PETROBRAS

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CONTEC
Comissão de Normalização Técnica

SC-09
Thermal Insulation and Refractories

Design of Cold Insulation

Revalidation

Revalidated in 05/2022.

Design of Cold Insulation

Procedure

This Standard replaces and cancels its previous revision.

The CONTEC - Authoring Subcommittee provides guidance on the interpretation of this Standard when questions arise regarding its contents. The Department of PETROBRAS that uses this Standard is responsible for adopting and applying the sections, subsections and enumerates thereof.

Technical Requirement: A provision established as the most adequate and which shall be used strictly in accordance with this Standard. If a decision is taken not to follow the requirement ("non-conformity" to this Standard) it shall be based on well-founded economic and management reasons, and be approved and registered by the Department of PETROBRAS that uses this Standard. It is characterized by imperative nature.

Recommended Practice: A provision that may be adopted under the conditions of this Standard, but which admits (and draws attention to) the possibility of there being a more adequate alternative (not written in this Standard) to the particular application. The alternative adopted shall be approved and registered by the Department of PETROBRAS that uses this Standard. It is characterized by verbs of a non mandatory nature. It is indicated by the expression: **[Recommended Practice]**.

Copies of the registered "non-conformities" to this Standard that may contribute to the improvement thereof shall be submitted to the CONTEC - Authoring Subcommittee.

Proposed revisions to this Standard shall be submitted to the CONTEC - Authoring Subcommittee, indicating the alphanumeric identification and revision of the Standard, the section, subsection and enumerate to be revised, the proposed text, and technical/economic justification for revision. The proposals are evaluated during the work for alteration of this Standard.

CONTEC
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SC - 09
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Introduction

PETROBRAS Technical Standards are prepared by Working Groups - WG (consisting specialized of Technical Collaborators from Company and its Subsidiaries), are commented by Company Units and its Subsidiaries, are approved by the Authoring Subcommittees - SCs (consisting of technicians from the same specialty, representing the various Company Units and its Subsidiaries), and ratified by the Executive Nucleus (consisting of representatives of the Company Units and its Subsidiaries). A PETROBRAS Technical Standard is subject to revision at any time by its Authoring Subcommittee and shall be reviewed every 5 years to be revalidated, revised or cancelled. PETROBRAS Technical Standards are prepared in accordance with PETROBRAS Technical Standard N-1. For complete information about PETROBRAS Technical Standards see PETROBRAS Technical Standards Catalog.

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Foreword

This Standard is the English version (issued in 012013 of PETROBRAS N-894 REV. E 06/2012. In case of doubt, the Portuguese version, which is the valid document for all intents and purposes, shall be used.

1 Scope

1.1 This Standard sets out the conditions required in the design of thermal insulation of equipment and piping operating at low temperature. However, it does not apply to services with operating temperatures below -100 °C.

1.2 This Standard applies to the material selection and sizing of thickness of thermal insulation material, according to the following criteria:

a) condensation control of moisture on the outer surface of the thermal insulation;
b) conservation of heat energy;
c) stabilization of industrial process phases;
d) personnel protection or comfort.

1.3 This Standard applies to designs started from its issue date as well as to existing facilities/equipment, at the time of maintenance or repair.

1.4 This Standard contains Technical Requirements and Recommended Practices.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document applies.

PETROBRAS N-896 - Installation of Cold Insulation;

PETROBRAS N-1618 - Thermal Insulation Material;

ASTM C 795 - Standard Specification for Thermal Insulation for Use in Contact With Austenitic Stainless Steel;

ASTM C 534 - Standard Specification for Preformed Flexible Elastomeric Cellular Thermal Insulation in Sheet and Tubular Form;

ASTM C 1728 - Standard Specification for Flexible Aerogel Insulation.

NOTE For documents referred in this Standard and for which only the Portuguese version is available, the PETROBRAS department that uses this Standard should be consulted for any information required for the specific application.

3 Terms and Definitions

For the purposes of this document, the following terms and definitions apply.

3.1
low temperature
operating temperature equal to or less than the average of the maximum ambient temperatures in the two hottest months of the year

3.2
thermal insulation material
material used to reduce the heat transfer

3.3
thermal insulation
set of materials that, when applied, reduces the heat transfer

3.4
economic thickness
thickness obtained taking into account the costs of absorbed energy, the investment in thermal insulation and maintenance, aimed at minimizing the total cost

3.5
energy conservation
criteria for establishing the economic thickness of insulation material(s), taking into account the costs of loss energy, the investment in thermal insulation and maintenance, aimed at minimizing the total cost

3.6
condensation control of moisture on the outer surface of the thermal insulation
criteria for establishing the thickness of the insulation material(s) that ensures non condensation of air humidity on the surface of the thermal insulation of piping or equipment

3.7
stabilization of industrial process phases
criteria for establishing the thickness of insulation material(s), taking into account the maximum allowable value for heat loss (heat flow), based on the needs and limitations of a particular industrial process

3.8
personnel protection or comfort
criteria for establishing the thickness of the insulation material(s) that aims to prevent damage or personnel discomfort

4 General Conditions

4.1 Sizing Criteria

4.1.1 The basic criteria for determining the thickness of the thermal insulation consists on the use of concepts of energy conservation and condensation control of moisture on the outer surface of the thermal insulation.

4.1.2 When there is more than one reason for sizing, the thickness shall be calculated in accordance with the corresponding criteria and the one that presents the highest value shall be used.

4.2 Materials

4.2.1 The insulation material normally used is the expanded polyurethane (pre-molded, sprayed or injected) or polyisocyanurate (pre-molded). Granular expanded perlite, elastomeric foam, cellular glass and aerogel may be used according to specific design.

4.2.2 The insulation materials used shall be in accordance with PETROBRAS N-1618, including the following materials:

a) elastomeric foam, according to ASTM C 534;
b) aerogel, according to ASTM C 1728.

4.2.3 The thermal insulation shall be applied according to PETROBRAS N-896. For applications not foreseen in PETROBRAS N-896, a procedure of specific installation shall be presented according to the instructions of the manufacturer and assembler.

4.2.4 For the same type of material, it is recommended that the distribution of layers of rigid thermal insulation material is made in accordance with Table 1. **[Recommended Practice]**

Table 1 - Thickness Distribution of Pre-Molded Rigid Insulation Materials

Total thickness mm (in.)	Layers mm (in.)	
	1st	2nd
25 (1”)	25 (1”)	-
38 (1½”)	38 (1½”)	-
51 (2”)	51 (2”)	-
63 (2½”)	38 (1½”)	25 (1”)
76 (3”)	38 (1½”)	38 (1½”)
89 (3½”)	51 (2”)	38 (1½”)
102 (4”)	51 (2”)	51 (2”)
114 (4½”)	63 (2½”)	51 (2”)
127 (5”)	63 (2½”)	63 (2½”)
139 (5½”)	76 (3”)	63 (2½”)
153 (6”)	76 (3”)	76 (3”)
165 (6½”)	89 (3½”)	76 (3”)
178 (7”)	102 (4”)	76 (3”)
191 (7½”)	102 (4”)	89 (3½”)
204 (8”)	102 (4”)	102 (4”)

4.2.5 Expansion-contraction joints shall be provided for the rigid thermal insulation, in accordance with PETROBRAS N-896.

4.2.6 For piping or equipment of 300 and 400 series stainless steel, the maximum content of chlorides and fluorides in thermal insulation shall comply with the criteria of ASTM C 795, in order to minimize the possibility of stress corrosion cracking.

4.2.7 When the equipment or piping is subjected to high and low temperature conditions, it shall be used, firstly, a layer of rigid thermal insulation for high temperature, sized so that the maximum temperature of its outer surface is less than 80 ºC.

NOTE 1 The sizing of the thickness of thermal insulation material for low temperature shall not consider the influence of the thermal conductivity of the rigid thermal insulation material for high temperature.

NOTE 2 If the piping or equipment is also subjected to high temperature conditions and there is a need for personal protection (hot), the maximum temperature of its outer surface, considering the last layer of thermal insulation, does not exceed 60 °C.

4.3 Equipment and Piping

4.3.1 Except as otherwise recommended by the system designer or if there is risk of freezing, it shall not be insulated:

a) if the gain of heat is necessary in view of process requirements;
b) piping and equipment sporadically cooled, such as:
— relief valves and release systems;
— vents and drains;
— flare system;
— drainage system;
c) hoses.

4.3.2 The insulation of interference parts of piping, equipment, handwheels and valve stems shall comply with the provisions of PETROBRAS N-896.

4.3.3 The materials applicable for equipment and piping insulation are shown in Table 2.

NOTE A technical and economic analysis shall be performed in order to select the best material and method of application.

Table 2 - Selection of Thermal Insulation Material to be Used

Material/ method of application	Piping and accessories		Tanks			Towers (Note 4)		Exchangers and vessels (Notes 2 and 4)		Rotating equipment	Spheres
	Aerial	Buried	Roof	Wall	Bottom	Small	Medium and large	Small and medium	Large		
Injected polyurethane	X	X	X (Note 1)	X (Note 1)		X	X	X	X	X	X (Note 1)
Sprayed polyurethane (Note 5)			X	X			X		X		X
Pre-molded polyurethane	X	X	X	X	X (Note 3)	X	X	X	X	X	X
Pre-molded polyisocyanurate	X	X	X	X	X (Note 3)	X	X	X	X	X	X
Granular expanded perlite				X		X	X	X	X		
Cellular glass	X	X	X	X	X	X	X	X	X	X	X
Elastomeric foam	X	X	X	X		X	X	X	X	X	X
Aerogel	X	X	X	X		X	X	X	X	X	X

NOTE 1 It is allowed the injection of polyurethane on the roof and wall of tanks and spheres, since it is applied with removable forms to enable the execution of a steam barrier.
NOTE 2 For Cold Box, only granular expanded perlite shall be used.
NOTE 3 Admitted only to support blocks of the bottom tank annular plate.
NOTE 4 For purposes of definition of large, medium and small equipment, Table 3 shall be considered.
NOTE 5 The design and performance guarantee are the responsibility of the applicator, which shall inform the design values (thickness, type and physical properties) that are checked in the acceptance of the application procedure, according to PETROBRAS N-896.

Table 3 - Classification of Equipment Size

Equipment/size	Small	Medium	Large
Exchangers	≤ 2 m^3	From 2 m^3 to 20 m^3	> 20 m^3
Vessels	≤ 2 m^3	From 2 m^3 to 20 m^3	> 20 m^3
Towers	≤ 5 m^3	From 5 m^3 to 40 m^3	> 40 m^3

5 Specific Conditions

5.1 Energy Conservation

5.1.1 To determine the economic thickness, a specific study that considers the updated costs of energy and the installation of thermal insulation shall be made.

5.1.1.1 The calculation route presented in Annex A can be used to determine the insulation thickness. **[Recommended Practice]**

5.1.1.2 Annex G can be used as an indicator of economic thickness, only in the quick sizing of lines or small equipment insulated with polyurethane/polyisocyanate and in accordance with the conditions specified on it. **[Recommended Practice]**

NOTE It is the responsibility of the designer to check if the energy cost calculations presented in this Standard apply to his specific case or if there are other costs to consider, such as loss of production or loss of separation efficiency.

5.2 Condensation Control of Moisture on the Outer Surface of the Thermal Insulation

5.2.1 The thermal insulation shall assure, on the outer surface, a temperature above the dew point obtained from Table F.1 in Annex F.

5.2.2 To determine the thickness of moisture control, it is recommended to use the calculation route from Annex B. **[Recommended Practice]**

5.3 Personnel Protection or Comfort

5.3.1 The thermal insulation shall assure, on the outer surface, a temperature above 0 °C.

5.3.2 The thermal insulation shall be done on equipment and piping in which the outer surfaces are located at a height less than 2 m of any floor or at a lateral distance of less than 1 m of stairs or platforms for personnel transit.

5.3.3 If the thermal insulation is not allowed due to operational problems, metallic protection (screens) and even appropriate signs, limiting people's access to non insulated outer surface, shall be provided.

5.3.4 To determine the thickness for personnel protection, a specific study to consider the local environmental conditions shall be made.

5.3.5 The calculation route presented in Annex B can be used to determine the insulation thickness. **[Recommended Practice]**

5.4 Stabilization of Industrial Process Phases

To determine the thickness for stabilization of industrial process phases, it is recommended the use of the calculation route in Annex C. **[Recommended Practice]**

Annex A - Energy Conservation - Calculation Route

A.1 Introduction

A.1.1 The calculation of thermal insulation thickness based on the concept of energy conservation aims, complying with the constraints of safety and process, to promote an economic benefit by reducing the heat absorbed through the walls of a piping or equipment. Because it is a calculation that involves material costs, maintenance and energy, the concept of "more economic solution" may vary over time.

A.1.2 The additional cost in material and the reduction of thermal energy cost, resulting from the increase of thickness of the thermal insulation, shall be analyzed. Therefore, it is necessary to calculate the heat absorbed for each new thickness analyzed, which requires an iterative calculation. The guide shown herein is only one way to determine the thickness. The nomenclature of the variables used is included in Table E.1 in Annex E.

A.2 Determination of the Heat Flux

A.2.1 Define a thickness configuration for the start of the analysis, for example, the value immediately above to the value obtained from another calculation criteria.

A.2.2 Estimate a value for the temperature of the outer surface of the thermal insulation, for example, the same value obtained from another calculation criteria.

A.2.3 Calculate the heat transfer coefficients appropriate to the problem, according to Annex D.

A.2.4 With the average temperature $(T_e+T_0)/2$, calculate the material thermal conductivity.

A.2.5 Calculate the new temperature of the outer surface using the equation balance of D.2.1.1 in Annex D or the equation of D.2.2 in Annex D with:

$$q = (h_c + h_r) . (T_a - T_e)$$

NOTE 1 For flat surfaces, it can be expressed as:

$$T_e = \frac{(h_c + h_r)\,T_a + k/L\;T_0}{h_c + h_r + k/L}$$

NOTE 2 For cylindrical surfaces:

$$T_e = \frac{(h_c + h_r)\,T_a + \dfrac{k}{r_e \ln\left(r_e/r_0\right)}\,T_0}{h_c + h_r + \dfrac{k}{r_e \ln\left(r_e/r_0\right)}}$$

A.2.6 If the value T_e differs by more than 2 °C of the previously established value of T_e, return to A.2.3 with the new value of T_e.

A.3 Determination of Costs

The calculation of the total cost of a thermal insulation system consists of five parts, each one constituted by the cost of:

a) the energy absorbed;
b) the cooling water;
c) the investment in the cooling unit;
d) the investment in the thermal insulation;
e) the maintenance of thermal insulation.

NOTE The costs can be calculated per unit of area or length, or total instalation.

A.3.1 Cost of Absorbed Energy

A.3.1.1 The annual absorbed energy cost can be evaluated by the following expression:

$$CE = \frac{Q \cdot N \cdot C_{ac}}{1\,000 \cdot \eta_{co} \cdot COP}$$

A.3.1.2 This cost, which is repeated throughout the life of the thermal insulation system, shall be updated to reflect its current value:

$$CE_{VA} = f\,(j, n) \cdot CE \qquad (1)$$

$$f\,(j, n) = \frac{(1 + j)^n - 1}{j \cdot (1 + j)^n} \qquad (2)$$

$$j = \frac{1 + i}{1 + \Delta} - 1 \qquad (3)$$

A.3.2 Cost of the Cooling Water

A.3.2.1 The annual cost of cooling water refers to the cost of replacement of the water consumed in the cooling system and can be evaluated by the following expression:

$$CA = 3\,600 \cdot Q \cdot N \cdot W \cdot S$$

A.3.2.2 This cost, which is repeated throughout the life of the thermal insulation system, shall be updated to reflect its current value:

$$CA_{VA} = f\,(j', n) \cdot CA \qquad (1)$$

$$f\,(j', n) = \frac{(1 + j')^n - 1}{j' \cdot (1 + j')^n} \qquad (2)$$

$$j' = \frac{1+i}{1+\Delta'} - 1 \qquad (3)$$

A.3.3 Cost of Investment in the Cooling Unit

The cost of investment in the cooling unit is a portion that shall be considered when a cooling system is to be installed or expanded to meet the increased demand. Special care shall be taken to limit cases, such as the change in the unit cost due to the total capacity of the cooling system.

$$CR = Q \,.\, R$$

A.3.4 Cost of the Investment in the Thermal Insulation

The cost of investment in thermal insulation, CI ($\$/m^2$, \$/m or \$), shall consider the thermal insulation material, the fixation and protection materials used in the installation, as well as the cost of personnel and equipment.

A.3.5 Cost of the Maintenance of Thermal Insulation

A.3.5.1 The cost of maintenance of thermal insulation is usually considered as a percentage of the investment in the thermal insulation.

$$CM = tm \,.\, CI$$

A.3.5.2 This cost, which is repeated throughout the life of the thermal insulation system, shall be updated to reflect its current value:

$$CM_{VA} = f\,(i, n)\,.\,CM = f\,(i, n)\,.\,tm\,.\,CI \qquad (1)$$

$$f\,(i, n) = \frac{(1+i)^n - 1}{i\,.\,(1+i)^n} \qquad (2)$$

A.3.6 Total Cost of Thermal Insulation

The total cost of thermal insulation shall be given by:

$$CT = CE_{VA} + CA_{VA} + CR + CI + CM_{VA}\text{ , or}$$

$$CT = CE_{VA} + CA_{VA} + CR + CI\,.\,[1 + tm\,.\,f\,(i, n)]$$

A.4 Determination of "Economic Thickness"

A.4.1 The determination of the "economic thickness" consists of checking for which thickness the total cost is lesser. Thus, it is necessary to determine, for various thicknesses, the heat gain from ambient, according to A.2, and the total cost associated, according to A.3, and then make a comparison between the various solutions analyzed.

A.4.2 The parameters used to determine the costs, such as costs of drive energy and thermal insulation, shall be based on historical values, in order to obtain a valid selection for throughout the life of the thermal insulation. Factors that can not be quantified in the cost shall also be analyzed (for example: availability in stock).

A.5 Example of Calculation

Determine the economic thickness of the thermal insulation of a tank, considering it as a flat surface of 10 m in length. The internal temperature is -25 °C and the ambient temperature is 24 °C. It is assumed the emissivity of 0.2 for aluminum and winds of 2 m/s (forced convection). Consider the parameters for the cost reference values according to Annex G, however considering that this is a new installation, where the unit cost of the cooling unit is R$ 1.8/W. From previous calculation to condensation control, it was determined that the minimum thickness shall be 38 mm of polyurethane, with a surface temperature of 18.4 °C and a heat flux of 31.94 W/m^2. Consider the thermal conductivity of the injected polyurethane mentioned in PETROBRAS N-1618.

Data:

T_0 = -25 ° C
T_a = 24 °C
L_C = 10 m
V = 2 m/s
ε = 0,2

A.5.1 Determination of the Heat Flow (1st Stage)

Step 1: The next commercial thickness is 51 mm.

Step 2: T_e, est. = 20 °C.

Step 3: T_a = 24 ° C ∴ $\overline{T} = (T_e + T_a)/2$ = 22 °C

properties of air (see Table D.3 in Annex D):

k = 0,0258 W/m . °C

υ = 15,44.10^{-6} m^2/s

Pr = 0,708

heat transfer coefficient by convection:

of D.4.1 in Annex D: L_c = 10 m

$$RE = \frac{\nu . L_c}{\upsilon} = 1{,}30 \,.\, 10^6$$

$$\therefore h_c = \frac{k}{L_c}\left(0{,}037\ Re^{0,8} - 871\right) Pr^{0,33} = 4{,}58\ W/m^2\ .\ °C$$

heat transfer coefficient by radiation:

of D.1 in Annex D:

$$h_r = 5{,}669\,.\,10^{-8}\,\varepsilon\left[(T_e + 273)^2 + (T_a + 273)^2\right](T_e + T_a + 546)$$

$$\therefore h_r = 1{,}17\ W/m^2\ .\ °C$$

Step 4: $\overline{T} = (T_0 + T_e)/2$ = - 5,5 °C of PETROBRAS N-1618: k = 0,0279 W/m .°C

Step 5: $T_e = \dfrac{(h_c + h_r)\,T_a + \frac{k}{L}\,T_0}{h_c + h_r + \frac{k}{L}}$ T_e = 19,7 °C

Step 6: The difference in relation to the previous value of T_e is less than 2 °C, thus it is not necessary to go back to step 3. The heat flow absorbed may be calculated by:

$$q = (h_c + h_r)\,.\,(T_a - T_e) = 24{,}72\ \text{W/m}^2$$

A.5.2 Determination of Costs (2nd Stage)

By repeating the procedure afore mentioned for other thicknesses and using the equations mentioned in A.3 to calculate the costs, with the reference values in Annex G, the data of Table A.1 is obtained.

Table A.1 - Example of Calculation - Summary

Thickness (mm)	Heat flow (W/m²)	Updated energy cost (R$/m²)	Cost of investment in the cooling unit (R$/m²)	Updated cost of the cooling water (R$/m²)	Invest. and maintenance cost (R$/m²)	Total cost (R$/m²)
38	31,94	140,29	57,49	0,14	367,86	565,78
51	24,72	107,47	44,50	0,11	374,74	526,82
63	20,12	88,39	36,22	0,09	391,94	516,64
76	16,88	74,12	30,38	0,08	404,03	508,61
89	14,53	63,83	26,15	0,06	415,56	505,60
102	12,76	56,04	22,96	0,06	427,08	506,14

NOTE Hence, the economic thickness is 89 mm. However, the gain in the total cost to the 76 mm thickness and even to the 63 mm thickness is not very significant; therefore these thicknesses shall also be considered in the decision.

Annex B - Condensation Control of Moisture on the Outer Surface of the Thermal Insulation and Personnel Protection - Calculation Route

B.1 Introduction

The calculation of the thermal insulation thickness based on the concepts of condensation control of moisture and personnel protection presupposes the existence of a minimum allowable temperature on the outer surface of the thermal insulation. This sizing requires an iterative calculation and the route presented herein is just one of the ways of determining the thicknesses. The nomenclature of the variables used is included in Table E.1 of Annex E.

B.2 Flat Surfaces

B.2.1 With the minimum temperature specified, calculate the heat transfer coefficients suitable to the problem, according to Annex D.

B.2.2 Calculate the heat flow:

$$q = (h_c + h_r) . (T_a - T_e)$$

B.2.3 Determination of the thickness:

a) with the average temperature $(T_0+T_e)/2$, calculate the material thermal conductivity;
b) calculate the thickness of the thermal insulation using the equation mentioned in D.2.1.1 of Annex D;
c) adopt the commercial thickness immediately above the calculated one.

B.3 Cylindrical or Spherical Surfaces

The calculation for cylindrical or spherical surfaces requires an additional iteration, since the external diameter, which depends on the thicknesses, affects heat flow calculations.

B.3.1 Estimate the value of the external diameter of the thermal insulation, based on prior experience or approaches:

a) D_e = 1,5 D_0 to $D_0 \leq$ 150 mm;
b) D_e = 1,3 D_0 to 150 < $D_0 \leq$ 300 mm;
c) D_e = 1,1 D_0 to D_0 > 300 mm.

B.3.2 With the minimum temperature specified, calculate the heat transfer coefficients suitable to the problem, according to Annex D.

B.3.3 Calculate the heat flow relating to the outer surface of the thermal insulation:

$$q_e = (h_c + h_r) . (T_a - T_e)$$

B.3.4 Determination of the thickness:

a) with the average temperature $(T_0+T_e)/2$, calculate the material thermal conductivity;
b) for cylindrical surfaces, calculate the external diameter of the thermal insulation using the equation mentioned in D.2.2 of Annex D, considering the product $q_e \cdot D_e/2$, on the left side of the equation; for spherical surfaces, calculate the external diameter of the thermal insulation using the equation mentioned in D.2.3.1 of Annex D, considering the product $q_e \,.\, D_e^2 / 4$, on the left side of the equation;
c) adopt the commercial thickness immediately above the calculated one.

B.3.5 Calculate the new value of De, if this value differs by more than 5% of the previously established, return to B.3.2 with the new value of De.

B.4 Example of Calculation

Calculate the thermal insulation of a 6" piping (D_0 = 0,168 m) for a minimum temperature on the outer surface of 12 °C. The internal temperature is -30 °C and the ambient temperature is 24 °C. It is assumed the emissivity of 0.2 for aluminum and no winds (natural convection). Expanded polyurethane shall be used with the following thermal conductivities:

a) 0,0273 W/m .°C @ -32 °C;
b) 0,0259 W/m .°C @ -18 °C;
c) 0,0237 W/m .°C @ 10 °C.

Data:

T_0 = -30 °C
T_e = 12 °C
T_a = 24 °C
D_0 = 0.168 m
E = 0,2

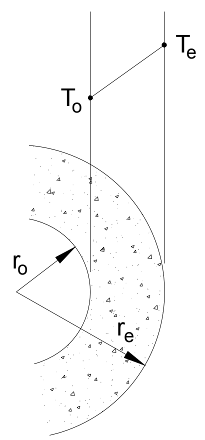

Figure B.1 - Thermal Insulation of a Piping

Step 1: D_e = 0,218 m (estimated)

Step 2: $T_f = \dfrac{T_e + T_a}{2} = 18\ °C$

$\Delta t = T_a - T_e = 12\ °C$

air properties (see Table D.3 of Annex D):

$$\Psi = 106{,}74\ .\ 10^6\ 1/m^3\ .\ °C$$

k = 0,0256 W/m . °C

heat transfer coefficient by convection:

of D.3 of Annex D: $L_c = D_e$ = 0,218 m

$$Ra = L_c^{\ 3}\ .\ \Psi\ .\ \Delta t = 1{,}33\ .\ 10^7$$

$$\therefore h_c = \frac{k}{L_c}\left(0{,}60 + 0{,}3213\ .\ Ra^{0{,}167}\right)^2 = 3{,}61\ W/m^2\ .\ °C$$

heat transfer coefficient by radiation:

of D.1 of Annex D:

$$h_r = 5{,}669\ .\ 10^{-8}\ \varepsilon \left[\left(T_e + 273\right)^2 + \left(T_a + 273\right)^2\right]\left(T_e + T_a + 546\right)$$

$$\therefore h_r = 1{,}12\ W/m^2\ .\ °C$$

Step 3: $q_e = \left(h_c + h_r\right)\Delta t = 56{,}7\ W/m^2$

Step 4: Of the equation of D.2.2 Annex D: $q_e\ \dfrac{D_e}{2} = \dfrac{k\left(T_2 + T_1\right)}{\ln\left(r_2/r_1\right)}$

Where:

$T_1 = T_0$ = -30 °C
$T_2 = T_e$ = 12 °C
$\overline{T} = \left(T_1 + T_2\right)/2$ = -9 °C
k = 0,0252 W/m . °C
$D_1 = D_0$ = 0,168 m
$D_2 = D_e$, to calculate:

$$56,7\ .\ \frac{D_e}{2} = \frac{0,0252\ .\ [12 - (-30)]}{\ln\left(D_e / 0,168\right)}$$

Solving, it is obtained:

$D_e = 0,202$ m

$\therefore L = (D_e - D_0) / 2 = 0,017$ m

NOTE The commercial thickness immediately above is 25 mm.

Step 5: With a 25 mm thickness, the new D_e is 0.218 m, therefore, it is not necessary to return to step 2.

Annex C - Stabilization of Industrial Processes Phases - Calculation Route

C.1 Introduction

The calculation of the thickness of the thermal insulation based on the concept of stabilization of phases presupposes the existence of a maximum allowable heat flow through the wall of the piping or equipment. This sizing requires an iterative calculation and the route presented herein is just one way of determining the thicknesses. The nomenclature of the variables used is given in Table E.1 of Annex E.

C.2 Flat Surfaces

C.2.1 Establish an initial value for the surface temperature, for example,

$$T_a - T_e = 0{,}10 \,.\, (T_a - T_0)$$

C.2.2 Calculate the heat transfer coefficients suitable to the problem, according to Annex D.

C.2.3 Calculate the new temperature of the outer surface using the formula:

$$T_e = T_a - \frac{q_{máx,\, e}}{h_c + h_r}$$

C.2.4 If the new value of Te differs by more than 2 °C of the previously established value, return to C.2.2 with the new value of Te.

C.2.5 Determination of the thickness:

a) with the average temperature $(T_0+T_e)/2$, calculate the material thermal conductivity;
b) calculate the thickness of the thermal insulation using the equation mentioned in D.2.1.1 of Annex D;
c) adopt the commercial thickness immediately above the calculated one.

C.3 Cylindrical or Spherical Surfaces

The calculation for cylindrical or spherical surfaces requires an additional iteration, since the external diameter, which depends on the thicknessess, affects the calculation of the temperature of the outer surface. It is assumed here that the maximum allowable heat flow refers to the outer surface of the piping or equipment, i.e., to the diameter D_0.

C.3.1 Estimate the value of the external diameter of the thermal insulation, based on prior experience or approaches:

a) $D_e = 1{,}5\ D_0$ to $D_0 \leq 150$ mm;
b) $D_e = 1{,}3\ D_0$ to $150 < D_0 \leq 300$ mm;
c) $D_e = 1{,}1\ D_0$ to $D_0 > 300$ mm.

C.3.2 Establish an initial value for the surface temperature, for example:

$$T_a - T_e = 0{,}10 \,.\, (T_a - T_0)$$

C.3.3 Calculate the heat transfer coefficients suitable to the problem, according to Annex D.

C.3.4 Calculate the new temperature on the outer surface using the formula:

$$T_e = T_a - \frac{q_{máx,e}}{h_c + h_r} \begin{cases} q_{máx,e} = q_{máx,0}\dfrac{D_0}{D_e}, \text{for cylindrical surfaces} \\ q_{máx,e} = q_{máx,0}\left(\dfrac{D_0}{D_e}\right)^2, \text{for spherical surfaces} \end{cases}$$

C.3.5 If the new value of Te differs by more than 2 °C of the previously established value, return to C.3.3 with the new value of Te.

C.3.6 Determination of the thickness:

a) with the average temperature $(T_0+T_e)/2$, calculate the material thermal conductivity;
b) for cylindrical surfaces, calculate the external diameter of the thermal insulation using the equation mentioned in D.2.2 of Annex D, considering the product $q_{max,o} \cdot D_o/2$, on the left side of the equation; for spherical surfaces, calculate the external diameter of the thermal insulation using the equation mentioned in D.2.3.1 of Annex D, considering the product $q_{max,o} \,.\, D_0^2 / 4$, on the left side of the equation;
c) adopt the commercial thickness immediately above the calculated one.

C.3.7 Calculate the new value of De, if this value differs by more than 5% of the previously established, return to C.3.2 with the new value of De.

C.4 Example of Calculation

Calculate the thermal insulation of a 6” piping (D_0=0.168 m) for a maximum heat flow on the outer surface of the pipe of 100 W/m^2. The internal temperature is -40 ºC and the ambient temperature is 24 ºC. It is assumed the emissivity of 0.2 for aluminum and winds of 2 m/s (forced convection). Expanded polyurethane shall be used with the following thermal conductivities:

a) 0,0273 W/m .°C @ -32 °C;
b) 0,0259 W/m .°C @ -18 °C;
c) 0,0237 W/m .°C @ 10 °C.

Data:

T_0 = -40 °C.
T_a = 24 °C.
$q_{máx,0}$ = 100 W/m^2
D_0 = 0,168 m
V = 2 m/s
E = 0,2

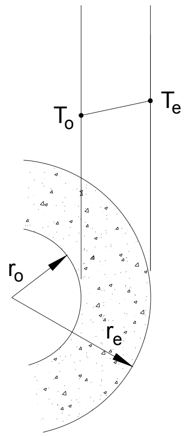

Figure C.1 - Thermal Insulation of a Piping

Step 1: D_e = 0,218 m (estimated)

Step 2: $T_e \cong T_a - 0{,}10\,(T_a - T_o) = 17{,}6$ °C $\quad\quad \therefore\ T_{e,\ est}$ = 18 °C

Step 3: T_a = 24 ° C

air properties (see Table D.3 of Annex D):

k = 0,0261 W/m· °C

υ = 15,64 · 10^{-6} m^2/s

Pr = 0,708

heat transfer coefficient by convection (independent of T_e):

of D.4.2 of Annex D:

$L_c = D_e$ = 0,218 m

$$Re = \frac{\nu\,.\,L_c}{\upsilon} = 27\ 884$$

$$\therefore h_c = 0{,}26\,\frac{k}{L_c}\,Re^{0{,}6}\,.\,Pr^{0{,}37} = 12{,}72\ W/m^2\,.\,°C$$

heat transfer coefficient by radiation (depends on T_e):

of D.1 of Annex D:

$$h_r = 5{,}669\,.\,10^{-8}\,\varepsilon\,\Big[\,(T_e + 273)^2 + (T_a + 273)^2\,\Big](T_e + T_a + 546)$$

Steps 4 and 5: Calculation of the temperature on the outer surface:

$$T_e = T_a - \frac{q_{máx,\,o} \cdot \left(D_0 / D_e \right)}{h_c + h_r}$$

the calculation of T_e is iterative, since h_r depends on T_e:

T_e estimated	h_r	$h_r + h_c$	T_e calculated
18	1,15	13,87	18,4
18,4	1,15	13,87	18,4

$\therefore$ T_e = 18,4 °C

Step 6: From the equation of D.2.2 of Annex D: $q_{máx,\,o} \dfrac{D_o}{2} = \dfrac{k\left(T_2 - T_1\right)}{\ln\left(r_2 / r_1 \right)}$

T_1 = T_0 = -40 °C
T_2 = T_e = 18,4 °C
$\overline{T}$ $= \left(T_1 + T_2\right) / 2 =$ -10,8 °C
k = 0,0253 W/m °C
D_1 = D_0 = 0,168 m
D_2 = D_e, to calculate:

$$100 \cdot \frac{0{,}168}{2} = \frac{0{,}0253\,.\,\left[18{,}4 - \left(-40\right)\right]}{\ln\left(D_e / 0{,}168 \right)}$$

$\therefore$ D_e = 0,200 m

$\therefore$ L = (D_e - D_o) / 2 = 0,016 m

NOTE The commercial thickness immediately above is 25 mm.

Step 7: With a 25 mm thickness, the new D_e is 0.218 m, therefore, it is not necessary to return to step 2.

Annex D - Heat Transfer Equations

D.1 Radiation

D.1.1 The heat flow resulting from the heat transfer by radiation between a surface and the environment is calculated using the equation:

$$q_r = 5{,}669 \cdot 10^{-8} \varepsilon \left[(T_a + 273)^4 - (T_e + 273)^4 \right]$$

D.1.2 It is convenient to write the equation in D.1.1 as follows:

$$q_r = h_r (T_a - T_e)$$

D.1.3 The heat transfer coefficient by radiation is defined as:

$$h_r = 5{,}669 \cdot 10^{-8} \varepsilon \left[(T_a + 273)^2 + (T_e + 273)^2 \right] (T_a + T_e + 546)$$

D.1.4 Typical surface emissivity values are shown in Table D4.

D.2 Conduction

The thermal conductivity of each material shall be obtained in specific standards or, in the absence of them, from the literature. Assuming a linear dependence of conductivity with temperature, it shall be used the arithmetic mean of the temperatures to which the material is subjected.

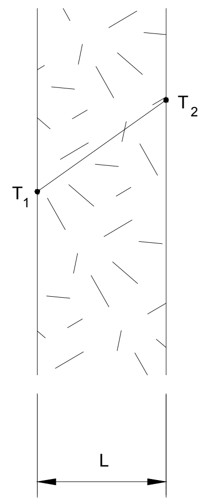

Figure D.1 - Simple Thermal Insulation on a Flat Surface

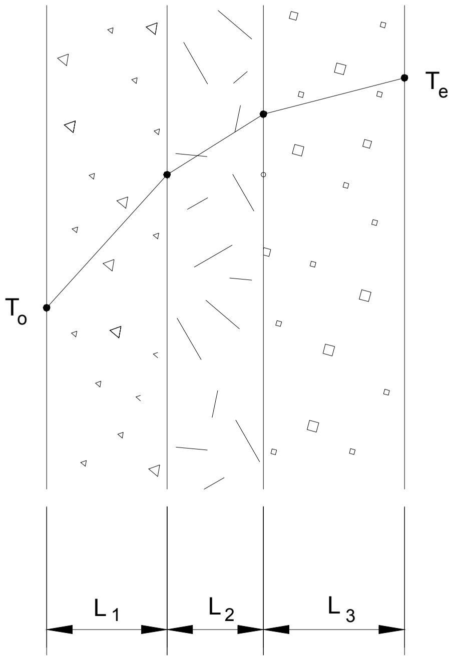

Figure D.2 - Three-Layer Wall Thermal Insulation on a Flat Surface

D.2.1 Flat Surfaces

D.2.1.1 For a single material wall, as shown in Figure D.1, the heat flow by conduction is given by:

$$q_k = \frac{k}{L}\left(T_2 - T_1\right)$$

D.2.1.2 For a general case, as shown in Figure D.2, of a three-layer wall, it can be written:

$$q_k = \frac{T_e - T_o}{\frac{L_1}{k_1} + \frac{L_2}{k_2} + \frac{L_3}{k_3}}$$

D.2.2 Cylindrical Surfaces

For a single material wall, as shown in Figure D.3, the heat flow by conduction is given by:

$$q_{k_1}\ r_1 = q_{k_2}\ r_2 = \frac{k\left(T_2 - T_1\right)}{\ln\left(r_2 / r_1\right)}$$

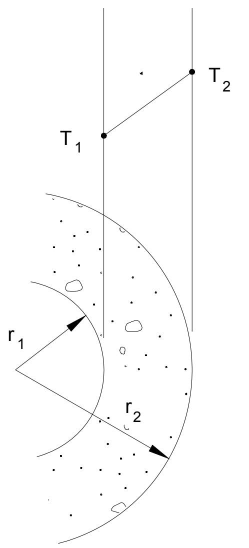

Figure D.3 - Simple Thermal Insulation on a Cylindrical Surface

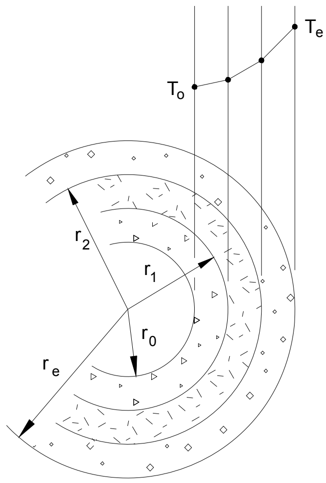

Figure D.4 - Three-Layer Wall Thermal Insulation on a Cylindrical Surface

NOTE For a general case, of a three-layer wall, it can be written:

$$q_{k_i}\ r_i = \frac{(T_e - T_o)}{\frac{\ln\left(\frac{r_1}{r_0}\right)}{k_1} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{k_2} + \frac{\ln\left(\frac{r_e}{r_2}\right)}{k_3}}$$

D.2.3 Spherical Surfaces

D.2.3.1 For a single material wall, similar to the cylindrical one represented above, the heat flow by conduction is given by:

$$q_{k_1}\, r_1^{\,2} = q_{k_2} r_2^{\,2} = \frac{k(T_2 - T_1)}{\left(\dfrac{1}{r_1} - \dfrac{1}{r_2}\right)}$$

D.2.3.2 For a general case, of a three-layer wall, it can be written:

$$q_{k_i} r_i^{\,2} = \frac{(T_e - T_o)}{\dfrac{\left(\dfrac{1}{r_o} - \dfrac{1}{r_1}\right)}{k_1} + \dfrac{\left(\dfrac{1}{r_1} - \dfrac{1}{r_2}\right)}{k_2} + \dfrac{\left(\dfrac{1}{r_2} - \dfrac{1}{r_e}\right)}{k_3}}$$

D.3 Natural Convection

D.3.1 The heat flow by natural convection (still air) may be expressed by:

$$q_c = h_c (T_a - T_e)$$

NOTE The heat transfer coefficient is obtained from appropriate expressions that take into account the surface shape and orientation, as well as the properties of air. The correlations here adopted for the heat transfer coefficient were taken from the book "Fundamentals of Heat Transfer", by F. P. Incropera and D. P. Dewitt.

D.3.2 These correlations, presented in Table D.1, have ranges of validity, determined by the Rayleigh dimensionless number, expressed by:

$$Ra = \psi \,.\, L^3{}_c \; \Delta t$$

Where:

$$\psi = \frac{\rho^2 \,.\, \beta \,.\, C_{p.}\; g}{\mu \,.\, k}$$

$$\Delta t = T_a - T_e$$

Table D.1 - Correlations for Natural Convection

Surface	Characteristic dimension L_c	Correlation for heat transfer coefficient by natural convection
Vertical flat	surface height	$h_c = 0{,}59\,k\left(\frac{\Psi\Delta t}{L_c}\right)^{0{,}25}$, for $10^4 < Ra < 10^9$ $h_c = 0{,}10\,k\,(\Psi\Delta t)^{0{,}33}$, for $10^9 < Ra < 10^{13}$
Vertical Cylindrical	surface height	the same as vertical flat surface, if $D_e \geq \frac{35 \cdot L_c}{\left(\frac{Ra}{Pr}\right)^{0{,}25}}$
Horizontal flat, Cold Face Down	$\frac{\text{area}}{\text{perimeter}}$	$h_c = 0{,}54\,k\left(\frac{\Psi\Delta t}{L_c}\right)^{0{,}25}$, for $10^5 < Ra < 10^7$ $h_c = 0{,}15\,k\,(\Psi\Delta t)^{0{,}33}$, for $10^7 < Ra < 10^{10}$
Horizontal flat, Cold Face Up	$\frac{\text{area}}{\text{perimeter}}$	$h_c = 0{,}27\,k\left(\frac{\Psi\Delta t}{L_c}\right)^{0{,}25}$, for $10^5 < Ra < 10^{10}$
Horizontal cylindrical	external diameter	$h_c = \frac{k}{L_c}\left(0{,}60 + 0{,}3213 \cdot Ra^{0{,}167}\right)^2$, for $10^{-5} < Ra < 10^{12}$
Spherical	external diameter	$h_c = \frac{k}{L_c}\left(2 + 0{,}43 \cdot Ra^{0{,}25}\right)$, for $1 < Ra < 10^5$

D.3.3 The use of equations out of ranges, though often necessary, may lead to inaccurate results.

D.3.4 The L_c dimension is a characteristic of each surface, depending on its shape and orientation. The parameter ψ is tabulated, together with other properties of air; in Table D.3 and it shall be calculated at an average temperature defined by:

$$T_f = \frac{T_e + T_a}{2}$$

D.4 Forced Convection

D.4.1 The heat flow by forced convection (wind) may be expressed by:

$$q_c = h_c(T_a - T_e)$$

NOTE The heat transfer coefficient is obtained from appropriate expressions that take into account the surface shape, the wind speed, and the properties of air. The correlations here adopted for the heat transfer coefficient were taken from the book "Fundamentals of Heat Transfer", by F. P. Incropera and D. P. Dewitt.

D.4.2 These correlations presented herein have ranges of validity, determined by the Rayleigh dimensionless number, Re, expressed by:

$$Re = \frac{\rho . \nu . L_c}{\mu} = \frac{\nu . L_c}{\upsilon}$$

D.4.3 The use of equations out of ranges, though often necessary, may lead to inaccurate results.

D.4.4 The L_c dimension is the length of the flat surface in the direction of the wind or the diameter of the cylindrical or spherical surface. The kinematic viscosity υ is tabulated, together with other properties of air, in Table D.3.

D.4.5 Flat Surface

$$h_c = 0{,}664 \frac{k}{L_c} Re^{0{,}5} . Pr^{0{,}33} \text{, for } Re < 5 \cdot 10^5 \tag{1}$$

$$h_c = \frac{k}{L_c} \left(0{,}037 . Re^{0{,}8} - 871\right) Pr^{0{,}33} \text{, for } 5 \cdot 10^5 < Re < 10^8 \tag{2}$$

Where:

Re and Pr shall be calculated at an average temperature $(T_e+T_a)/2$.

D.4.6 Cylindrical Surface

$$h_c = C \frac{k}{L_c} Re^m . \ Pr^{0{,}37} \text{, for } 40 < Re < 10^6$$

Where:

Re and Pr shall be calculated at ambient temperature and the values of "C" and "m" are obtained in Table D.2, based on the value of Re.

Table D.2 - Parameters "C" and "M"

Re	C	m
40 to 1 000	0,51	0,5
1 000 to $2 \cdot 10^5$	0,26	0,6
$2 \cdot 10^5$ to 10^6	0,076	0,7

D.4.7 Spherical Surface

$$h_c = \frac{k}{L_c} \left[2 + (0{,}4 \cdot Re^{0{,}50} + 0{,}06 \cdot Re^{0{,}67}) \cdot Pr^{0{,}4}\right] \text{, for } 3{,}5 < Re < 7{,}6 \cdot 10^4$$

Where:

Re and Pr shall be calculated at ambient temperature.

D.5 Physical Properties

Table D.3 - Properties of Air

Temperature (°C)	Thermal conductivity k (W/m. °C)	Ψ (1/m^3 . °C)	Kinematic viscosity U (m^2/s)	Prandtl number Pr
-30	0,0217	$249{,}7 \cdot 10^{6}$	$10{,}9 \cdot 10^{-6}$	0,722
-20	0,0226	$204{,}3 \cdot 10^{6}$	$11{,}7 \cdot 10^{-6}$	0,719
-10	0,0234	$172{,}1 \cdot 10^{6}$	$12{,}6 \cdot 10^{-6}$	0,717
0	0,0242	$145{,}0 \cdot 10^{6}$	$13{,}5 \cdot 10^{-6}$	0,714
10	0,0250	$122{,}1 \cdot 10^{6}$	$14{,}4 \cdot 10^{-6}$	0,711
20	0,0257	$102{,}9 \cdot 10^{6}$	$15{,}3 \cdot 10^{-6}$	0,709
30	0,0264	$87{,}4 \cdot 10^{6}$	$16{,}2 \cdot 10^{-6}$	0,707
40	0,0272	$75{,}8 \cdot 10^{6}$	$17{,}2 \cdot 10^{-6}$	0,705
50	0,0280	$65{,}7 \cdot 10^{6}$	$18{,}2 \cdot 10^{-6}$	0,704

Table D.4 - Surface Typical Emissivities

Material	ε
Aluminum plate	0,1 to 0,2
Matte black paint	0,96 to 0,98
Aluminum-based paint	0,3 to 0,7
Steel plate	0,94 to 0,97
White paint	0,84 to 0,92
Asphalt mass	0,93

NOTE The nomenclature of the variables used is included in Table E.1 of Annex E.

Annex E - Nomenclature

Table E.1 - Nomenclature

Variable	Description	Unit
c_p	specific heat	J/kg . °C
C_{ac}	cost of compressor drive energy	$/kWh
CA, CA_{VA}	annual cost of cooling water, and updated cost of cooling water	$/year.m^2, $/year.m or $/year
EC CE_{VA}	annual cost of energy absorbed and updated cost of energy absorbed	$/year.m^2, $/year.m or $/year
CI	investment cost of thermal insulation	$/year.m^2, $/year.m or $/year
CM, CM_{VA}	maintenance cost of thermal insulation and updated maintenance cost of thermal insulation	$/year.m^2, $/year.m or $/year
COP	coefficient of performance of the cooling unit	-
CR	cost of investment in the cooling unit	$/year.m^2, $/year.m or $/year
CT	total cost	$/year.m^2, $/year.m or $/year
D_e	diameter of the outer surface of the thermal insulation	m
D_0	diameter of the outer surface of the equipment or piping (internal for thermal insulation)	m
f(i,n), f(j,n) and f(j´,n)	update factors	-
H	depth	m
h_c	heat transfer coefficient by convection	W/m^2 . °C
h_r	heat transfer coefficient by radiation	W/m^2 . °C
i	annual hurdle rate	%
k_1, k_2, ...	thermal conductivity of the materials 1, 2, ...	W/m . °C
L_1, L_2, ...	thickness of the materials 1, 2, ...	m
L_c	characteristic dimension	m
L_t	length of piping	m
n	service life of thermal insulation	year
N	number of operating hours per year	h/year
Pr	Prandtl number	-
Q	amount of heat per time unit	W/m^{2,} W/m or W
q_c	heat flow by convection	W/m^2
q_k	heat flow by conduction	W/m^2

Table E.1 - Nomenclature (Continued)

Variable	Description	Unit
$q_{max, e}$	maximum allowable heat flow on the outer surface of the thermal insulation	W/m^2
$q_{max, o}$	maximum allowable heat flow on the outer surface of the pipe	W/m^2
q_r	heat flow by radiation	W/m^2
R	unit cost of the cooling unit	$/W
r_1, r_2	radius of the faces of a wall of thermal insulation material	m
Ra	Rayleigh number	-
Re	Reynolds number	-
r_e	radius of the outer surface of the thermal insulation	m
r_0	radius of the outer surface of the equipment or piping (internal for thermal insulation)	m
S	consumption of cooling water	m^3/J
T_1, T_2	temperature of the faces of a wall of thermal insulation material	°C
T_a	ambient temperature	°C
T_e	temperature of the outer surface of the thermal insulation	°C
T_0	temperature of the outer surface of the equipment or piping (internal for thermal insulation)	°C
tm	percentage of maintenance cost in relation to investment	-
v	speed	m/s
W	cost of the cooling water	$\$/m^3$
Δ	differential growth rate of the cost of energy	-
Δ'	differential growth rate of the cost of cooling water	-
ε	surface emissivity	-
η_{co}	compressor efficiency	-
μ	dynamic viscosity	kg/ms
υ	kinematic viscosity	m^2/s
ρ	specific mass	kg/m^3
Ψ	parameter of properties of air	$m^{-3}.°C^{-1}$
g	gravitational constant	m/s^2
β	coefficient of thermal expansion of the fluid	$°C^{-1}$
q_e	heat flow on the outer surface of the thermal insulation	W/m^2

Annex F - Point

Table F.1 - Dew Point

Ambient temperature (°C)	Relative humidity (%)																		
	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
-15	-37	-34	-32	-29	-27	-26	-24	-23	-22	-21	-20	-20	-19	-18	-17	-17	-16	-15	-15
-12	-35	-32	-29	-27	-25	-23	-22	-21	-19	-19	-18	-17	-16	-15	-15	-14	-13	-13	-12
-9	-33	-29	-27	-25	-22	-21	-19	-18	-17	-16	-15	-14	-13	-13	-12	-11	-10	-10	-9
-7	-31	-27	-24	-22	-20	-19	-17	-16	-14	-13	-12	-11	-10	-10	-9	-9	-8	-7	-7
-4	-29	-26	-22	-20	-18	-16	-14	-13	-12	-11	-9	-9	-8	-7	-7	-6	-5	-4	-4
-1	-26	-23	-20	-17	-15	-13	-12	-11	-9	-8	-7	-6	-5	-4	-4	-3	-2	-2	-1
2	-24	-21	-17	-15	-13	-11	-9	-8	-7	-6	-5	-3	-3	-2	-1	0	1	1	2
4	-22	-18	-15	-13	-10	-9	-7	-6	-4	-3	-2	-2	-1	1	2	2	3	4	4
7	-20	-16	-13	-11	-8	-7	-5	-4	-2	-1	0	1	2	3	4	5	6	7	7
10	-18	-14	-11	-8	-6	-4	-3	-1	0	1	3	4	5	6	7	7	8	9	10
13	-16	-12	-9	-6	-4	-2	0	1	3	4	5	6	7	8	9	10	11	12	13
16	-14	-10	-7	-4	-2	0	2	4	6	7	8	9	10	11	12	13	14	15	16
18	-12	-8	-5	-2	1	3	4	6	8	9	11	12	13	14	15	16	17	17	18
21	-10	-6	-2	1	3	5	7	9	10	12	13	14	16	17	18	18	19	20	21
24	-8	-4	0	3	6	8	9	11	13	14	16	17	18	19	20	21	22	23	24
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29	-5	0	4	7	10	12	14	16	18	19	21	22	23	24	25	26	27	28	29
32	-3	2	7	9	12	14	17	19	21	22	23	25	26	27	28	29	30	31	32
35	-1	4	9	12	15	17	19	21	23	24	26	28	29	30	31	32	33	34	35
38	1	7	11	14	17	20	22	24	26	27	29	30	31	33	33	34	35	36	38
41	3	9	13	17	19	22	24	26	28	29	31	32	34	35	36	37	38	39	41
43	5	11	16	19	22	25	27	29	31	32	33	35	37	38	39	40	41	42	43
46	7	13	18	21	24	27	29	31	33	34	36	38	39	41	42	43	44	45	46
49	8	15	20	23	26	29	31	33	35	37	39	41	42	43	44	45	47	48	49
52	11	17	22	25	29	32	34	36	38	40	42	43	44	45	47	48	49	51	52

Annex G - Energy Conservation - Recommended Thicknesses

G.1 The Table G.1 shows the thicknesses recommended for thermal insulation systems using pre-molded polyurethane and polyisocyanurate and injected polyurethane, according to the criterion of energy conservation. The following parameters were considered:

a) ambient temperature: 25 °C;
b) wind speed: 10 km/h;
c) surface emissivity: 0,20;
d) reference value of the cost of the thermal insulation: as shown in Table G.2;
e) drive energy cost: R$ 0,173/kWh (reference: MAY/2010);
f) cost of the cooling water: R$ 0,043 /m^3 (reference: MAY/09);
g) cost of the cooling unit: it is not considered to existing units;
h) compressor efficiency: 95 %;
i) coefficient of performance: 2;
j) consumption of cooling water: $9{,}0 \cdot 10^{-10}$ m^3/J;
k) hurdle rate: 15 %;
l) differential growth rate of the cost of energy: 0 %;
m) differential growth rate of the cost of cooling water: 0 %;
n) thermal insulation system life: 15 years;
o) hours of operation: 8 250 h/year;
p) maintenance cost: 2 % of the cost of the thermal insulation, per year.

G.2 For conditions other than those presented above, the Table G.1 can be used as an indicator of economic thickness, only in the quick sizing of lines or small equipment. **[Recommended Practice]**

G.3 For larger systems, a specific calculation shall be made, according to 5.1.

Table G.1 - Economic Thicknesses, in mm, for Thermal Insulation Based on Pre-Molded Polyurethane and Polyisocyanurate and Injected Polyurethane

Diameter (pol)	Temperature (°C)												
	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15	20
1/2													
3/4													
1													
1 1/2													
2													
2 1/2													
3													
4													
6													
8													
10													
12													
14													
16													
18										25			
20													
22					38								
24													
26													
28													
30		63											0
32													
34													
36													
42													
49													
54													
60													
Plano			51										

NOTE 1 See 5.1.1 and 5.1.2.
NOTE 2 For diameters above 60", consider flat surface.
NOTE 3 Example of use: for a 8" line operating at - 25 °C, the economic thickness is 38 mm.
NOTE 4 The Table G.1 only considers the criterion of energy conservation.

Table G.2 - Reference Values of the Cost of Thermal Insulation Based on Pre-Molded Polyurethane and Polyisocyanurate and Injected Polyurethane

Diameter (pol)	Thickness (mm)										
	25	38	51	63	76	89	102	114	126	140	153
1/2	42,90	58,29	77,73	87,82	109,25	131,47	151,07	171,79	190,49	212,03	227,08
3/4	47,90	63,59	83,53	93,45	115,31	137,91	157,69	178,65	197,47	219,13	234,11
1	54,11	70,18	90,74	100,43	122,83	145,90	165,90	187,16	206,14	227,93	242,84
1 1/4	62,26	78,83	100,20	109,59	132,71	156,38	176,68	198,33	217,52	239,50	254,30
1 1/2	67,91	84,83	106,76	115,95	139,56	163,66	184,15	206,08	225,41	247,52	262,25
2	79,03	96,62	119,66	128,45	153,03	177,96	198,86	221,31	240,93	263,29	277,89
2 1/2	90,80	109,10	133,31	141,68	167,29	193,10	214,42	237,44	257,35	279,99	294,43
3	105,53	124,73	150,40	158,24	185,15	212,05	233,90	257,63	277,91	300,89	315,15
4	129,06	149,70	177,71	184,70	213,66	242,32	265,02	289,88	310,76	334,28	348,24
5	154,07	176,24	206,74	212,83	243,98	274,51	298,10	324,16	345,68	369,77	383,41
6	179,09	202,78	235,77	240,96	274,29	306,69	331,18	358,44	380,59	405,26	418,59
8	226,16	252,71	290,38	293,88	331,33	367,24	393,43	422,94	446,29	472,04	484,77
10	276,09	305,69	348,33	350,03	391,85	431,49	459,47	491,38	515,99	542,89	554,99
12	323,16	355,62	402,94	402,95	448,88	492,04	521,71	555,88	581,69	609,66	621,17
14	352,62	386,88	437,13	436,08	484,59	529,94	560,67	596,26	622,81	651,47	662,60
16	399,69	436,81	491,74	489,00	541,63	590,50	622,91	660,76	688,51	718,24	728,78
18	446,57	486,55	546,14	541,71	598,44	650,81	684,91	725,01	753,94	784,76	794,70
20	493,82	536,67	600,97	594,84	655,70	711,60	747,40	789,77	819,90	851,80	861,14
22	541,07	586,80	655,80	647,97	712,96	772,39	809,89	854,52	885,85	918,83	927,59
24	588,32	636,93	710,63	701,10	770,22	833,18	872,37	919,28	951,80	985,87	994,03
26	634,64	686,08	764,39	753,19	826,36	892,78	933,64	982,76	1016,46	1051,60	1059,17
28	681,89	736,21	819,21	806,32	883,62	953,56	996,12	1047,52	1082,42	1118,64	1125,61
30	729,15	786,34	874,04	859,45	940,88	1014,35	1058,61	1112,27	1148,37	1185,68	1192,05
32	776,40	836,46	928,87	912,58	998,15	1075,14	1121,10	1177,03	1214,33	1252,72	1258,50
34	823,65	886,59	983,70	965,71	1055,41	1135,93	1183,59	1241,79	1280,28	1319,76	1324,94
36	869,97	935,74	1037,46	1017,79	1111,55	1195,53	1244,85	1305,27	1344,94	1385,48	1390,08
42	1011,54	1085,93	1201,73	1176,97	1283,11	1377,66	1432,06	1499,28	1542,54	1586,34	1589,14
48	1152,74	1235,73	1365,57	1335,74	1454,22	1559,32	1618,79	1692,79	1739,63	1786,67	1787,69
54	1293,93	1385,52	1529,42	1494,50	1625,33	1740,97	1805,52	1886,29	1936,71	1987,00	1986,23
60	1435,13	1535,32	1693,26	1653,26	1796,44	1922,63	1992,25	2079,80	2133,80	2187,33	2184,78
Plan	294,91	329,34	335,50	350,90	361,73	372,05	382,36	395,37	408,37	430,05	451,73

NOTE 1 The reference values of the costs above consider all the necessary materials and installation service.

NOTE 2 Costs expressed in R$/m for piping and in R$/m^2 for flat surfaces (reference: NOV/2010).

INDEX OF REVISIONS	
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REV. D	
Affected Parts	**Description of Alteration**
1.1	Revised
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3.5 to 3.8	Revised
4.1.2	Revised
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4.2.3 to 4.2.9	Revised and Renumbered
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5.2.2	Revised
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ANNEX A-1.2	Revised
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ANNEXES C-1 and C-3	Revised
ANNEX D-2.3	Included
TABLE D-1	Revised
ANNEX D-4.3	Included
TABLE E-1	Revised
REV. E	
Affected Parts	**Description of Alteration**
All	Revised