On Thermal Insulation Thickness

September 30, 2017

PreFEED Corporation

Yasuhiro Kawai

Introduction

Thermal insulation work using insulation materials is performed on equipment and piping having high temperature contents, in order to reduce thermal energy losses, to stabilize operations, and to take safety measures. Strictly speaking, the insulation is never completely adiabatic, and since the rate of heat loss and the surface temperature of the thermal insulation material will differ depending on its thickness, it is necessary to find the optimum insulation thickness after clarifying the prerequisites when determining the actual insulation construction specifications.
In this document, the contents specified in JIS-A9501 (“Hoon Horei Kouji Sekou Hyoujun” *in Japanese*: “Heat and Cold Insulation Construction and Installation Standard”) are introduced as an example of the method for calculating the thickness of the thermal insulation material.

Thermal Insulation Thickness Calculation Methods

The following three cases can be broadly classified as design conditions for calculating the thickness of the thermal insulation material.

1. When the heat dissipation from the thermal insulation material surface is less than the design value.
2. When the thermal insulation material surface temperature is less than the design value.
3. When adopting an economical thermal insulation thickness.

Hereinafter, the methods for calculating the thickness of the thermal insulation material in each case will be explained separately for plane surfaces and pipes.

1. When Heat Dissipation from Thermal Insulation Material Surface is Less than Design Value

The internal fluid temperature (θ_i), the ambient temperature (θ_a), and the surface heat transfer coefficient (h_{se}) and the type of the thermal insulation material are known. Also, let q be the design value of the heat dissipation.

1. The surface temperature (θ_{se}) of the thermal insulation material is determined from the following equation.

$$q = h_{se} \times (\theta_{se} - \theta_a) \quad \Rightarrow \quad \theta_{se} = \frac{q}{h_{se}} + \theta_a$$

2. Since the thermal conductivity of the thermal insulation material is generally a function of temperature, the average heat conduction (λ_m) between the surface temperature (θ_{se}) and the inner temperature (θ_{si}) of the thermal insulation material is determined using a relational expression that depends on the type of material that is used.

$$\lambda = f(\theta) \quad \Rightarrow \quad \lambda_m = \frac{1}{(\theta_{si} - \theta_{se})} \int_{\theta_{se}}^{\theta_{si}} f(\theta) d\theta$$

Examples of the relational expressions of the thermal conductivities of various thermal insulation materials are shown on the next page.

Temperature Dependence of Thermal Conductivities of Thermal Insulation Materials

Table 22 Properties of Various Insulation Materials

Item Name	Quality Shape	Bulk Specific Gravity [g/cm3]	Safe Operating Temp. [°C]	Thermal conductivity [kcal/m.h.C] (θ = Average Temp.)	Notes
Foam Glass	Polyfoam glass, black, closed cell, red, open cell	0.184 0.170	450 450	$0.0407+0.000180\theta$ $0.0408+0.000138\theta$	Used as a cold insulator. Minimum temperature-196 C, ASTM C 552, non-combustible.
Rubber Sponge	Semi-rigid, closed cell	0.117	70	$0.0310+0.00008\theta$	
Vinyl Chloride Sponge Foam	Semi-rigid, closed cell	0.042 0.102	70 70	$0.027+0.00013\theta$ $0.0313+0.000108\theta$	Self-extinguishing, non-water absorbing, suitable as a cold insulator
Rigid Urethane Foam	Polyester + TDI + R-11 Foam, closed cell Polyester + TDI + R-11 Foam	0.030 0.033	120 120	$0.016+0.00013\theta$ $0.015+0.00012\theta$	Can be installed on site by injection method or spraying method. Handle with care while foaming. Efficient at low temperatures, self-extinguishing, JIS A 9511-1984
Polystyrene Foam	Styrofoam sponge, closed cell	0.015~0.035	70	$0.0308+0.00014\theta$ ~ $0.0278+0.00011\theta$	Self-extinguishing, bending strength varies depending on density, JIS A 9511-1984
Phenolic Foam	Open cell	0.044~0.072	150	$0.025+0.00011\theta$	Wide temperature range, minimum temperature -196C, self-extinguishing
Polyethylene Foam		0.033	80	0.027	Low water absorption, large linear expansion, flammable
Glass Fiber Felt (Glass Wool)	1 to 7 µm glass fiber bonded with phenolic resin, plates, mats, cylinders	0.005~0.031	300~350	$0.0440+0.000246\theta$ $0.0267+0.000155\theta$	Can be used from low to high temperatures. Non-combustible, JIS A 9505-1984
Rock Wool	Felts, mats, plates, tubes, fiber	0.04 0.1 0.025	400 600 650	$0.027+0.0002\theta$ $0.024+0.00012\theta$ $0.025+0.00011\theta$	Can be used from low to high temperature. Cheap. Non- combustible. JIS A 9504-1984
Calcium Silicate	Formed into plates and cylinders with silica and lime	0.15 0.22	650 1000	$0.035+0.00006\theta$ $0.045+0.0001\theta$	High heat resistance, light weight, large strength, Non-combustible, JIS A 9510-1984
Perlite	Plate-like, cylindrical molded products	0.2	700	$0.047+0.00014\theta$	Pearlite, foaming of black iodine powder, non-combustible, JIS A 5007-1977
Ceramic Fiber		0.1~0.16	1260	0.1~0.2	Pure alumina with silica as a raw material. Withstands high temperatures. Fibrous and excellent for thermal insulation and soundproofing

"Kagaku Souchi Binran", *in Japanese*: "Chemical Equipment Handbook", 2nd Ed, (Chemical Engineering Association) p.1038

1. When Heat Dissipation from Thermal Insulation Material Surface is Less than Design Value

- For Plane Surfaces

The thermal insulation material thickness (d) is determined by the following equation.

$$h_{se} \times (\theta_{se} - \theta_a) = \frac{\lambda_m}{d} \times (\theta_{si} - \theta_{se}) \quad \Rightarrow \quad d = \frac{\lambda_m \times (\theta_{si} - \theta_{se})}{h_{se} \times (\theta_{se} - \theta_a)}$$

A product thickness (d') is selected that is slightly greater than the d obtained by the above equation.

The heat dissipation (q') is determined from the following equation using the selected d', and it is confirmed that the heat dissipation is less than the design value.

$$q' = h_{se} \times (\theta_{se} - \theta_a) = \frac{\lambda_m}{d'} \times (\theta_{si} - \theta_{se})$$

$$\theta_{se} - \theta_a = \frac{q'}{h_{se}} 、 \quad \theta_{si} - \theta_{se} = \frac{q' \cdot d'}{\lambda_m}$$

$$\therefore \theta_{si} - \theta_a = \frac{q'}{h_{se}} + \frac{q' \cdot d'}{\lambda_m} \quad \Rightarrow \quad q' = \frac{\theta_{si} - \theta_a}{\dfrac{1}{h_{se}} + \dfrac{d'}{\lambda_m}}$$

1. When Heat Dissipation from Thermal Insulation Material Surface is Less than Design Value

- For Plane Surfaces

Here, the variables are as follows.

q : Design value of heat dissipation [W/m^2]

q' : Heat dissipation in the product thickness of the insulation in the case of a flat surface [W/m^2]

d : Thermal insulation thickness [m]

d' : Thermal insulation material product thickness [m]

λ : Thermal conductivity of insulation material [W/(m·K)]

λ_m : Average thermal conductivity of insulation material [W/(m·K)]

h_{se} : Heat transfer coefficient of the surface of insulation material [W/(m^2·K)]

θ_i : Internal fluid temperature [°C]

θ_{si} : Inside temperature of insulation material [°C]

θ_{se} : Surface temperature of insulation material [°C]

θ_a : Ambient temperature [°C]

1. When Heat Dissipation from Thermal Insulation Material Surface is Less than Design Value

- For Pipes

The thermal insulation material thickness (d) is determined by the following equation.

$$h_{se}\times\pi\times D_e\times(\theta_{se}-\theta_a)=\frac{\pi(D_e-D_i)}{\frac{1}{2}(D_e-D_i)\times\ln\left(\frac{\pi D_e}{\pi D_i}\right)}\times\lambda_m\times(\theta_{si}-\theta_{se})$$

$$\Rightarrow D_e\times\ln\left(\frac{D_e}{D_i}\right)=\frac{2\times\lambda_m\times(\theta_{si}-\theta_{se})}{h_{se}\times(\theta_{se}-\theta_a)}\quad\dots\quad(1)$$

$$D_e=D_i+2\times d\Rightarrow d=\frac{D_e-D_i}{2}$$

In JIS9501, the calculation results of the left side of Eq. (1) by combinations of various pipe diameters and insulation thicknesses are shown in the table (JIS9501 Table 6). An insulation thickness d which is slightly greater than the calculated value on the right side of Eq. (1) is obtained, and a product thickness (d') close to the value is selected.

1. When Heat Dissipation from Thermal Insulation Material Surface is Less than Design Value

Table 6- D_e × ln (D_e / D_i)
(Upper) Pipe Nominal Diameter
(Bottom) Pipe Outer Diameter (mm)

Temperature
Cold Insulation Thickness

表 6−D_e×ln(D_e/D_i) の表
（上段） 配管の呼び径
（下段） 管外径（mm）

保温・保冷厚さ	10A	15A	20A	25A	32A	40A	50A	65A	80A	100A	125A	150A	200A	250A	300A
d(mm)	17.3	21.7	27.2	34.0	42.7	48.6	60.5	76.3	89.1	114.3	139.8	165.2	216.3	267.4	318.5
20	0.069	0.064	0.061	0.058	0.055	0.053	0.051	0.049	0.048	0.046	0.045	0.044	0.043	0.043	0.042
25	0.091	0.086	0.081	0.076	0.072	0.070	0.067	0.064	0.062	0.060	0.058	0.057	0.055	0.054	0.054
30	0.116	0.108	0.102	0.096	0.090	0.087	0.083	0.079	0.077	0.074	0.071	0.070	0.068	0.066	0.065
35	0.141	0.132	0.124	0.116	0.109	0.106	0.100	0.095	0.092	0.088	0.085	0.083	0.080	0.078	0.077
40	0.168	0.157	0.147	0.138	0.130	0.125	0.118	0.112	0.108	0.103	0.099	0.097	0.093	0.091	0.089
45	0.196	0.183	0.171	0.160	0.150	0.145	0.137	0.130	0.125	0.119	0.114	0.111	0.107	0.104	0.102
50	0.225	0.210	0.196	0.184	0.172	0.166	0.157	0.148	0.142	0.135	0.129	0.126	0.120	0.117	0.114
55	0.254	0.237	0.222	0.208	0.195	0.188	0.177	0.166	0.160	0.151	0.145	0.140	0.134	0.130	0.127
60	0.284	0.266	0.249	0.233	0.218	0.210	0.197	0.185	0.178	0.168	0.161	0.156	0.148	0.144	0.140
65	0.315	0.295	0.276	0.258	0.241	0.232	0.219	0.205	0.197	0.186	0.177	0.171	0.163	0.157	0.154
70	0.347	0.325	0.304	0.284	0.266	0.256	0.240	0.225	0.216	0.203	0.194	0.187	0.178	0.172	0.167
75	0.380	0.355	0.332	0.311	0.290	0.280	0.262	0.246	0.236	0.222	0.211	0.204	0.193	0.186	0.181
80	0.413	0.386	0.361	0.338	0.316	0.304	0.285	0.267	0.256	0.240	0.229	0.220	0.208	0.200	0.195
85	0.446	0.418	0.391	0.366	0.342	0.329	0.308	0.289	0.277	0.259	0.247	0.237	0.224	0.215	0.209
90	0.480	0.450	0.421	0.394	0.368	0.354	0.332	0.311	0.297	0.278	0.265	0.254	0.240	0.230	0.223
95	0.515	0.482	0.451	0.422	0.395	0.380	0.356	0.333	0.319	0.298	0.283	0.272	0.256	0.246	0.238
100	0.550	0.515	0.482	0.451	0.422	0.406	0.380	0.356	0.340	0.318	0.302	0.290	0.273	0.261	0.253

JIS A9501: 2014
p.29 (Excerpt)

1. When Heat Dissipation from Thermal Insulation Material Surface is Less than Design Value

- For Pipes

The heat dissipation (q_l') is determined from the following equation using the selected d'.

(The outer diameter of the heat insulator used is $D_e' = D_i + 2 \times d'$.)

$$q_l' = h_{se} \times \pi \times D_e' \times (\theta_{se} - \theta_a) = \frac{\pi (D_e' - D_i)}{\frac{1}{2}(D_e' - D_i) \times \ln\left(\frac{\pi D_e'}{\pi D_i}\right)} \times \lambda_m \times (\theta_{si} - \theta_{se})$$

$$\theta_{se} - \theta_a = \frac{q_l'}{h_{se} \times \pi \times D_e'}, \qquad \theta_{si} - \theta_{se} = q_l' \times \frac{\ln\left(\frac{D_e'}{D_i}\right)}{2 \times \pi \times \lambda_m}$$

$$\therefore \theta_{si} - \theta_a = \frac{q_l'}{h_{se} \times \pi \times D_e'} + q_l' \times \frac{\ln\left(\frac{D_e'}{D_i}\right)}{2 \times \pi \times \lambda_m} \Rightarrow q_l' = \frac{\theta_{si} - \theta_a}{\frac{1}{h_{se} \times \pi \times D_e'} + \frac{\ln\left(\frac{D_e'}{D_i}\right)}{2 \times \pi \times \lambda_m}}$$

1. When Heat Dissipation from Thermal Insulation Material Surface is Less than Design Value

- For Pipes

When the design value (q) of heat dissipation is the heat dissipation per unit area, the heat dissipation q_l' obtained on the previous page is converted into the heat dissipation per unit area (q_a') by the following equation to confirm that it is less than the design value q.

$$q_a' = \frac{q_l'}{D_e' \times \pi} = \frac{q_l'}{(D_i + 2d') \times \pi}$$

1. When Heat Dissipation from Thermal Insulation Material Surface is Less than Design Value

- For Plane Surfaces

Here, the variables are as follows.

q : Design value of heat dissipation [W/m^2]

q_l' : Heat dissipation in the product thickness of the insulation in the case of a flat surface [W/m^2]

q_a' : Heat dissipation per unit area at the product thickness d' of the insulation material in the case a pipe [W/m^2]

d : Thermal insulation thickness [m]

d' : Thermal insulation material product thickness [m]

λ : Thermal conductivity of insulation material [W/(m·K)]

λ_m : Average thermal conductivity of insulation material [W/(m·K)]

h_{se} : Heat transfer coefficient of the surface of insulation material [W/(m^2·K)]

θ_i : Internal fluid temperature [°C]

θ_{si} : Inside temperature of insulation material [°C]

θ_{se} : Surface temperature of insulation material [°C]

θ_a : Ambient temperature [°C]

D_i : Inner diameter of thermal insulation material [m]

D_e : Outer diameter of thermal insulation material [m]

D_e' : Product outer diameter of thermal insulation material [m]

PreFEED

2. When Thermal Insulation Material Surface Temperature is Less than Design Value

The concept of making the surface temperature of the thermal insulation material smaller than the design value is basically the same as the case where heat dissipation from the surface is smaller than the design value. In the case of a plane surfaces and of pipes, the product thickness (d') of the thermal insulation material is determined by the previously mentioned equations and the surface temperature (θ_{se}') at the product thickness is calculated by the following equation to confirm that it is less than the design value (θ_{se}).

For plane surfaces

$$q' = h_{se} \times (\theta_{se}' - \theta_a) \quad \Rightarrow \quad \theta_{se}' = \frac{q'}{h_{se}} + \theta_a$$

For pipes

$$q_l' = \pi \times D_e' \times h_{se} \times (\theta_{se}' - \theta_a) \quad \Rightarrow \quad \theta_{se}' = \frac{q_l'}{\pi \times D_e' \times h_{se}} + \theta_a$$

PreFEED

3. When Adopting an Economical Thermal Insulation Thickness

When the surface temperature of the thermal insulation material is below the design value or when the heat dissipation from the surface is below the design value, it is often not economically optimal. Generally the most economical thickness will be determined when there is no restriction regarding the heat loss and the surface temperature.

In both the cases of plane surfaces and pipes, the total annual cost may be calculated as the sum of the construction costs for one year and the heat costs equivalent to the heat dissipation, to obtain the thermal insulation thickness (d) at which the total cost reaches a minimum.
It is necessary for the designer to determine the construction costs, the heat costs , annual usage time, annual interest rates, the number of years of usage, and the like.

3. When Adopting an Economical Thermal Insulation Thickness

Total annual cost (F_f) for plane surfaces

$$F_f = a \times d \times N + b \times t \times q$$

Total annual cost (F_l) for pipes

$$F_l = \frac{\pi (D_e^{\,2} - D_i^{\,2})}{4} \times a \times N + b \times t \times q_l$$

$$d = \frac{D_e - D_i}{2}$$

The variables are explained on the next page.

3. When Adopting an Economical Thermal Insulation Thickness

F_f : Total annual cost of thermal insulation for plane surfaces [yen/m^2]

F_l : Total annual cost of thermal insulation for tubes [yen/m]

a : Construction cost per unit volume [yen/m^3]

b : Heat cost [yen/(kW·h)]

t : Annual usage time [h]

n : Annual interest rate [-]

y : Number of years of use [years]

N : Amortization rate [-] $\quad N = \dfrac{n \times (1+n)^y}{(1+n)^y - 1}$

q : Heat dissipation of plane surfaces [W/m^2]

q_l : Heat dissipation of tubes [W/m]

d : Thermal insulation thickness [m]

D_i : Inner diameter of thermal insulation material [m]

D_e : Outer diameter of thermal insulation material [m]

λ_m : Average thermal conductivity of insulation material [W/(m·K)]

h_{se} : Heat transfer coefficient of the surface of insulation material [W/(m^2·K)]

θ_{si} : Inside temperature of insulation material [°C]

θ_a : Ambient temperature [°C]

$$q = \frac{\theta_{si} - \theta_a}{\dfrac{1}{h_{se}} + \dfrac{d}{\lambda_m}}$$

$$q_l = \frac{\theta_{si} - \theta_a}{\dfrac{1}{h_{se} \times \pi \times D_e} + \dfrac{\ln\left(\dfrac{D_e}{D_i}\right)}{2 \times \pi \times \lambda_m}}$$

As previously mentioned, the construction cost per unit volume (*a*) and the heat costs (*b*) need to be determined by the designer based on the design standards and actual results . The concept is shown in Appendix H of JIS A9501. (How to Determine the Economical Insulation Thickness)

In addition, a concrete calculation example is shown in Appendix M (for calculation cases). The main calculation conditions of the example shown in the appendix are as follows.

Ambient temperature	20 [˚C]
Surface heat transfer coefficient	12 [W/(m^2·K)]
Annual interest rate	5 [%]
Years of usage	15 [years]
Annual usage time	4000 [h], 8000 [h]

Thicknesses and heat dissipation for various insulation materials are listed and can be used.

Appendix H (Reference)
How to Determine the Economical Insulation Thickness

In 3.14, the economical insulation thickness is defined as "The thermal insulation thickness when the sum of construction costs for one year and the heat costs equivalent to the heat dissipation is at a minimum." The concept of the calculation method is as follows.

H.1 Concept of Economical Insulation Thickness
In thermally insulated equipment and piping, heat is always dissipated from the surface, and a heat loss cost corresponding to the heat dissipation is generated.
From the viewpoint of energy savings, the thicker the thermal insulation thickness, the smaller the amount of heat released, which leads to a cost reduction according to the amount of heat released. On the other hand, from the viewpoint of the construction costs in consideration of the material costs, the labor costs, and the management costs, the construction expenses (hereinafter referred to as the construction costs) increase as the thermal insulation thickness increases.
That is, in the graph in which the thermal insulation thickness is taken along the horizontal axis, and the construction costs and the heat costs corresponding to the heat dissipation are taken along the vertical axis, the former draws a curve rising to the right and the latter draws a downward curve.
The economical thermal insulation thickness is determined in consideration of the balance between the construction costs and the heat costs equivalent to the heat dissipation, and the thermal insulation thickness which minimizes the sum of the two is selected.
The calculation methods of construction costs and heat costs are as follows.

JIS A9501: 2014
p.71 (Excerpt)

Appendix M (Reference)
Calculation Case Study

M.1 General

This appendix summarizes the results of trial calculations under the following conditions for the convenience of users. Therefore, the calculation results in this appendix are valid only under limited conditions.

M.2 Economical Thermal Insulation Thickness

See Appendix H for concepts and formulas for economical insulation thicknesses. The conditions and numerical values for calculating the economical insulation thickness should basically be determined by the users themselves and setting the conditions and the numerical values can be complicated. Here, the following conditions are assumed.

a) Calculation conditions

Ambient temperature (θ_a)	20 [˚C]
Surface heat transfer coefficient (h_{se})	12 [W/(m²·K)]
Annual interest rate (n)	5 [%]
Years of usage (y)	15 [years]
Thermal energy cost (b)	5 [yen/(kW·h)]
Annual usage time (h)	4000 or 8000 [hours]

a: Construction cost per unit volume of thermal insulation material [yen/m³]

$a = 10^3 \times (12 \times d^{-k} + 200)$ (in the case of artificial mineral fiber insulation materials)

$a = 10^3 \times (12 \times d^{-k} + 300)$ (in the case of an inorganic porous insulation materials)

JIS A9501: 2014
p.81 (Excerpt)

PreFEED
3. When Adopting an Economical Thermal Insulation Thickness

Table M1.2-Economical Thermal Insulation Thickness and Heat Dissipation of Rock Wool Insulation Cylinder (8000 Hours of Annual Usage)

Inner Pipe Temp. ℃	Item	Nominal Pipe Diameter (Upper A / Lower B)																			
		15	20	25	32	40	50	65	80	100	125	150	200	250	300	350	400	450	500	550	600
		½	¾	1	1¼	1½	2	2½	3	4	5	6	8	10	12	14	16	18	20	22	24
100	保温厚さ a)	30	35	35	40	40	45	45	50	55	55	55	60	60	65	65	65	65	70	70	70
	放散熱量 b)	15	16	18	19	21	22	26	27	30	35	40	46	55	59	65	73	81	83	91	98
150	保温厚さ	40	45	45	50	55	55	60	65	70	70	75	80	80	85	85	85	90	90	90	90
	放散熱量	23	25	28	30	31	35	39	41	46	53	57	66	78	86	94	105	110	121	131	141
200	保温厚さ	50	50	55	60	65	65	70	75	80	85	90	95	95	100	100	105	105	110	110	110
	放散熱量	32	36	38	42	43	48	53	56	64	70	76	88	104	114	125	134	147	155	168	181
250	保温厚さ	55	60	65	70	75	80	85	85	95	95	100	110	110	115	120	120	125	125	130	130
	放散熱量	43	46	50	54	55	60	67	73	80	91	98	111	130	144	152	168	179	195	205	220
300	保温厚さ	65	70	75	80	80	90	95	100	105	110	115	120	125	130	135	135	140	145	145	145
	放散熱量	54	57	62	67	72	76	84	89	100	111	120	140	158	175	185	205	219	232	250	269
350	保温厚さ	70	75	85	90	90	100	105	110	115	120	125	135	140	145	150	155	155	160	160	165
	放散熱量	67	72	75	82	87	93	102	109	123	135	147	167	189	209	221	239	261	277	299	313
400	保温厚さ	80	85	90	100	100	110	115	120	130	135	140	150	155	160	165	170	175	175	180	180
	放散熱量	80	86	93	98	105	111	123	131	144	159	173	197	222	246	261	281	301	326	344	369
450	保温厚さ	90	95	100	105	110	120	125	130	140	145	155	165	170	175	180	185	190	195	195	200
	放散熱量	95	102	110	119	124	132	146	155	171	189	201	229	259	286	304	328	351	373	401	421
500	保温厚さ	95	105	110	115	120	130	135	140	150	160	165	175	185	195	195	200	205	210	215	220
	放散熱量	114	120	129	140	146	156	172	183	202	218	236	270	299	325	351	379	406	431	455	478

a) Insulation Thickness, b) Heat Dissipation

JIS A9501: 2014
p.86 (Excerpt)

Conclusion

The more insulation can be done, the more thermal losses can be suppressed, but construction costs will increase.
Therefore, it is common practice to determine the actual insulation thickness by considering both the costs of thermal losses associated with heat dissipation and the construction costs.

The calculation examples shown in the annex of the JIS are widely used because they are very easy to use. On the other hand, considering the energy saving efforts in recent years and the fluctuations of fuel unit costs and construction unit costs, it is always important to conduct detailed investigations based on actual results and design criteria , and it is necessary to fully understand heat transfer in thermal insulation materials and cost calculation methods.