United Nations ECE/TRANS/WP.11/2015/19

Economic and Social Council

Distr.: General
20 August 2015
English
Original: English and Russian

Economic Commission for Europe

Inland Transport Committee

Working Party on the Transport of Perishable Foodstuffs

Seventy-first session
Geneva, 6-9 October 2015
Item 6 of the provisional agenda
ATP Handbook

Introducing provisions in the ATP Handbook concerning the determination of the inner and outer heat transfer surface areas of railway carriages[1, 2]

Transmitted by the Government of the Russian Federation

Summary

Executive summary:	According to paragraph 1.2 of Annex l, Appendix 2 to the ATP, the outer and inner heat transfer surface area of a body of special equipment is determined taking into account its structural peculiarities. However, this ATP provision does not take into account the known peculiarities of railway carriage bodies, due to which experts and ATP testing centres may use ambiguous methods of determining the inner and outer heat exchange surface areas of a railway carriage body and, as a result, issued ATP certificates may be rejected by other parties to the ATP.
Action to be taken:	Using the proposals made by the United Kingdom regarding the measurement of the outer surface areas of walls of vans without windows in cargo compartment that were considered and generally approved at the 70th session of the Working Party (WP.11), propose provisions on the methods for determining the inner and outer heat transfer surface areas of a body with common structures of railway

[1] This document was submitted late for document processing as clearances from relevant parties were received late.
[2] The English translation of this document was supplied by the Russian Federation.

	carriages other than tank carriages to be included in the ATP Handbook. The basic proposals of the United Kingdom must be corrected as regards organizations that use the proposed methods of determining the outer and inner heat transfer surface areas of the body of special equipment.
Related documents:	ECE/TRANS/WP.11/2014/14 and Corr. 1

Introduction

1. According to Article 3 of the ATP, ATP standards and requirements extend to the carriage of perishable foodstuffs by both rail and road vehicles. Methods of and requirements for tests and checks of bodies and special equipment of special transportation vehicles (hereinafter, STVs) are the same for both road and rail STVs.

2. In practice, the bodies of different STVs may differ considerably by shape and have additional structural elements that should be taken into account during tests and expert checks. It is often difficult to take such structural peculiarities into account completely.

In certain cases, STVs with body structures that, for various reasons, cannot be accurately determined may be subject to tests.

3. The 70th session of the WP.11 considered the proposals made by the United Kingdom concerning methods of determining the outer surface area of a van body without windows in the cargo compartment. As a result of these discussions, the Working Party proposed that the proposals of the United Kingdom be included in the ATP Handbook.

4. During the discussions of the proposals made by the United Kingdom, the Russian experts expressed the opinion that the same methods should be used to determine the outer surface area of both road and rail STVs.

The Russian Federation suggested that the Working Party consider applying methods to determine the outer surface area of vans without windows in the cargo compartment proposed by the United Kingdom to the most common rail carriage body structures, but not tank carriages. As a result, appropriate proposals are made for inclusion in the ATP Handbook.

5. Given the above, the Russian Federation prepared proposals for appropriate provisions to be included in the ATP Handbook in the form of an official document.

An careful examination of test report No. 1A including information about the surface areas of STV body walls revealed that its form is insufficient (taking into account remark 5) for achieving the goal of concretising methods of determining the inner and outer heat transfer surfaces of STV bodies.

The Russian version of the ATP Handbook in use at the time that this official document was prepared (2014), as well as proposals made by the United Kingdom stated in document ECE/TRANS/WP.11/2014/14, were used as a basis. The Russian Federation makes full use of the proposals made by the United Kingdom in the section pertaining to vans without windows in the cargo compartment, with changes to the organization using the proposed methods of determining the inner and outer heat transfer surface areas of the bodies of STVs and supplements them (in bold) with relevant provisions concerning the most common structures of rail carriage bodies other than tank carriages. In order to make this official document shorter, the Russian Federation does not provide drawings and sample calculations regarding vans without windows in the cargo compartment.

Proposals

6. Include in the ATP Handbook a comment on 1.2 of Annex l, Appendix 2 to the ATP that reads as follows:

"For calculating the mean surface area of the body of a panel van, ***test centres appointed or authorized by*** *competent authorities shall select from one or a combination of the following three methods.*

Method A. The manufacturer shall provide drawings and calculations of the inside and outside surfaces.

The surface areas S_e and S_i are determined taking into consideration the projected surface areas of specific design features of the irregularities of its surface such as curves, corrugations, wheel boxes, etc.

Method B. The manufacturer shall provide drawings and the competent authority's ***test centres*** *shall use the calculations according to the schemes and formulae in the ATP Handbook (using either figures 1, 2 or 3 along with figures 4 and 5).*

$$S_i = [(WI \cdot LI) + (WI \cdot LI) + (W_i \cdot W_i)] \cdot 2$$

$$S_e = [(WE \cdot LE) + (WE \cdot LE) + (W_e \cdot W_e)] \cdot 2$$

Where:

WI is the Y axis of the internal surface area

LI is the X axis of the internal surface area

W_i is the Z axis of the internal surface area

WE is the Y axis of the external surface area

LE is the X axis of the external surface area

W_e is the Z axis of the external surface area

Method C. If neither of the above is acceptable to the experts, the internal surface shall be measured according to the figures and formulae in method B.

The K value shall then be calculated based on the internal surface area, taking the insulation thickness as nil. From this K value, the average insulation thickness is calculated from the assumption that λ for the insulation has a value of 0.025 W/m·K.

$$d = \frac{S_i \cdot \Delta T \cdot \lambda}{W}$$

Once the thickness of the insulation has been estimated, the external surface area is calculated and the mean surface area is determined. The final K value is derived from successive iteration.

…

<figures 1, 2, 3, 4, 5>

…

The above methods may also be applied to other special transportation vehicles (STVs), particularly for calculating rail carriage bodies other than tank wagons that are covered bodies with a rounded roof. In this case, the schemes provided in Figure 6 should be used and the inner and outer surface areas of the STV body should be calculated according to the formulas given below:

$$\boldsymbol{S_i = L_i \cdot B_i + 2 \cdot (L_i + B_i) \cdot H_i + L_i \cdot \frac{P_i}{2} + \pi \cdot \frac{B_i}{2} \cdot (HH_i - H_i)}$$

$$\boldsymbol{S_e = L_e \cdot B_e + 2 \cdot (L_e + B_e) \cdot H_e + L_e \cdot \frac{P_e}{2} + \pi \cdot \frac{B_e}{2} \cdot (HH_e - H_e)}$$

$$\boldsymbol{P_i = 4 \cdot \left(\left(\frac{B_i}{2} \right)^x + (HH_i - H_i)^x \right)^{\frac{1}{x}}}$$

$$\boldsymbol{P_e = 4 \cdot \left(\left(\frac{B_e}{2} \right)^x + (HH_e - H_e)^x \right)^{\frac{1}{x}}}$$

$$\boldsymbol{x = \frac{ln\, 2}{ln \frac{\pi}{2}}}$$

where:

P_i, P_e is the length of the ellipse perimeter, in the form of which the roof rounding of a covered rail carriage is presented mathematically, m²^2.

Figure 6

Estimated scheme of a rail carriage body with a rounded roof

Sample calculations

7. Sample calculations performed in MathCAD are presented in appendices A and B to this official document.

Justification

8. Corrections to the proposal made by the United Kingdom concerning an organization using the proposed methods of determining the inner and outer heat transfer surface areas of the body of special transportation vehicles must be made to bring these proposals in line with the general requirements of the ATP.

9. Concretizing the methods for determining the heat transfer surface area of STV bodies, including the inner and outer surface areas, is an important task aimed at ensuring a common understanding of the ATP standards and requirements by all Contracting Parties, experts and test centres. The use of common, understandable and available methods for measuring the heat transfer surface area of any given STV will increase the level of mutual

trust with respect to ATP certificates and positively impact the operation of the entire system of control and certification of STVs in general.

10. Solving the issue of determining the heat transfer surface area of STV bodies should also help achieve the main objective of the ATP, which is to preserve the quality and safety of perishable foodstuffs during transportation.

11. With respect to STVs with complicated body shapes or structures with poor technical descriptions, the aforementioned approach implies determining the STV heat transfer surface area so that the K coefficient cannot be lower than the real value.

Obviously, the estimated heat exchange surface must correspond to the minimum value in this case, which should correspond to the minimum estimated insulation thickness directly depending on the coefficient of heat conductivity of the materials the insulating surfaces of the STV body are made of.

At present, polyurethane foam is often used to insulate STV bodies, which is characterized by its low heat conductivity coefficient compared to other known heat insulation materials used in STV bodies. Studies indicate that industrially made polyurethane foam can have a heat conductivity coefficient of up to 0.019 W/(m·K). In real conditions (temperature, humidity and the conditions of manufacturing and applying polyurethane foam onto the body surface), however, this value is rarely below 0.023-0.025 W(m·K), including with new rail carriages. And it grows considerably in the process of operation, as polyurethane foam ages and is subject to humidity. Therefore, the estimated heat transfer coefficient, 0.025 W (m·K), proposed by the United Kingdom in document ECE/TRANS/WP.11/2014/14 is acceptable and reasonable for both road STVs and rail carriages.

12. Taking into account the known formula for the theoretical determination of the heat transfer coefficient (without taking into consideration convection and radiation), the estimated average insulation thickness *d* can be derived using the following equation:

$$\frac{1}{\frac{1}{\alpha_e}+\frac{d}{\lambda}+\frac{1}{\alpha_i}}=\frac{W}{\Delta T\cdot S}$$

where:

α_e, α_i is the relevant estimated heat capacity coefficient of the outer and inner surfaces of the STV body (heat capacity has a minor impact on the K coefficient and can be ignored in practical calculations);

λ = 0.025 W(m·K) is the estimated heat conductivity coefficient;

S, in this case, should be determined as follows:

$$S=\sqrt{S_i\cdot S_e}=\sqrt{S_i\cdot f(S_i,d)}$$

The estimated outer heat transfer surface area of the STV body is determined according to formulas provided in the proposal made by the United Kingdom (ECE/TRANS/WP.11/2014/14) and in this document, providing that all the estimated outer dimensions of the body increase by the estimated average insulation thickness.

The average insulation thickness can be derived, as has been mentioned above, by a solution of the equation provided in paragraph 11 hereof. However, in the case of a complicated body surface, as well as the impossibility of applying multiple methods for solving such equations, the method of successive iterations is the simplest way of solving the problem (method C in the proposal made by the United Kingdom). The necessary number of iterations must correspond to the accuracy of deriving the target value (when determining *d*, this accuracy must be equal to 0.001 m).

Costs

13. No additional costs are required. The concretisation of methods for determining the inner and outer heat transfer surface areas of rail carriage bodies other than tank carriages implies no additional instruments, complicated mathematical calculations or other costly procedures.

Feasibility

14. The proposed changes create better conditions for achieving the main targets and objectives of the ATP without any additional costs and the need to introduce a transition period, and also increase the level of mutual trust among the Contracting Parties to the ATP.

Enforceability

15. There are no problems with tests and expert checks.

Appendix A

Determination of the outer surface area of a railway carriage body (case study of a new thermos car manufactured by the Dessau Plant, Germany, No. 80000011, 1985)

Source data

Outer dimensions of the carriage body (*according to the technical documentation of TH 4-201-90 models*):

length, m: $Le := 21.000$

width, m: $Be := 3.094$

sidewall height, m: $He := 2.763$

longitudinal height, m: $HHe := 3.610$

Inner dimensions of the carriage body (*according to the technical documentation of TH 4-201-90 models*):

length, m: $Li := 20.596$

width, m: $Bi := 2.702$

sidewall height, m: $Hi := 2.550$

longitudinal height, m: $HHi := 3.195$

Estimated heat transfer coefficient of the carriage's inner walls, W/(m²K): $\alpha i := \infty$

Estimated heat transfer coefficient of the carriage's outer walls, W/(m²K): $\alpha e := \infty$

Note: this parameter slightly affects the results of the calculation and is ignored for simplicity.

Parameters during stable condition mode:

average electricity consumed, W: $W := 1080$

average temperature difference inside and outside the carriage body, °C: $\Delta T := 25$

Estimated thermal conductivity coefficient of the body insulation, W/(mK): $\lambda := 0.025$

Calculation according to method A:

Heat transfer surface of the carriage body (determined on a trial basis), m^2: $F\_A := 252.5$

Function for calculation of K coefficient: $fK(W, \Delta T, F) := \frac{W}{F \cdot \Delta T}$

K coefficient, W/(m2K): $coefK\_A := fK(W, \Delta T, F\_A) = 0.171$

Calculation according to method B:

Determining the perimeter of the carriage roof rounding:

Note: below is an approximate formula to determine the perimeter of the carriage roof rounding, assuming that it is elliptical. Maximum error of the formula: ~0.3619%, with an ellipse eccentricity of ~0.979811(axis ratio ~1/5). The error is always positive.

Empirical parameter: $$x := \frac{\ln(2)}{\ln\left(\frac{\pi}{2}\right)}$$

Function for calculating the perimeter of the carriage roof rounding:

$$fP(B, H, HH) := 4\cdot\left[\left(\frac{B}{2}\right)^{x} + (HH - H)^{x}\right]^{\frac{1}{x}}$$

Function for calculating the carriage body surface:

$$fF'(L, B, H, HH) := L\cdot B + 2\cdot(L + B)\cdot H + L\frac{fP(B, H, HH)}{2} + \pi\frac{B}{2}\cdot(HH - H)$$

Function for calculating the surface area of the estimated heat transfer surface of the carriage body:

$$fF(Le, Be, He, HHe, Li, Bi, Hi, HHi) := \sqrt{fF'(Le, Be, He, HHe)\cdot fF'(Li, Bi, Hi, HHi)}$$

Carriage body heat transfer surface, m^2: $F\_B := fF(Le, Be, He, HHe, Li, Bi, Hi, HHi) = 262.749$

Carriage body outer surface area, m^2: $Fe := fF'(Le, Be, He, HHe) = 283.008$

Coefficient K, $W/(m^2K)$: $coefK\_B := fK(W, \Delta T, F\_B) = 0.164$

Calculation according to method C:

$$
\begin{aligned}
&\mathrm{proc}(Li, Bi, Hi, HHi, W, \Delta T, \lambda, \alpha e, \alpha i) := \\
&\quad prec \leftarrow 0.001 \\
&\quad n \leftarrow 0 \\
&\quad D_n \leftarrow 0 \\
&\quad LE_n \leftarrow Li + 2 \cdot D_n \\
&\quad BE_n \leftarrow Bi + 2 \cdot D_n \\
&\quad HE_n \leftarrow Hi + D_n \\
&\quad HHE_n \leftarrow HHi + 2 \cdot D_n \\
&\quad FE_n \leftarrow fF'(LE_n, BE_n, HE_n, HHE_n) \\
&\quad coefK\_C_n \leftarrow \frac{W}{\Delta T \cdot fF(LE_n, BE_n, HE_n, HHE_n, Li, Bi, Hi, HHi)} \\
&\quad \Delta d \leftarrow \infty \\
&\quad \text{while } \Delta d > prec \\
&\quad\quad n \leftarrow n + 1 \\
&\quad\quad D_n \leftarrow \left(\frac{\Delta T \cdot fF(LE_{n-1}, BE_{n-1}, HE_{n-1}, HHE_{n-1}, Li, Bi, Hi, HHi)}{W} - \frac{1}{\alpha e} - \frac{1}{\alpha i} \right) \cdot \lambda \\
&\quad\quad LE_n \leftarrow Li + 2 \cdot D_n \\
&\quad\quad BE_n \leftarrow Bi + 2 \cdot D_n \\
&\quad\quad HE_n \leftarrow Hi + D_n \\
&\quad\quad HHE_n \leftarrow HHi + 2 \cdot D_n \\
&\quad\quad FE_n \leftarrow fF'(LE_n, BE_n, HE_n, HHE_n) \\
&\quad\quad coefK\_C_n \leftarrow \frac{W}{\Delta T \cdot fF(LE_n, BE_n, HE_n, HHE_n, Li, Bi, Hi, HHi)} \\
&\quad\quad \Delta d \leftarrow \left| D_n - D_{n-1} \right| \\
&\quad \text{return } (D \;\; LE \;\; BE \;\; HE \;\; HHE \;\; FE \;\; coefK\_C)
\end{aligned}
$$

List of additional variables:

prec=10-^{3}*m – accuracy of choosing the average insulation thickness;*

n-number of iteration starting from 0 (massive indexation MathCAD);

D_n*- average insulation thickness derived in iteration n, m;*

LE_n*- estimated outer length of the carriage body derived in iteration n, m;*

BE_n*- the same, width, m;*

HE_n*- the same e, side wall height, m;*

HHE_n*- the same, longitudinal height, m;*

FE_n*- estimated outer surface of the carriage body derived in iteration n, m;*

$coefK\_C_n$*- estimated coefficient K, derived in iteration n according to method C, W/(*m^2K*);*

Δd- module of absolute change of the average insulation thickness, m (Δd>prec).

Results of choosing parameters (columns: D | LE | BE | HE | HHE | FE | coefK_C) in iterations (lines):

$$\mathrm{proc}(Li, Bi, Hi, HHi, W, \Delta T, \lambda, \alpha e, \alpha i) = \left[\begin{pmatrix}0.000\\0.141\\0.149\\0.149\end{pmatrix} \begin{pmatrix}20.596\\20.878\\20.894\\20.894\end{pmatrix} \begin{pmatrix}2.702\\2.984\\3.000\\3.000\end{pmatrix} \begin{pmatrix}2.550\\2.691\\2.699\\2.699\end{pmatrix} \begin{pmatrix}3.195\\3.477\\3.493\\3.493\end{pmatrix} \begin{pmatrix}243.940\\271.067\\272.561\\272.641\end{pmatrix} \begin{pmatrix}0.177\\0.168\\0.168\\0.168\end{pmatrix}\right]$$

Determination of the average insulation thickness according to method D:

$$\frac{1}{\frac{1}{\alpha e} + \frac{d}{\lambda} + \frac{1}{\alpha i}} = \frac{W}{\Delta T \cdot fF(Li + 2 \cdot d, Bi + 2 \cdot d, Hi + d, HHi + 2 \cdot d, Li, Bi, Hi, HHi)} \text{ solve } \rightarrow 0.14924416242198620967$$

Appendix B

Determination of the outer surface area of a railway carriage body (case study of tests of car No. 80007990 conducted in April 2015)

Source data

Outer dimensions of the carriage body (*according to the technical documentation of 11-280 carriages*):

length, m: $Le := 15.750$

width, m: $Be := 2.790$

sidewall height, m: $He := 2.915$

longitudinal height, m: $HHe := 3.323$

Inner dimensions of the carriage body (*according to results of measuring several dimensions of carriage body No. 80007990*):

length, m: $LI := (15.340 \quad 15.340)$ $Li := \mathrm{mean}(LI) = 15.340$

width, m: $BI := (2.470 \quad 2.470)$ $Bi := \mathrm{mean}(BI) = 2.470$

sidewall height, m: $HI := (2.635 \quad 2.635 \quad 2.630 \quad 2.620)$ $Hi := \mathrm{mean}(HI) = 2.630$

longitudinal height, m: $HHI := (2.900 \quad 2.900)$ $HHi := \mathrm{mean}(HHI) = 2.900$

Estimated heat transfer coefficient of the carriage's inner walls, W/(m²K): $\alpha i := \infty$

Estimated heat transfer coefficient of the carriage's outer walls, W/(m²K): $\alpha e := \infty$

Note: this parameter slightly affects the results of the calculation and is ignored for simplicity.

Parameters during stable condition mode:

average electricity consumed, W: $W := 1627$

average temperature inside the carriage body, °C: $Ti := 35.7$

average temperature outside the carriage body, °C: $Te := 10.3$

average temperature difference inside and outside the carriage body, °C: $\Delta T := \mathrm{round}(Ti - Te, 1)$ $\Delta T = 25.4$

Estimated thermal conductivity coefficient of the body insulation, W/(mK): $\lambda := 0.025$

Calculation according to method B:

Determining the perimeter of the carriage roof rounding:

Note: below is an approximate formula to determine the perimeter of the carriage roof rounding, assuming that it is elliptical. Maximum error of the formula: ~0.3619 % with an ellipse eccentricity of ~0.979811(axis ratio ~1/5). The error is always positive.

Empirical parameter: $x := \dfrac{\ln(2)}{\ln\left(\dfrac{\pi}{2}\right)}$

Function for calculating the perimeter of the carriage roof rounding:

$$fP(B,H,HH) := 4\cdot\left[\left(\frac{B}{2}\right)^{x} + (HH - H)^{x}\right]^{\frac{1}{x}}$$

Function for calculating the carriage body surface:

$$fF'(L,B,H,HH) := L\cdot B + 2\cdot(L + B)\cdot H + L\frac{fP(B,H,HH)}{2} + \pi\frac{B}{2}\cdot(HH - H)$$

Function for calculating the surface area of the estimated heat transfer surface of the carriage body:

$$fF(Le,Be,He,HHe,Li,Bi,Hi,HHi) := \sqrt{fF'(Le,Be,He,HHe)\cdot fF'(Li,Bi,Hi,HHi)}$$

$$F := fF(Le,Be,He,HHe,Li,Bi,Hi,HHi) = 186.860$$

Outer surface area of the carriage body, m^2: $Fe := fF'(Le,Be,He,HHe) = 201.992$

Function calculating coefficient K: $fK(W,Ti,Te,F) := \frac{W}{F\cdot(Ti - Te)}$

Coefficient K, $W/(m^2K)$: $coefK\_B := fK(W,Ti,Te,F) = 0.343$

Calculation according to method C:

$$
\mathrm{proc}(Li, Bi, Hi, HHi, W, \Delta T, \lambda, \alpha e, \alpha i) :=
\left|
\begin{array}{l}
prec \leftarrow 0.001 \\
n \leftarrow 0 \\
D_n \leftarrow 0 \\
LE_n \leftarrow Li + 2 \cdot D_n \\
BE_n \leftarrow Bi + 2 \cdot D_n \\
HE_n \leftarrow Hi + D_n \\
HHE_n \leftarrow HHi + 2 \cdot D_n \\
FE_n \leftarrow fF'\left(LE_n, BE_n, HE_n, HHE_n\right) \\
coefK\_C_n \leftarrow \dfrac{W}{\Delta T \cdot fF\left(LE_n, BE_n, HE_n, HHE_n, Li, Bi, Hi, HHi\right)} \\
\Delta d \leftarrow \infty \\
\text{while } \Delta d > prec \\
\quad \left|
\begin{array}{l}
n \leftarrow n + 1 \\
D_n \leftarrow \left(\dfrac{\Delta T \cdot fF\left(LE_{n-1}, BE_{n-1}, HE_{n-1}, HHE_{n-1}, Li, Bi, Hi, HHi\right)}{W} - \dfrac{1}{\alpha e} - \dfrac{1}{\alpha i}\right) \cdot \lambda \\
LE_n \leftarrow Li + 2 \cdot D_n \\
BE_n \leftarrow Bi + 2 \cdot D_n \\
HE_n \leftarrow Hi + D_n \\
HHE_n \leftarrow HHi + 2 \cdot D_n \\
FE_n \leftarrow fF'\left(LE_n, BE_n, HE_n, HHE_n\right) \\
coefK\_C_n \leftarrow \dfrac{W}{\Delta T \cdot fF\left(LE_n, BE_n, HE_n, HHE_n, Li, Bi, Hi, HHi\right)} \\
\Delta d \leftarrow \left| D_n - D_{n-1} \right|
\end{array}
\right. \\
\text{return } \left(D \;\; LE \;\; BE \;\; HE \;\; HHE \;\; FE \;\; coefK\_C\right)
\end{array}
\right.
$$

List of additional variables:

prec=10^{-3}*m – accuracy of choosing the average insulation thickness;*

n-number of iteration starting from 0 (massive indexation MathCAD);

D_n*- average insulation thickness derived in iteration n, m;*

LE_n*- estimated outer length of the carriage body derived in iteration n, m;*

BE_n*- the same, width, m;*

HE_n*- the same e, side wall height, m;*

HHE_n*- the same, longitudinal height, m;*

FE_n*- estimated outer surface of the carriage body derived in iteration n, m;*

$coefK\_C_n$*- estimated coefficient K, derived in iteration n according to method C, W/(*m^2K*);*

Δd*- module of absolute change of the average insulation thickness, m (*$\Delta d > prec$*).*

Results of choosing parameters (columns: D | LE | BE | HE | HHE | FE | coefK_C) in iterations (lines):

$$\mathrm{proc}[Li, Bi, Hi, HHi, W, (Ti - Te), \lambda, \alpha e, \alpha i] = \left[\begin{pmatrix} 0.000 \\ 0.067 \\ 0.069 \\ 0.069 \end{pmatrix} \begin{pmatrix} 15.340 \\ 15.475 \\ 15.479 \\ 15.479 \end{pmatrix} \begin{pmatrix} 2.470 \\ 2.605 \\ 2.609 \\ 2.609 \end{pmatrix} \begin{pmatrix} 2.630 \\ 2.697 \\ 2.699 \\ 2.699 \end{pmatrix} \begin{pmatrix} 2.900 \\ 3.035 \\ 3.039 \\ 3.039 \end{pmatrix} \begin{pmatrix} 172.862 \\ 182.778 \\ 183.062 \\ 183.070 \end{pmatrix} \begin{pmatrix} 0.371 \\ 0.360 \\ 0.360 \\ 0.360 \end{pmatrix} \right]$$

Determination of the average insulation thickness according to method D:

$$\frac{1}{\frac{1}{\alpha e} + \frac{d}{\lambda} + \frac{1}{\alpha i}} = \frac{W}{\Delta T \cdot fF(Li + 2 \cdot d, Bi + 2 \cdot d, Hi + d, HHi + 2 \cdot d, Li, Bi, Hi, HHi)} \text{ solve } \rightarrow 0.069429644663008042\text{29}$$