure. 2). The thermal resistance of the system is primarily composed of soil thermal resistance, thermal resistance of pipe and thermal resistance of thermal insulation layer.

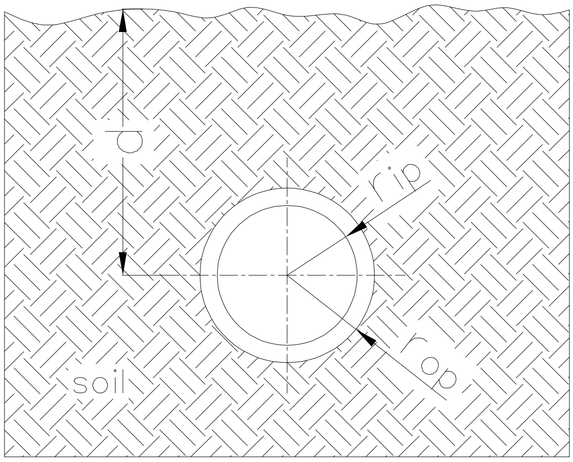

Figure 1. *Single Buried Uninsulated Pipe.*

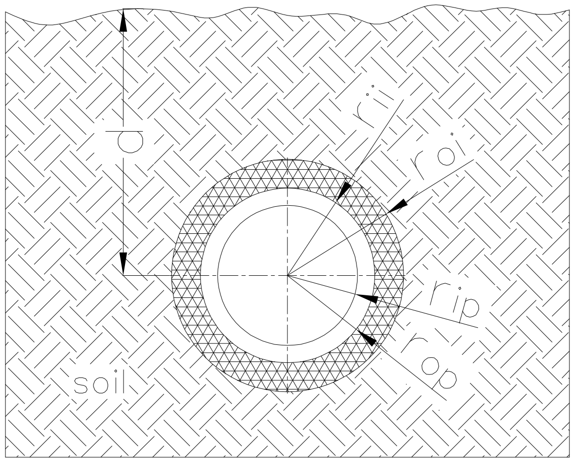

Figure 2. *Single Buried Insulated Pipe.*

4.1. Calculation of Soil Thermal Resistance

According to the ratio of burial depth to pipe radius, a method for estimating soil thermal resistance is given in reference [4]. The estimation error is less than 1% in formula (6).

$$R_s = \frac{ln\left\{(d/r_{op})+\left[(d/r_{op})^2-1\right]^{1/2}\right\}}{2\pi k_s} \quad (d/r_{op}>2)$$

$$R_s = \frac{ln(2d/r_{op})}{2\pi k_s} \quad (d/r_{op}>4) \tag{6}$$

Where

R_s –thermal resistance of soil, (m·K)/W

d–burial depth to centerline of pipe, m

r_{op}– outer radius of pipe or conduit, m

k_s –thermal conductivity of soil, W/(m·K)

d – burial depth to centerline of pipe, m

4.2. Calculation of Thermal Resistance of Pipe and Insulation Layer

The formula (7) can be used to calculate the thermal resistance of the pipe itself and the insulation layer, which is used to calculate the heat transfer resistance of the cylinder wall in the heat transfer theory. The iterative method should be used, when the thermal conductivity of thermal insulation material is a function of temperature. In general, the thermal resistance of the pipe itself and the protective casing is less than 5% of the total thermal resistance when the pipe is insulated. In order to simplify the calculation, the thermal resistance of the pipe itself and the protective casing can be neglected for the insulated pipe.

$$R_p = \frac{ln(r_{op}/r_{ip})}{2\pi k_p} \tag{7}$$

Where

R_p –thermal resistance of pipe wall, (m·K)/W

k_p –thermal conductivity of pipe, W/(m·K)

r_{ip} –inner radius of pipe, m

5. Calculation Method of Heat Transfer of Two Direct-buried Pipes

Two direct-buried pipes (Figure. 3) may be formulated in terms of the thermal resistances used for a single buried pipe and some correction factors. Reference [4] gives the calculation method of the correction factors and thermal resistance of each pipe. Subscripts 1 and 2 differentiate between the two pipes.

$$\theta_1 = (t_{p2} - t_s)/(t_{p1} - t_s) \tag{8}$$

$$\theta_2 = \frac{1}{\theta_1} = (t_{p1} - t_s)/(t_{p2} - t_s) \tag{9}$$

$$P_1 = \frac{1}{2\pi k_s} ln\left[\frac{(d_1+d_2)^2+a^2}{(d_1-d_2)^2+a^2}\right]^{1/2} \tag{10}$$

$$P_2 = \frac{1}{2\pi k_s} ln\left[\frac{(d_2+d_1)^2+a^2}{(d_2-d_1)^2+a^2}\right]^{1/2} \tag{11}$$

where

a –horizontal separation distance between centerline of two pipes, m

θ –temperature correction factor, dimensionless

t_s–temperature of soil, °C

P –geometric/material correction factor, (m·K)/W

d–burial depth to centerline of pipe, m

The thermal resistance for each pipe is given by

$$R_{e1} = \frac{R_{t1}-(P_1^2/R_{t2})}{1-(P_1\theta_1/R_{t2})} \tag{12}$$

$$R_{e2} = \frac{R_{t2}-(P_2^2/R_{t1})}{1-(P_2\theta_2/R_{t1})} \tag{13}$$

where

R_e –effective thermal resistance of one pipe in two-pipe system, (m·K)/W,

R_t –total thermal resistance of one pipe if buried separately, (m·K)/W

Note that when the resistances and geometry for the two pipes are identical, the total heat flow from the two pipes is the same if the temperature corrections are used. The individual losses vary somewhat, however.

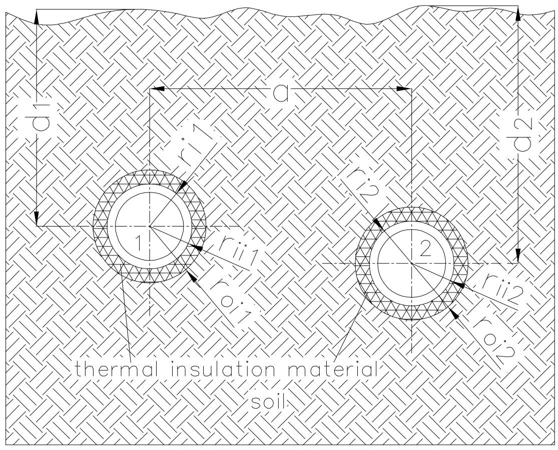

Figure 3. Two Direct-buried Pipes.

6. Calculation Method of Heat Transfer of Direct-buried Pipe in Conduit with Air Space

6.1. Calculation of Thermal Resistance of Single Buried Pipe in Conduit with Air Space

For single buried pipe in conduit with air space (Figure. 4), not only soil thermal resistance, thermal resistance of pipe and thermal resistance of insulation layer should be taken into account, but also it should be treated by adding an appropriate resistance for the air space. For simplicity, assume a heat transfer coefficient of 17 W/(m^2·K) (based on the outer surface area of the insulation), which applies in most cases.

The resistance caused by this heat transfer coefficient is then

$$R_a = \frac{1}{17\times2\pi\times r_{oi}} = \frac{0.0094}{r_{oi}} \tag{14}$$

where

r_{oi} –outer radius of insulation, m

R_a –thermal resistance of air space, (m·K)/W

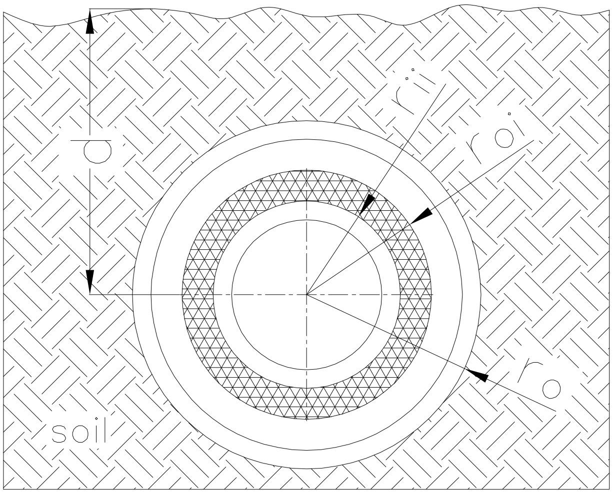

Figure 4. *Single Buried Pipe in Conduit with Air Space.*

6.2. Calculation of Thermal Resistance of Two Buried Pipes in Conduit with Air Space

For two buried pipes in conduit with air space (Figure 5), make the same assumption as made in the single buried pipe in conduit with air space. For convenience, add some of the thermal resistances as follows. Subscripts 1 and 2 differentiate between the two pipes within the conduit.

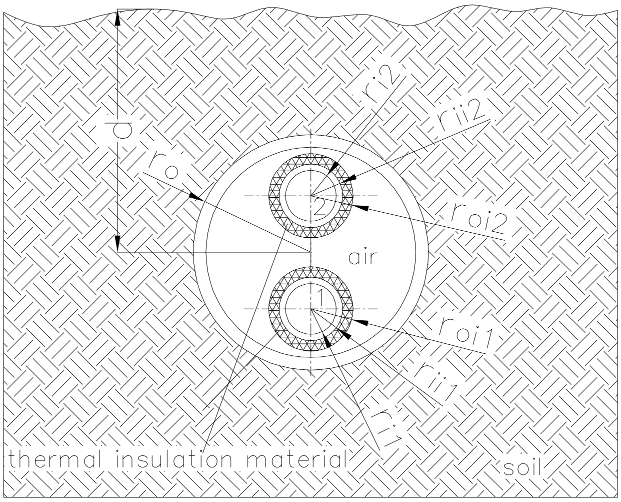

Figure 5. *Two Buried Pipes in Conduit with Air Space.*

$$R_1 = R_{p1} + R_{i1} + R_{a1} \tag{15}$$

$$R_2 = R_{p2} + R_{i2} + R_{a2} \tag{16}$$

The combined heat loss is then given by reference [1].

$$q = \frac{\left[\frac{t_{f1}-t_s}{R_1}\right]+\left[\frac{t_{f2}-t_s}{R_2}\right]}{1+\frac{R_{cs}}{R_1}+\frac{R_{cs}}{R_2}} \tag{17}$$

where

R_i –thermal resistance of insulation layer, (m·K)/W

R_{cs}–total thermal resistance of conduit shell and soil, (m·K)/ W;

t_f–temperature of fluid, °C,

Once the combined heat flow is determined, calculate the bulk temperature in the air space:

$$t_a = t_s + qR_{cs} \tag{18}$$

Then calculate the insulation outer surface temperature:

$$t_i = t_a + (t_f - t_a)(R_a/R) \tag{19}$$

The heat flows from each pipe are given by

$$q_p = (t_f - t_a)/R \tag{20}$$

7. Calculation Method of Heat Transfer of Pipes in Buried Trenches or Tunnels

Buried rectangular trenches or tunnels (Figure 6) require several assumptions to obtain approximate solutions for heat transfer. First, assume that air within the tunnel or trench is uniform in temperature and that the same is true for the inside surface of the trench/tunnel walls. Field measurements by Phetteplace et al. (1991) on operating shallow trenches indicate maximum spatial air temperature variations of about 6 K. Air temperature variations of this magnitude within a tunnel or trench do not cause significant errors for normal operating temperatures when using the following calculation methods.

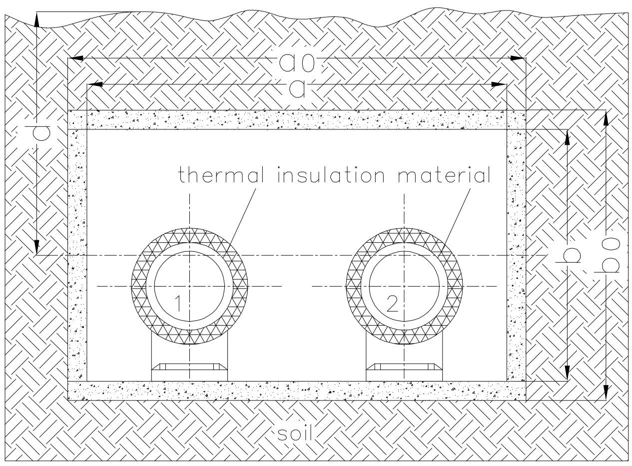

Figure 6. *Pipes in Buried Trenches or Tunnels.*

For rectangular trench/tunnel, it is usually to assume linear heat flow through the trench or tunnel walls, which yields the following resistance for the walls. The method of calculation is given in reference [4]. When the thermal conductivity of the trench/tunnel wall material is similar to that of the soil, the thickness of the trench/tunnel walls may be included in the soil burial depth.

$$R_w = \frac{x_w}{2k_w(a+b)} \quad (21)$$

where

R_w –thermal resistance of trench/tunnel walls, (m·K)/W

x_w –thickness of trench/tunnel walls, m

a –width of trench/tunnel inside, m

b –height of trench/tunnel inside, m

k_w –thermal conductivity of trench/tunnel wall material, W/(m·K)

The thermal resistance of the soil surrounding the buried trench/tunnel is calculated using the following formula:

$$R_{ts} = \frac{\ln[3.5d/(b_0^{0.75}a_0^{0.25})]}{k_s[(\frac{a_0}{2b_0})+5.7]} \ (a_0 > b_0) \quad (22)$$

where

R_{ts} –thermal resistance of soil surrounding trench/tunnel, (m·K)/W

a_o –width of trench/tunnel outside, m

b_o –height of trench/tunnel outside, m

d –burial depth of trench to centerline, m

The heat transfer processes in the air space inside the trench/tunnel are too complex to warrant a complete treatment for design purposes. The thermal resistance of this air space may be approximated by several methods. For example, formula (14) may be used to calculate an approximate resistance for the air space.

Thermal resistances at the pipe insulation/air interface can be calculated from heat transfer coefficients. Thermal resistance of the air/trench wall interface is calculated from formula (23):

$$R_{aw} = 1/[2h_t(a+b)] \quad (23)$$

where

R_{aw} –thermal resistance of air/trench wall interface, (m·K)/W

h_t –total heat transfer coefficient at air/trench wall interface, W/(m^2·K)

The total heat loss from the trench/tunnel is calculated from the following relationship:

$$q = \frac{\frac{t_{p1}-t_s}{R_1}+\frac{t_{p2}-t_s}{R_2}}{1+\frac{R_{ss}}{R_1}+\frac{R_{ss}}{R_2}} \quad (24)$$

where

R_1, R_2 –thermal resistances of two-pipe/insulation systems within trench/tunnel, (m·K)/W

R_{ss} –total thermal resistance on soil side of air within trench/tunnel, (m·K)/W

8. Conclusion

According to the basic principles of heat transfer theory, methods of heat transfer analysis of buried pipeline system based on the heat resistance, gives the calculation formulas of soil thermal resistance, pipe heat resistance (including insulation layer) and air layer thermal resistance. Heat loss per unit length and temperature distribution can be calculated. This method is suitable for the calculation of heat transfer calculation as follows: single direct-buried pipe, two direct-buried pipes, single buried pipe in conduit with air space, two buried pipes in conduit with air space and pipes in buried trenches or tunnels. The thermal resistance of the insulation layer takes a large proportion of the total thermal resistance, so the calculation can be further simplified, which the thermal resistance of the pipe and air layer can be neglected. This method avoids the complicated calculation process and greatly simplifies the calculation workload, and the calculation results can meet the needs of the engineering, which is suitable for popularization and application in engineering.

References

[1] Phetteplace, G., and V. Meyer. 1990. Piping for thermal distribution systems. CRREL Internal Report 1059. U. S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH.

[2] ASHRAE. 2011 ASHRAE Handbook—HVAC Application Chapter 34 Geothermal Energy. America: ASHRAE, 2011.

[3] China Academy of Building Research. GB 50736—2012 Design code for heating ventilation and air conditioning for civil buildings [S]. Beijing: China Construction Industry Press, 2012.

[4] ASHRAE. 2012 ASHRAE Handbook—HVAC Systems and Equipment Chapter 12 District Heating and Cooling. America: ASHRAE, 2012.

[5] Phetteplace, G. E., D. Carbee, and M. Kryska. 1991. Field measurement ofheat losses from three types of heat distribution systems. CRREL SR 631. U. S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH.

[6] Zhang Ximin, Ren Zeipei, Mei Feiming. Science of heat transmission [M]. Version 5. Beijing: China Construction Industry Press, 2007.

[7] Beijing gas thermal engineering design institute co., Ltd. CJJ 34—2010 Design code for city heating network[S]. Beijing: China Construction Industry Press, 2010.

[8] Urban construction research institute, Beijing gas thermal engineering design institute co., Ltd. CJJ/T81-2013 Technical specification for directly buried hot-water heating pipeline in city [S]. Beijing: China Construction Industry Press, 2013.