12.   HEAT LOSS

The main use of this module is to estimate total heat loss or draw the temperature profile of a wall or reactor. However, it can also be used to compare different materials and different setups, for example the use of insulation when a material has a critical maximum temperature or when the outside air cannot exceed a certain temperature. The conduction, convection and radiation databases also provide a resource as simple reference tables for material properties. Figure 1 shows an example of a heat loss wall calculation for a smelting reactor with the temperature profile shown in rows 9 and 10.
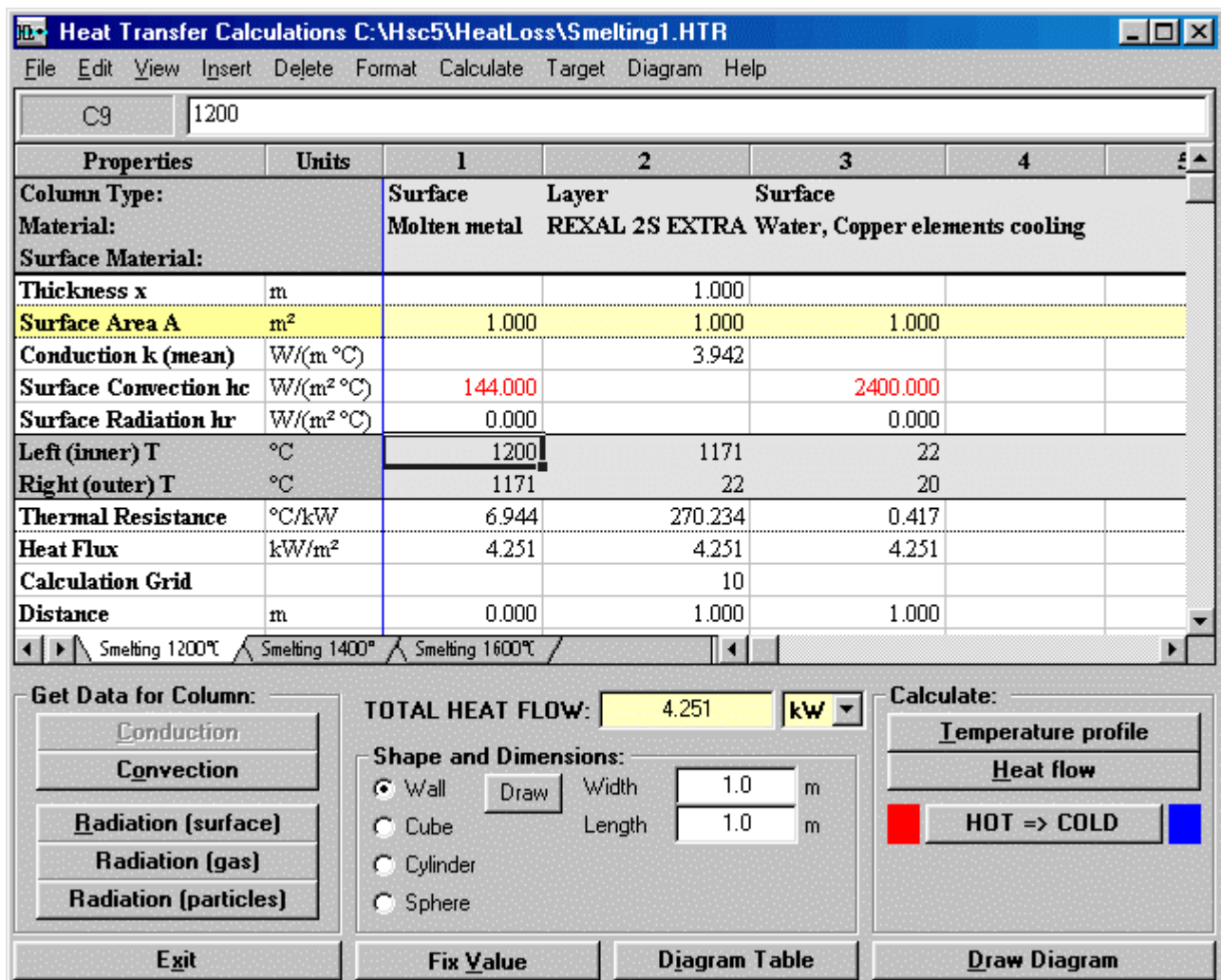

Figure 1: *Heat Loss calculation example of a smelting reactor wall.*

The basic concept of the module is that the user specifies the system setup by selecting the geometry of the object, inserting columns, specifying a material for each column, specifying thicknesses (if any) and entering either one temperature point and a total heat loss or two arbitary temperature points within the same sheet. From these inputs the program can calculate either the temperature profile or the total heat loss. The temperature profile (profiles) can then be plotted graphically.

The main workbook is very similar to Excel-type worksheets in terms of the properties that can be found in the menu and also most of the Excel worksheet functions are available.

The new Heat Loss module may be used, for example, to estimate heat loss values needed in the Balance module. The user must first specify the column types, which can be **Layer**, **Layer contact**, **Surface** and **Enclosure**. The thickness must be specified for **Layer** and **Enclosure** columns, while **Layer contact** and **Surface** columns have zero thickness. Two basic types of calculations may be carried out:

1. **Temperature profile** with fixed heat loss and one temperature point.
2. **Heat Loss** with two fixed temperature points. This will return the heat loss but also the temperature profile.

The calculation routine handles conduction, convection and radiation properties as functions of temperature but fixed values may also be used by selecting the value and pressing the **Fix Value** button. These fixed values are shown in red on the calculation sheet.

Temperature profile as well as some other user specified values may also be presented in graphical form. Target dialog may be used to find, for example, minimum layer thickness. The calculation specifications may be saved to files for later use.

12.1   Basic Calculation Procedure

1. Select geometry.

To select the choice of geometry, click on the desired option button in the frame **Shape and Dimensions**. The available options are wall, cube, cylinder and sphere. *It is highly recommended to start the calculations with a simple wall case* and then to continue with more complicated shapes later.

2. Select dimension.

When selecting the geometry, appropriate dimension textboxes automatically pop up. The dimensions are always *inner* dimensions.

3. Insert new column.

The user may specify the layout of the heat transfer object by selecting **Insert** from the menu bar and then the desired column type. There are four types of columns: **Surface**, **Enclosure**, **Layer** and **Layer contact**. **Surface** columns must be inserted to the left and/or to the right of the other columns. **Enclosure** columns must be inserted between two **Layer** columns. Finally **Layer contact**, **Enclosure** and **Layer** columns must all be inserted between **Surface** columns.

4. Specify heat transfer type.

You can select the type of heat transfer to study in two ways: either *manually* or *using the database.*

***Manually*:**
1. Write the name of the material/gas/liquid on the second row of the table in the current column.
2. Select the desired heat transfer factor:
   − Layer column: Enter the mean conductivity for the material (k) on row 6.
   − Surface column: Enter the convection and/or the radiation coefficient

(h_c and/or h_r) on row 7 and/or row 8. It is also possible to specify the emissivities and/or absorptivities on rows 20-23, in this case please make sure that the radiation coefficient is *unfixed*.

− Layer contact column: Enter the thermal resistance on row 11.

− Enclosure column: Enter the convection coefficient on row 7 and/or the radiation coefficient on row 8. It is also possible to specify the emissivities on the *adjacent layer columns*, in this case please make sure that the radiation coefficient is *unfixed*.

3. For each value entered press the **Fix Value** button, unless the value is already fixed. By doing this the program will use these given values, indicated by a red font, when calculating instead of the database values.

*Using the database***:**

1. Press the corresponding button in the frame **Get Data for Column:**

− Layer column: *Conduction* button.

− Surface column: *Convection* or *Radiation* button.

− Enclosure column: *Convection* or *Radiation* button (radiation for adjacent layer columns).

− To specify the desired material/gas/liquid, place the cursor on top of it and press **Select**. Now the data for the material will be transferred automatically to the column on the main sheet where the cursor is located. Note that sometimes several database sheets are available, for example the convection *table* or *function sheet*. You will know that the data has been transferred from the database sheet to the calculation sheet, once the selected material name appears on the material name rows 2 or 3.

5. Specify thicknesses.

Type the *Thickness x* on row 4 for every **Layer** and **Enclosure** column. **Surface** and **Layer contact** columns have zero thickness.

6. Repeat steps 3, 4 and 5 until the desired layout is achieved.

7. Calculate results.

To calculate results for a cylinder or cube, first select whether to calculate all sheets or just the active sheet, by pressing the appropriate option button in the **Calculate** frame. By, for example, calculating only the wall sheet of a cylinder, pipe calculations can be obtained. The two basic calculation types are:

Temperature Profile (press the **Temperature profile** button)*:*

− Specify the total heat loss by selecting the appropriate unit (W, kW or MW) and by typing the heat loss in the textbox.

− Specify *one* fixed temperature point by the cursor.

− For cube or cylinder geometry, specify calculation range by selecting either **Calculate all sheets** (calculates all walls) or **Calculate active sheet** (calculates active wall) from the option buttons.

− Note that when calculating all sheets, the temperature profiles will be iterated so that the temperatures in the first columns (inside temperatures), as well as the outside temperatures, are the same for all sheets.

Heat Flow (press the **Heat flow** button):
− Specify temperature points using the cursor.
− 0 or 1 point selected (by cursor position): The *whole range* will be calculated.
  − Cube or cylinder geometry: Specify calculation range by selecting either **Calculate all sheets** (calculates all walls) or **Calculate active sheet** (calculates active wall).
  − *All* sheets will have the same inside and outside temperatures as on the current sheet, once the calculation is completed.
− 2 points selected (by selection): The range *between these points* will be calculated.
  − Cube or cylinder geometry: The other sheets will *not* be calculated.
  − The *end temperature points* in the selection will remain constant.

8. Press the *Draw Diagram* button for a graphical plot of the temperature profile.

12.2 Heat Loss Examples

12.2.1 Examples provided by HSC

See the examples provided by the HSC package by selecting **File/Open** from the menu and selecting the appropriate file (examples exist in \HSC5\Heatloss -folder).

1. **Simple Case with fixed conduction and convection values (SimpleCase.HTR)**

   In this example the furnace wall is made of two layers, the inside temperature is 700 °C and the outer surface is cooled with air (20 °C). The conduction and convection values are fixed. In this case the heat flow through each layer and through the surface may easily also be calculated manually:

   Firebrick: 1.5 m^2 * (700 - 418 °C) * 0.4 W/(mK) / (0.23 m) = 735 W
   Silica brick: 1.5 m^2 * (418 - 50.63 °C) * 0.2 W/(mK) / (0.15 m) = 735 W
   Air: 1.5 m^2 * (50.63 - 20 °C) * 16 W/(m^{2}K) = 735 W

2. **Radiator heat (Radiator.HTR-file)**

   This example calculates the heat output of a radiator at room temperature (20 °C) and at three different water temperatures, when the water flow to the radiator is zero. Select the appropriate sheet according to the inside water temperature (40 °C, 50 °C or 60 °C) and press the **Heat flow** button to view changes in the output heat. Adjustments can also be made to the width or length (height for a vertical wall) of the radiator to examine what influence this has on the result.

Heat Transfer Calculations C:\Hsc5\HeatLoss\Radiator.HTR

File Edit View Insert Delete Format Calculate Target Diagram Help

C9 | 40

Properties	Units	1	2	3	4
Column Type:		Surface	Layer	Surface	
Material:		Water H2O (li	Carbon steel: (0.2% C)	Air (gas)	
Surface Material:				Paint, white (acrylic) (h)	
Thickness x	m		0.003		
Surface Area A	m²	1.000	1.000	1.000	
Conduction k (mean)	W/(m °C)		50.000		
Surface Convection hc	W/(m² °C)	261.184		3.322	
Surface Radiation hr	W/(m² °C)	0.000		5.674	
Left (inner) T	°C	40	39	39	
Right (outer) T	°C	39	39	20	
Thermal Resistance	°C/kW	3.829	0.060	111.164	
Heat Flux	kW/m²	0.174	0.174	0.174	
Calculation Grid			10		
Distance	m	0.000	0.003	0.003	

Radiator 40°C \ Radiator 50°C \ Radiator 60°C

Get Data for Column:
- Conduction
- Convection
- Radiation (surface)
- Radiation (gas)
- Radiation (particles)

TOTAL HEAT FLOW: 0.174 kW ▼

Shape and Dimensions:
- ● Wall   Draw   Width   2.0   m
- ○ Cube   Length 0.5   m
- ○ Cylinder
- ○ Sphere

Calculate:
- Temperature profile
- Heat flow
- HOT => COLD

Exit   Fix Value   Diagram Table   Draw Diagram

Figure 2: *Radiator calculation example.*

3.   Heat loss from uninsulated pipe at constant T (incropera94_503.HTR file)

This is an example taken from Fundamentals of Heat and Mass Transfer by F. P. Incropera and D. P. DeWitt (page 503 in the 4th edition) /1/. In this example the heat loss from an uninsulated horizontal pipe is calculated with knowledge of the surface temperature (165 °C) and the air temperature (23 °C).

4.   Heat loss from insulated pipe at constant T (incropera94_504.HTR file)

Example 3 above is extended by insulating the pipe with a 25 mm thick urethane layer. Notice how the heat loss decreases significantly.

5.   Heat loss from a hot water tank (Hotwatertank.HTR file)

This example is a calculation of heat loss from a hot water tank. By specifying the materials, dimensions, geometry, water and air temperatures; the total heat loss for the tank can be calculated. The insulation thickness can easily be increased separately for the top, wall and bottom sides, in order to lower the heat loss from the tank.
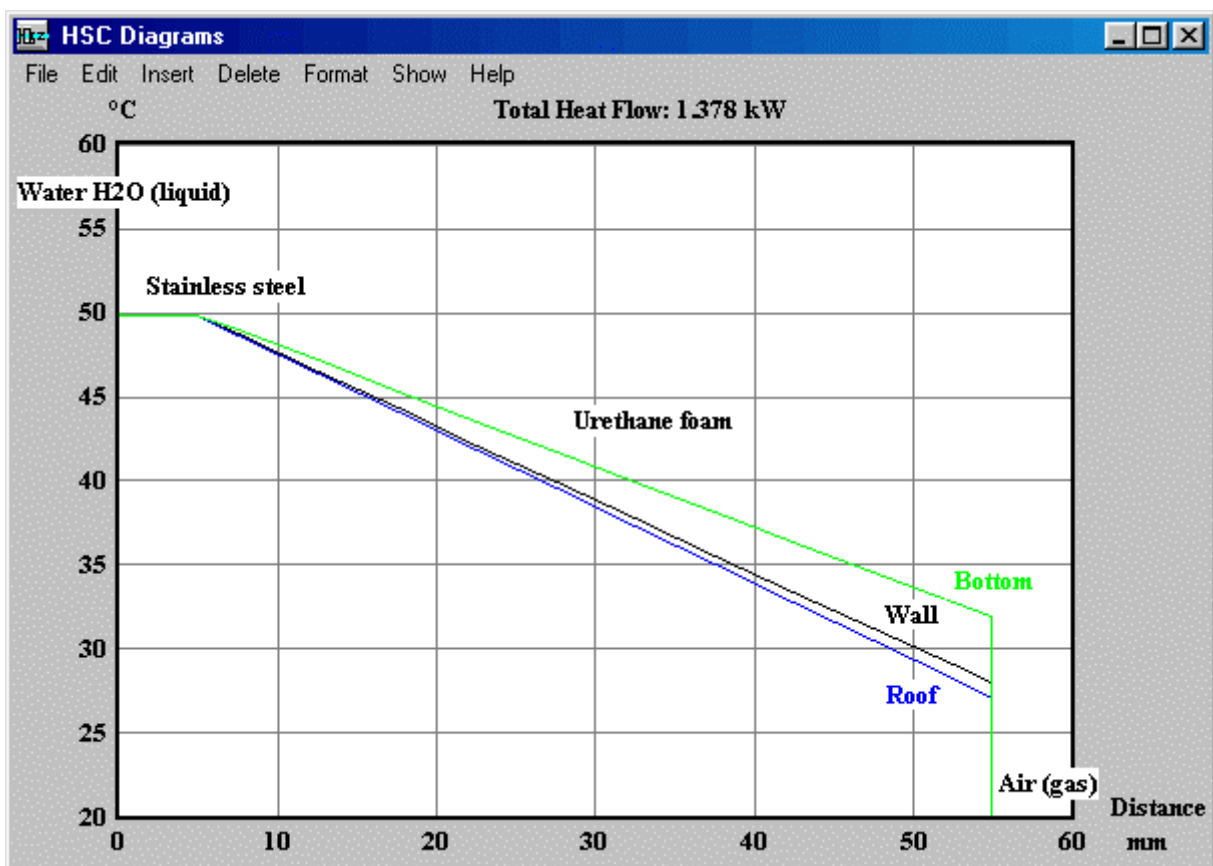

Figure 3: *Temperature profiles for the hot water tank.*

6.   Oil furnace (OilFurnace.HTR file)

In this example the heat flow due to hot flue gases and internal convection in a furnace is calculated. The flue gas composition can be seen from the **Gas Mixture Radiation** dialog by pressing the **Radiation (gas)** button. The gas contains the following radiating species: $H_2O(g)$ 11.08 vol-%, $CO_2(g)$ 11.69 vol-% and $SO_2(g)$ 0.05 vol-%. This is a typical flue gas composition for fuel oils. The gas temperature

is 1200 °C and the wall temperature is 500 °C. The wall surface material is *"Steel (sheet with skin due to rolling)"* and the convective gas is approximated as *"Air (p = 1 bar)"*. These can both be found from the database. There is a 10 mm thick *"Plain carbon steel"* layer surrounding the furnace. It is important to insert a **Layer** or a **Layer contact** column to the *right* of the **Surface** column, in order to calculate *internal* radiation (or convection), since the program otherwise assumes *outside* radiation (or convection). By entering a very low thickness value for the **Layer** column (row 4), or by entering zero thermal resistance for the **Layer contact** column (row 11), the inside surface temperature may still be used in the **Layer** or **Layer contact** column.

7. **Reactor heat loss calculation (Reactor1.HTR and Reactor2.HTR)**

   In this example the total heat loss of a reactor is estimated. The given input data are the dimensions of the reactor, the surface temperature and the surrounding temperature (room temperature). The surface material in the Reactor1 example is *"Steel (sheet with rough oxide layer)"* and in Reactor2 *"Paint, white (acrylic)"*. The convective gas is *"Air (p = 1 bar)"* in both examples. Since the surface emissivity is lower in Reactor2, the heat loss is smaller.

8. **Smelting reactor calculation (Smelting1.HTR, Smelting2.HTR and Smelting3.HTR files)**

   In this example the temperature profiles and heat losses of three different types of smelting reactors are calculated. The default input values given in this example have not been taken from any specific reactor type, however the input values may easily be changed in order to achieve a more realistic situation.

12.2.2   Simple Step-by-step Example (creating Smelting1.HTR)

The following steps describe how to create the Smelting1.HTR example from the very beginning. The final example can be used to approximate heat losses through a smelting reactor wall. The temperature profiles for different inside temperatures can be plotted using the Draw Diagram button.

1. Select **File/New** from the menu.

2. Select **Insert/Surface column** and press the **Convection** button.

3. From the Convection window (to the left), select the **Function** sheet.

4. Select **Water, Copper elements cooling** by moving the cursor to row 10.

5. Press the **Select** button.

6. Select **Insert/Layer column** in the main sheet and press the **Conduction** button.

7. Type **REXAL 2S EXTRA** in the yellow textbox in the Conduction window and press the **Find** button. The cursor will now automatically move to the correct position in the database.

8. Press the **Select** button.

9. Type **1** as the layer thickness on row 4 in the main window.

10. Select **Insert/Surface column** and press the **Convection** button.

11. Select the **Function** sheet from the Convection window.

12. Select **Molten metal** by moving the cursor to row 4.

13. Click the **Forced Convection** option button and type **0.02** (= 2 cm/s) in the speed textbox.

14. Press the **Select** button.

15. Type **1200** as the inside temperature in cell C9 and **20** as the outside temperature in cell E10.

16. Press the **Heat loss** button.

Heat Loss will now calculate the total heat loss from a 1x1 m square of the reactor wall. The inside and outside convection coefficients, calculated from the Function sheet, are based on generalized empirical data. They can, however, be used up to a reasonable accuracy for **smelting reactor** walls with **corresponding cooling methods**. The temperature profile may be plotted graphically by pressing the **Draw Diagram** button. The following procedure describes how it is possible to compare several temperature profiles within the same diagram.

1. Select **Insert/Wall sheet** from the menu *twice*. Two copies of the reactor wall are created.

2. Select **Wall2** sheet and type **1400** as the inside temperature (cell C9).

3. Press the **Heat loss** button.

4. Select **Wall3** sheet and type **1600** as the inside temperature (cell C9).

5. Press the **Heat loss** button.

6. Press the **Draw Diagram** button.

Now the temperature profiles for three different inner temperatures (1200 °C, 1400 °C and 1600 °C) are plotted. After modifying the diagram labels and their positioning, the final diagram might look similar to the enclosed diagram (Figure 4). The setup should now also be similar to that of the Smelting1.HTR example.
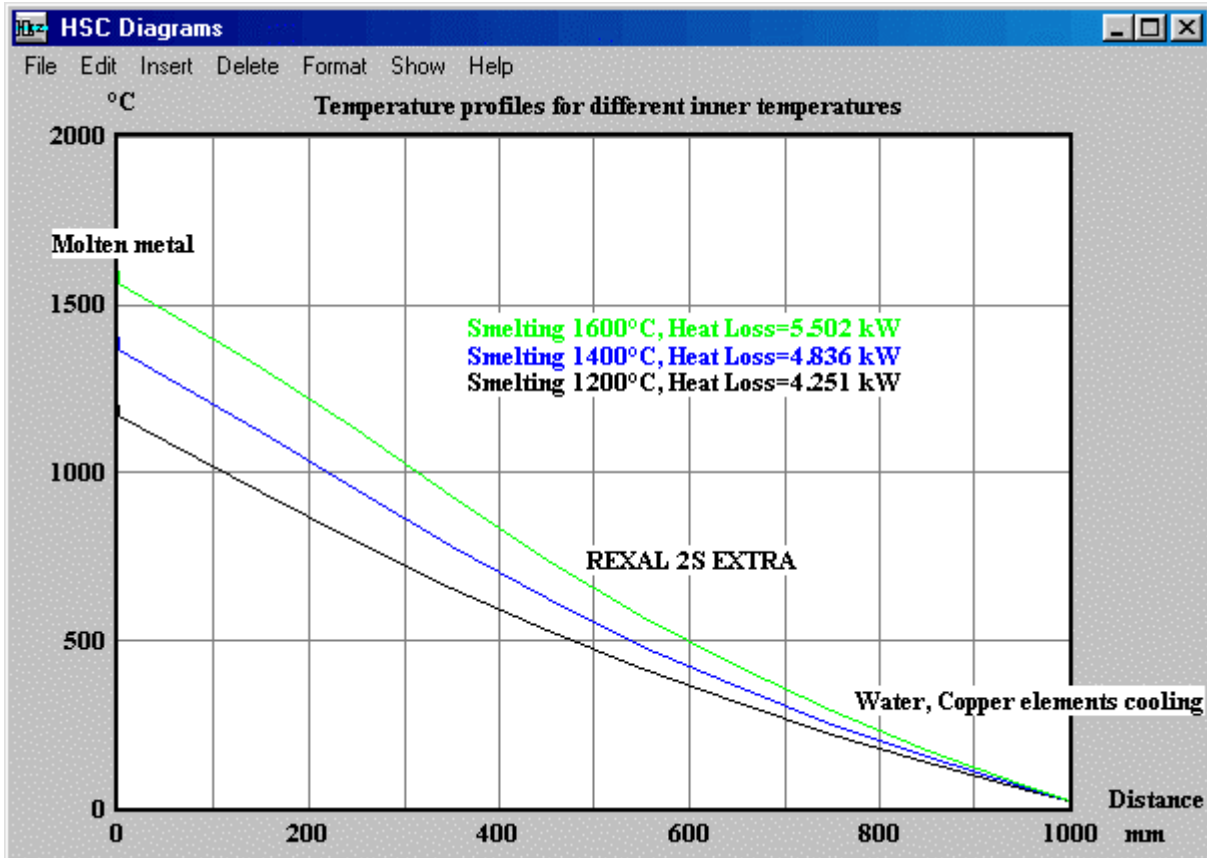
Figure 4: *Temperature profiles for Smelting1.HTR calculation example.*

12.3.   Detailed Description of the Program

12.3.1   Using the Fix Value Button and the logic behind it

Once the **Fix Value** button is activated the user is able to fix values manually to make these a direct input for the calculation. A fixed value is indicated by **red font** and the caption on the button changing to **Unfix Value**. If, for example, the user wishes to specify the convection coefficient h_c directly, the specified value must be fixed (and the fluid name typed manually), otherwise the program will iterate the value using the database for the selected fluid. The program will always *first look for fixed values* and if the value is unfixed then it will use iterative methods and the databases. In the end the iteration result will be returned to the cell, for example the h_c-value. Using fixed values significantly improves the calculation speed, however these values are not always available. As a rule of thumb, the accuracy of the result will improve if it is possible to accurately specify and fix values, for example the convection and the radiation coefficients. The cells on rows 6-8 and 20-23 can be fixed, as well as row 11 if the column is of **Layer contact** type.

12.3.2   Main Window

Figure 5: *Main window layout.*

1. Headings area

This is the headings area and it cannot be altered, except for the second and third row if the material is user-specified.

2. Calculation area

The main inputs are entered in this area, with the thickness of a layer or enclosure column being mandatory. The surface area row is automatically calculated from the geometry and layer thicknesses.

3. Temperature inputs/results

In this area the temperature points are entered. In order to calculate the temperature profile **one** temperature point must be specified. In order to calculate the heat loss **two** points must be specified. For three-dimensional objects (**cube and cylinder**), the user can select **Calculate all sheets** (calculate the whole object simultaneously) or **Calculate active sheet** (calculate only the active wall), by selecting the appropriate option button from the **Calculation** frame. It is also possible to select a calculation area by selecting a temperature range with the mouse. In this case *only the range within this selection* will be calculated. An example of this would be to select the range between C9 and F10 in figure 5.

4. Detailed information

Here you can find more detailed information about the setup. If more precise layer calculations are required, the **Calculation grid** (row 13) value may be changed. By default this is set to 10, i.e. the layer is divided into 10 elements. Note that the calculation time increases with an increasing grid size. **Speed** (row 16) indicates the speed of the fluid for forced convection. If this is zero, free convection is assumed. The **minimum** and **maximum temperatures** (rows 17-18) give the valid range for a certain material; N/A indicates that the limit is not available from the database. If a temperature point in the calculation result exceeds one of these points, it will be indicated by a warning message box.

5. Available data (frame)

These buttons are enabled/disabled depending on the column type the cursor is placed on.

Conduction: *Layer column*

Convection: *Surface column* or *Enclosure column*

Radiation (surface): *Surface column* or *Layer column* (adjacent to an Enclosure column only)

Radiation (gas): *Surface column*, left of a Layer or Layer contact column (internal radiation)

Radiation (particles): *Surface column*, left of a Layer or Layer contact column (internal radiation)

6. Geometry input

The option box selects the geometry and the appropriate dimension textboxes. Note that when changing from a **wall** or **sphere** (one sheet calculations) to a **cube** or **cylinder** (one or multiple sheets calculations) the wall sheet will be copied to the joining sheets of the cube or cylinder. This is useful if all walls consist of the same materials, since the user thus only has to specify the layout of one wall and then change to the correct geometry. The **Draw** button draws a simple drawing of the current geometry.

7. Heat loss input/result

This can be used both as input or output data. If calculating the temperature profile the total heat loss must be entered here, but when calculating heat loss, this can also be used as a starting approximation to achieve faster calculations. The starting approximation has a maximum value of 10 MW. If a higher value is specified, the maximum value is simply inserted in the textbox by default.

8. Radiation inputs/results

> Rows 30-349 consist of Convection and Conduction data and rows 350- of Radiation data. These are automatically collected from the database sheet when pressing the **Select** button and these should not be changed.

12.3.3   Conduction Database

	B	C	D	E	F	G
1	**Thermal**	Data				
2	**Conduction**					
3	**Database**	**Property**	**Units**	**T1**	**T2**	**T3**
4	**Aluminium Al**	Temperature	K	100	200	300
5	(pure)	Thermal conductivity	W/m K	302	237	237
6	**Aluminium 2024-T6**	Temperature	K	100	200	300
7	(4.5%Cu, 1.5%Mg, 0.6%Mn)	Thermal conductivity	W/m K	65	163	177
8	**Aluminium 195, cast**	Temperature	K	300	400	600
9	(4.5%Cu)	Thermal conductivity	W/m K	168	174	185
10	**Antimony Sb**	Temperature	K	293.15		
11		Thermal conductivity	W/m K	21		
12	**Beryllium Be**	Temperature	K	100	200	300
13		Thermal conductivity	W/m K	990	301	200
14	**Bismuth Bi**	Temperature	K	100	200	300
15		Thermal conductivity	W/m K	16.5	9.69	7.86
16	**Boron B**	Temperature	K	100	200	300
17		Thermal conductivity	W/m K	190	55.5	27
18	**Cadmium Cd**	Temperature	K	100	200	300
19		Thermal conductivity	W/m K	203	99.3	96.8
20	**Chromium Cr**	Temperature	K	100	200	300
21		Thermal conductivity	W/m K	159	111	93.7
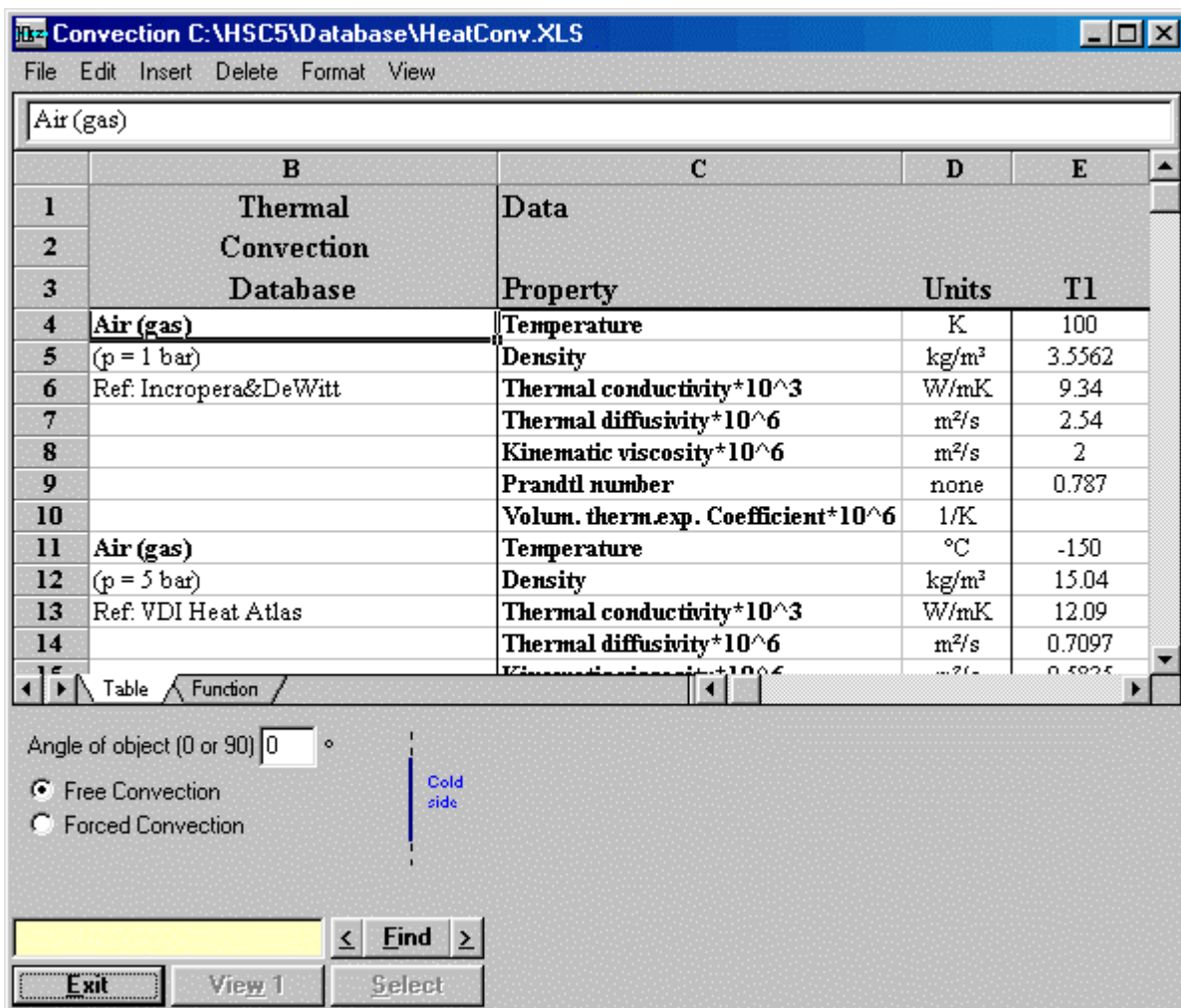
Figure 6: *Thermal Conduction database window.*

> The conduction database can be edited by selecting **Edit/Conduction Database** from the menu bar. Since the files are of XLS type you can also edit them directly from Excel. It is important to notice that when editing or adding new materials it is very important to follow the same pattern and syntax as the rest of the table. Temperature units can be entered in either **K** or **°C** and the program will automatically calculate accordingly. The maximum and minimum temperatures are available in column A and are always given in Kelvin. This window is used when selecting the layer material by pressing the **Conduction** button.

12.3.4   Convection Database, Table sheet

Figure 7: *Thermal Convection database window, Table sheet.*

The convection database can be edited by selecting **Edit/Convection Database** from the menu bar. Since the files are of XLS type you can also edit them directly from Excel. Temperature units available are **K** and **°C**. The density is not a key requirement, although it can be used in order to calculate the other properties. If the thermal expansion coefficient is not given, the program will assume that the material is an ideal gas and calculate the coefficient as $\beta = 1/T_\infty$. The maximum and minimum temperatures are in the hidden column A and are always given in Kelvins. This window is used when selecting the surface or enclosure material and pressing the **Convection** button.

12.3.5   Convection Database, Function sheet
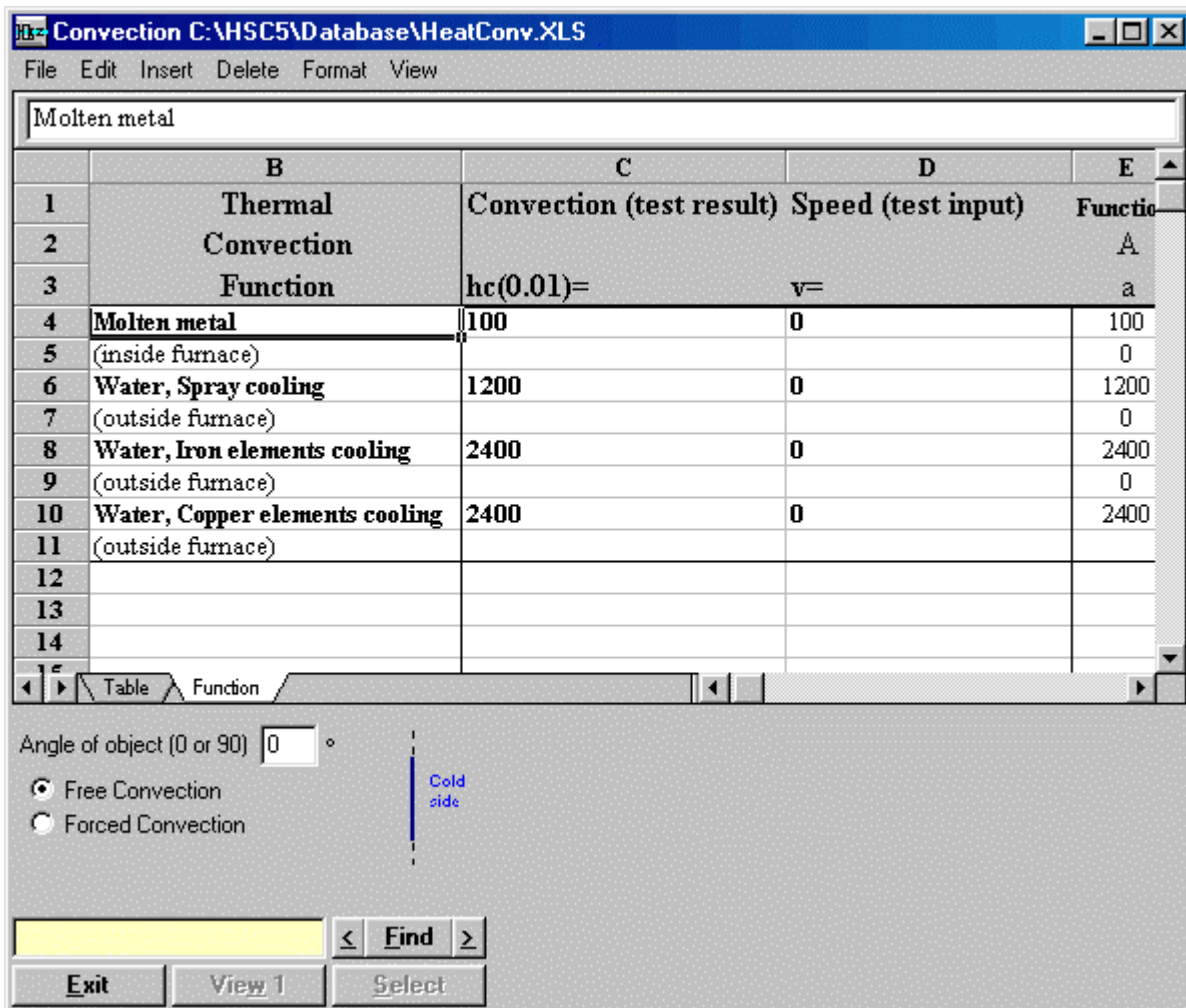
Figure 8: *Thermal Convection database window, Function sheet.*

The function sheet can be used for special cases of forced convection. For example, the **Molten meta**l selection is an approximation of h_c based on a **polynomial function** of the speed of the molten metal inside a smelting reactor. The database uses a function of the type $h_c(v) = Av^a + Bv^b + \ldots + Gv^g$ where v is [m/s]. The coefficients (A-G) are located between column E and K and the exponents (a-g) in the cells directly underneath these. This sheet can also be used if the convection coefficient is considered constant: simply type the constant value in column E and a zero underneath. This is shown in rows 6, 8 and 10.

For a wall or cylinder it is possible to specify an angle of 0° or 90°, which means either a **horizontal** or a **vertical** object. When selecting the **Forced Convection** option button, a textbox for the fluid/gas speed appears under the option buttons.

12.3.6   Surface Radiation Database

Surface Radiation C:\HSC5\Database\HeatRadi.XLS

Ideal black surface

	B	C	D	E	F	G	H
1	Thermal	Data	(h)=hemispherical emissivity, (n)=normal emissivity				
2	Radiation						
3	Database	Property	Units	T1	T2	T3	T4
4	**Ideal black surface**	Temperature	K	273.15			
5	(absorbs all radiation)	Emissivity	none	1			
6	**Aluminium (h)**	Temperature	K	100	200	300	400
7	(highly polished, film)	Emissivity	none	0.02	0.03	0.04	0.05
8	**Aluminium (h)**	Temperature	K	100	200	300	
9	(foil, bright)	Emissivity	none	0.06	0.06	0.07	
10	**Aluminium (h)**	Temperature	K	300	400		
11	(anodized)	Emissivity	none	0.82	0.76		
12	**Chromium (n)**	Temperature	K	100	200	300	400
13	(polished or plated)	Emissivity	none	0.05	0.07	0.1	0.12
14	**Copper (h)**	Temperature	K	300	400	600	800
15	(highly polished)	Emissivity	none	0.03	0.03	0.04	0.04
16	**Copper (h)**	Temperature	K	600	800	1000	
17	(stably oxidized)	Emissivity	none	0.5	0.58	0.8	
18	**Gold (h)**	Temperature	K	100	200	300	400
19	(highly polished or film)	Emissivity	none	0.01	0.02	0.03	0.03
20	**Gold (h)**	Temperature	K	100	200	300	
21	(foil, bright)	Emissivity	none	0.06	0.07	0.07	

Table

Find

Exit   View 1   Select

Figure 9: *Thermal Radiation database window.*

The radiation database can be edited by selecting **Edit/Radiation Database** from the menu bar. Since the files are of XLS type you can also edit them directly from Excel. Temperature units available are **K** and **°C**. An (n) after the material indicates that the emissivities are normal emissivities and an (h) indicates that they are hemispherical emissivities. Note that the emissivity for a material can vary a lot depending on the surface, for example, a polished surface emits much less radiation than an unpolished one. This window is used when selecting the surface material and pressing the **Radiation** button.

12.3.7   Gas Mixture Radiation Calculator
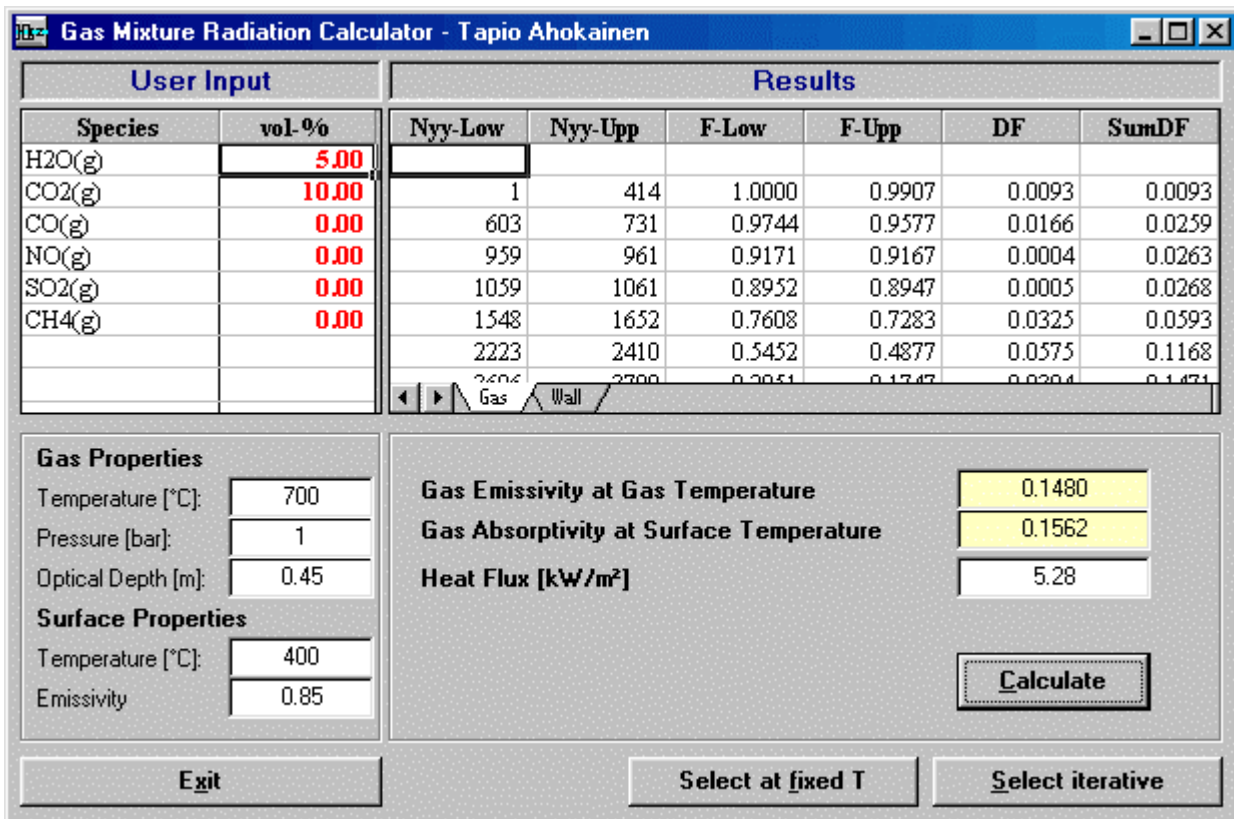
Figure 10: *Thermal radiation from a gas mixture.*

Using this window it is possible to calculate the gas emissivity and absorptivity by specifying the **volume fractions** (indicated by a red font), **pressure**, **gas temperature** and **surface (wall) temperature**. If the object is a cube, cylinder or sphere the **optical depth** is *automatically* calculated accordingly, although it can still be changed in the textbox. See Table 1 for examples of optical depths for simple geometries.

The **Calculate** button calculates using the specified inputs. The **Gas** sheet shows the detailed results for the gas emissivity at the gas temperature and the **Wall** sheet shows the detailed results for the gas absorptivity at the wall temperature.

There are two ways of using the results from the calculation in the main sheet:

Select at fixed T: By selecting this the gas temperature, surface temperature and surface emissivity will be used directly in the main sheet. This is a fast way of calculating if the *gas and surface temperatures are known*.

Select iterative: By selecting this the program iterates emissivity and absorptivity values in the range 0 °C – 3000 °C for every 50 °C step. The results are transferred to the main sheet for use in iterative calculations. Outside this range the values will be extrapolated. This is useful when the *gas temperature and/or surface temperature are unknown*.

Outotec

HSC Chemistry® 6.0

12 - 19

Peter Bjorklund

August 10, 2006

06120-ORC-T

12.3.8 Particle Radiation Calculator

Particle Suspension Radiation Calculator

User Input:

Property	Unit	Value
Gas Amount	Nm³/h	24100
Particle Amount	t/h	69
Particle Density	g/ml	4.3
Particle Diameter	mm	0.050
Particle Emissivity		0.148
Cube Width & Height	m	0.002
Cube Thickness	m	0.100
Tube diameter	m	4.200

Results:

Property	Unit	Value
Gas	m³/h	85861
Particles	m³/h	16.0
Gas + Particles	m³/h	85877
Particles	g/m³	803
Particles	ml/m³	186.9
Particles	vol-%	0.0187
Particle Radius	mm	0.02500
P. Cross-sectional Area	mm²	0.00196
Particle Volume	mm³	0.00007
Particle Weight	g	2.81E-07
Particles/m³		2.85E+09
Cube Volume	m³	4E-007
Particles in Cube		1142
Particle Distances	mm	0.70
Gas Speed	m³/sec	23.85
Gas Speed in Tube	m/sec	1.72

Gas Properties

Temperature [°C]: 700

Gas emissivity at gas temp: 0.1480

Gas absorptivity at surface temp: 0.1562

Surface Properties

Temperature [°C]: 400

Emissivity: 0.85

Particle cloud Emissivity 0.0796

Heat Flux [kW/m²] 8.06

[Calculate]

[Exit] [Diagram] [Select at fixed T] [Select iterative]

Figure 11: *Particle radiation window.*

Using this window it is possible to calculate a particle cloud emissivity when some detailed data about the particles and the geometry of the container are known. The results can also be used at a fixed T or iteratively as in the **Gas Mixture Radiation** dialog. The **Diagram** button shows a simple drawing of a particle distribution in the container. The Gas emissivity at gas temperature and the gas absorptivity at surface temperature are automatically taken from the **Gas Mixture Radiation** dialog when available.

Outotec

HSC Chemistry® 6.0

12 - 20

Peter Bjorklund

August 10, 2006

06120-ORC-T
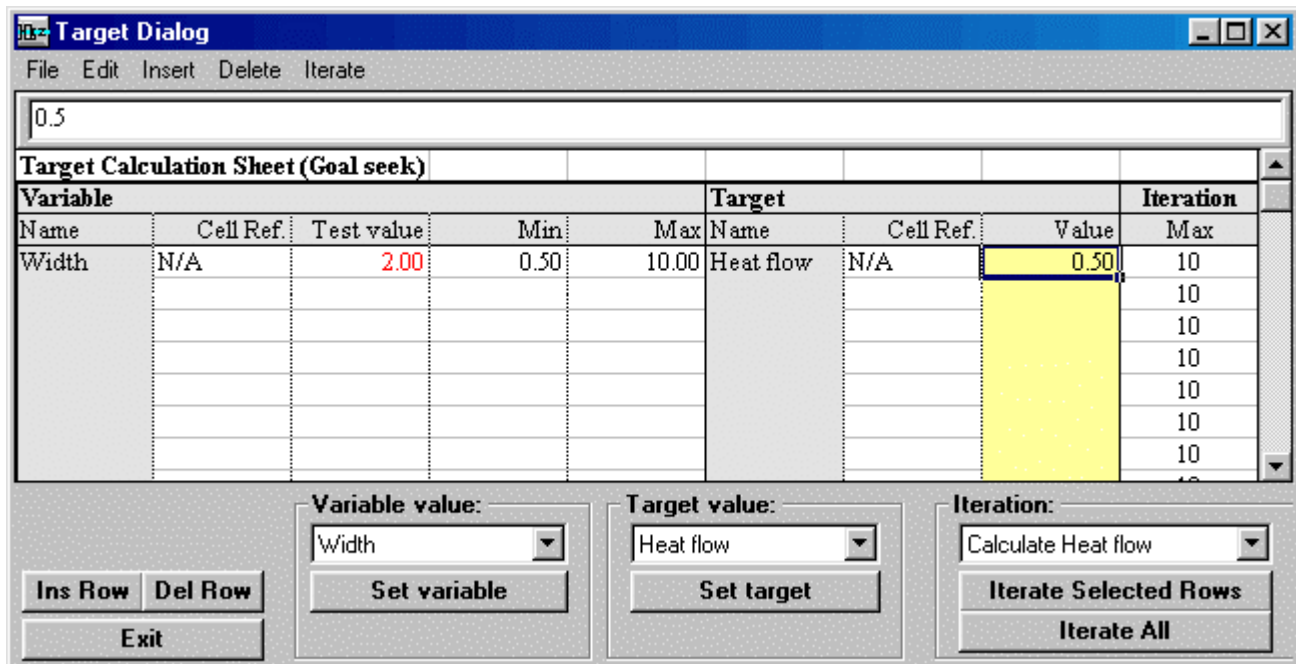
12.3.9 Target Calculations (Target Dialog)

Figure 12: *Target Dialog window.*

The **Target Dialog** extends the calculation possibilities of Heat Loss. For example it is possible to calculate the required insulation thickness to achieve a certain heat loss or, as the example in Figure 12, the required width of a radiator to achieve a heat loss (in this case heat output) of 0.5 kW. The following step-by-step procedure describes how the Target dialog can be used for this iteration.

1. Open the file **Radiator.HTR** from the **Hsc5\HeatLoss** directory.

2. Select **Target/Target Dialog** from the menu.

3. Choose **Width** from the drop-down box in the **Variable value** frame.

4. Press **Set variable**, which sets the width of the radiator as the variable value.

5. Choose **Heat flow** from the drop-down box in the **Target value** frame.

6. Press **Set target**, which sets the Heat loss of the radiator (heat output) as the target value.

7. Choose **Calculate Heat flow** (calculation method) from the drop-down box in the **Iteration** frame.

8. Write **1** in the Min column, **10** in the Max column and **0.5** in the Value column. This specifies the minimum and maximum widths and the goal value for the heat loss (heat output).

9. Press **Iterate Selected Rows**, which calculates the required width for a heat output of 0.5 kW. The required width of the radiator is 5.747 m, as can be seen from the main window.

If the **Worksheet cell** option in a drop-down box is selected, any worksheet cells in the main window may be used as either a variable or target value. An example of this could

be to iterate the required thickness of a layer (row 4) in order to achieve a certain heat loss.

12.3.10   User-specified Diagrams (Diagram Dialog)

Instead of only iterating a certain goal value, the **Diagram Dialog** may be used for graphically plotting the whole range. In the example below (Figure 13), the influence of the inside water temperature on the heat flow (in this case the radiator heat output), is shown. Step-by-step the diagram may be achieved in the following manner:

1. Open **Radiator.HTR** from the **Hsc5\HeatLoss** directory.

2. Select **Diagram/Diagram Dialog** from the menu.

3. Select **Worksheet cell** from the drop-down box in the **X-value** frame.

4. Move to cell C9 in the main window (inner temperature) and press **Set X value** in the dialog box.

5. Select **Heat loss** from the drop-down box in the **Y-value** frame and press **Set Y1 value**.

6. Select **Calculate Heat loss** from the drop-down box in the **Diagram** frame.

7. Type **90** in the MAX textbox and **5** in the STEP textbox. This means that the inner temperature will range from 30 °C to 90 °C calculated every 5 °C. The dialog box should now look similar to Figure 13.
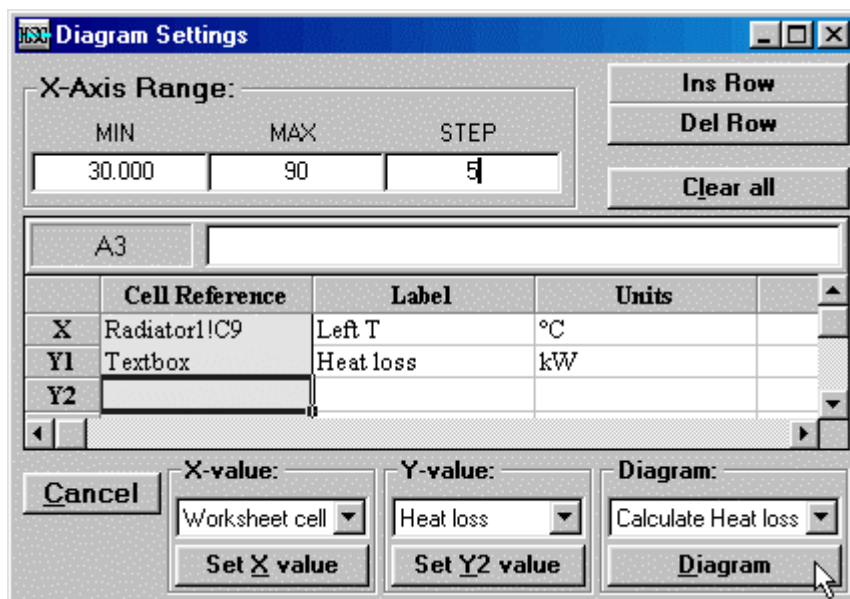

Figure 13: *Diagram dialog window. Specifying the diagram.*

8. Press **Diagram**.

9. In the **Diagram Table** window, it is possible to specify properties in detail. However, if this is not necessary just press **Diagram** here too. The resulting diagram is shown in Figure 14.
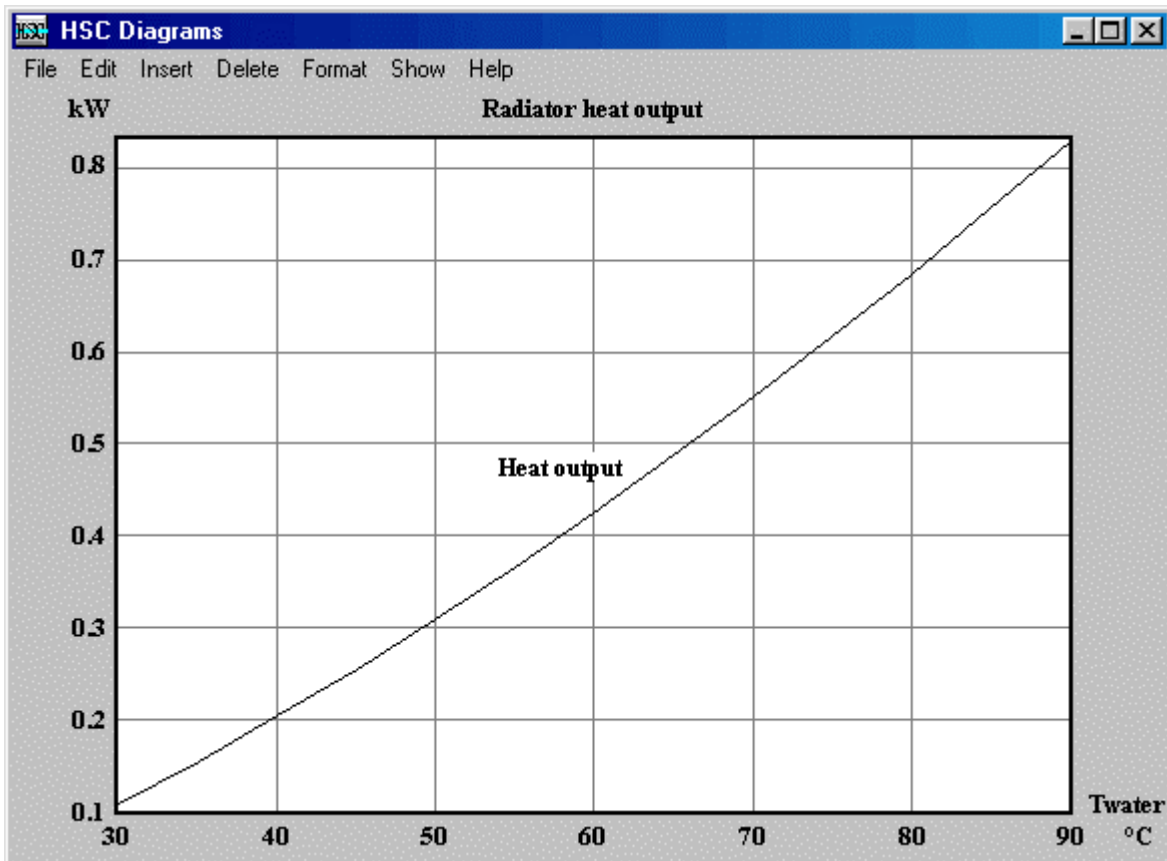
Figure 14: *Diagram showing the influence of the inside temperature on the radiator heat output.*

Another useful diagram would be to study the optimum insulation thickness of a cylinder geometry (for example a pipe or a cylindrical tank). An optimum thickness is available due to an increasing outside surface area, thus increasing convective and radiative heat loss. The following step-by-step instructions show how this diagram may be created:

1. Open **Hotwatertank.HTR** from the **Hsc5\HeatLoss** directory.

2. Select **Diagram/Diagram Dialog** from the menu.

3. Select **Worksheet cell** from the drop-down box in the **X-value** frame.

4. Move to cell E4 in the main window (urethane insulation thickness) and press **Set X value** in the dialog box.

5. Select **Heat loss** from the drop-down box in the **Y-value** frame and press **Set Y1 value**.

6. Select **Calculate Heat loss** from the drop-down box in the **Diagram** frame.

7. Type **0.2** in the MIN textbox, **0.5** in the MAX textbox and **0.02** in the STEP textbox. This means that the insulation thickness varies from 0.2 m to 0.5 m and is calculated every 0.02 m.

8. Press **Diagram**. Notice that the calculation time may be significant on slow computers.

9. Press **Diagram** again in the **Diagram table** window. The final diagram should look similar to Figure 15. The theoretical optimum insulation thickness is now roughly 33 cm.
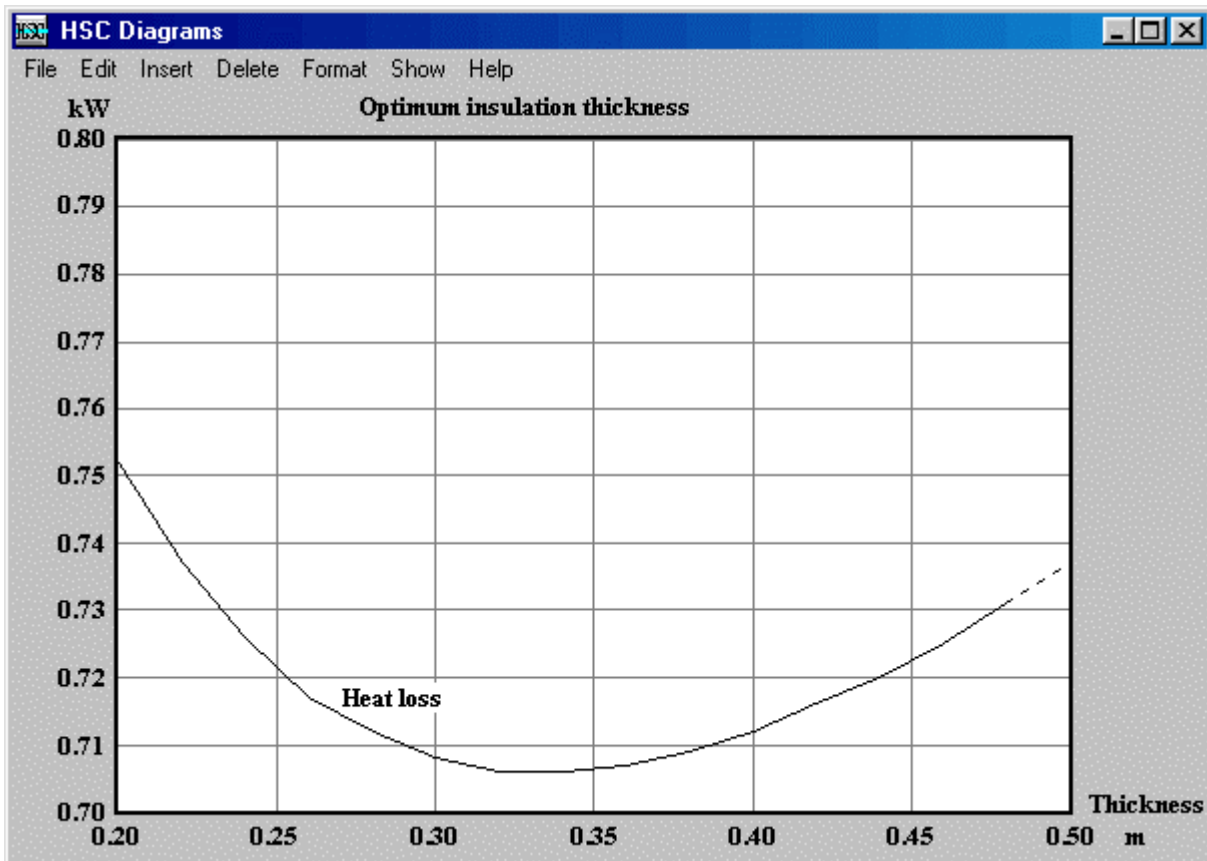
Figure 15: *Diagram showing the theoretical optimum side wall insulation thickness for a cylindrical hot water tank.*

12.3.11 Limitations

The current version of Heat Loss has some limitations, some of which are listed below.

- The maximum number of *calculation* sheets for the wall and the sphere is ten, for the cube four and the cylinder three. It is possible to insert up to 255 *own* sheets.

- Inaccuracy increases with thick walls for the cube and cylinder, since the roof and bottom layers are "stretched" to overlap the walls. Please use surface columns only if the outer surface temperature is known, see examples Reactor1.HTR and Reactor2.HTR.

- If minimum and/or maximum temperatures are not entered into the database, or directly on the sheet on rows 17 and/or 18, then the extrapolated heat transfer coefficients (k, h_c and h_r) may be inaccurate.

- The convection correlations are not valid for all ranges and the results cannot be trusted outside these ranges. Detailed specifications of the valid ranges are given in Chapter 12.4.

- Inaccuracy increases with convection for small geometries.

- Forced convection cannot be used for internal calculations (gas/liquid to surface) with a cube, cylinder and sphere, since the correlations are only valid for forced

external convection. Instead the heat convection coefficient h_c must be specified manually or using the **Function** sheet in the **Conduction Database**.

- If only surface columns are given for a cube, cylinder or sphere, then *external* convection is assumed.

- If the speed of a fluid is very low and the **Table** sheet is selected as input, the combined free and forced convection plays an important role, however this is not taken into account in this module.

- Radiation from a surface to the surroundings (or vice versa): the surface is considered gray and diffuse, that is $\alpha(T) = \varepsilon(T)$ only, this is however a valid approximation for most cases.

- Radiation emissivities for surfaces in the database are given as either normal (n) or hemispherical (h).

- The minimum temperature is –200 °C and the maximum is 8000 °C, however data for extreme temperatures such as these are seldom available.

- Sometimes the program is not able to iterate the answer correctly. If this happens try using a different starting heat loss (better starting approximation) and recalculate. Make sure that the minimum or maximum temperature is not exceeded.

- When calculating temperature profiles it is advised to fix the outer (cooler) temperature and let the program calculate the inner temperature. The reverse selection may easily lead to temperatures lower than 0 K if the heat loss specified is too high.

12.4.   Basic Theory behind Heat Transfer

This chapter explains the basic theory of heat transfer used by the module. The equations and theory given are utilized within the program.

The *total heat flow* in one dimension (x) is

$$q_x = q_x^{''} A,$$ [1]

where $q_x^{''}$ is the heat flux and A is the unit area. It is often practical to use an analogy between heat transfer and Ohm's law in electricity. The *thermal resistance* is defined as

$$R = \frac{T_1 - T_2}{q_x},$$ [2]

where T_1 and T_2 are the temperature points and q_x is the heat flow. The *thermal conductance* is then

$$G = \frac{1}{R},$$ [3]

where R is the thermal resistance.

Time-dependent heat flows, where $q_x = q(x, t)$, and *steady-state* non-time-dependent heat flows $q_x = q(x)$ are two basic ways of identifying heat transfer problems. This program is concerned only with steady-state non-time-dependent conditions, which means that the condition is valid for infinite t.

A number of dimensionless parameters are used in this chapter. Some of them are only material-specific and can be listed in a table, while others are geometry-specific or directly related. Equations [4] to [7] show the most important ones.

The *thermal diffusivity* is defined as

$$\alpha = \frac{k}{c_p \rho},$$ [4]

where k is the thermal conductivity, c_p is the heat capacity at constant pressure and ρ is the density.

The *kinematic viscosity* is defined as

$$v = \frac{\mu}{\rho},$$ [5]

where μ is the dynamic viscosity.

Outotec

HSC Chemistry® 6.0

12 - 26

Peter Bjorklund

August 10, 2006

06120-ORC-T

The *Prandtl number* describes the ratio of the momentum and thermal diffusivities. This is defined as

$$\mathrm{Pr} = \frac{\nu}{\alpha},$$ [6]

where ν is the kinematic viscosity and α is the thermal diffusivity.

The *thermal expansion coefficient* is defined as

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \approx -\frac{1}{\rho}\frac{\Delta \rho}{\Delta T},$$ [7]

where p denotes the derivative at constant pressure.

In order to calculate the heat flux, it must be separated into the three main forms: *conduction*, *convection* and *radiation*. A more detailed description of these forms will be given in the following chapters.

12.4.1   Conduction

Heat transfer due to conduction occurs between points inside a material or materials connected to each other. Thermal conductivity is very dependent on the phase the material is in and on the temperature of the material/materials. Therefore accurate calculations with a simple non-iterative formula are sometimes impossible. The use of a numerical technique such as an element method can be applied in order to achieve more accurate results.

The conduction heat flux for one dimension (Fourier's law) is calculated as

$$q_x^{''} = -k \frac{dT}{dx},$$ [8]

where dT/dx is the temperature derivative in x-direction. The function $k = k(T)$ is generally not expressed the same way as the heat capacity function $c_p = c_p(T)$, which is a fitted equation in other parts of HSC, i.e. the Kelley equation. Instead the values of k are known at certain temperature points and linear interpolation and extrapolation may be used for temperatures outside these points. When calculating the heat flux (or flow) the distance between the two temperature points is divided into a *grid*. Hence we can calculate the heat flux by using the following approximate equation that calculates the average heat flux through a layer

$$q_x^{''} = \frac{-\sum_{n=1}^{m} k_n \cdot \left(T_{n+1/2} - T_{n-1/2}\right)}{m \cdot \sum_{n=1}^{m} \Delta x_n},$$ [9]

where $k_n = k_n(T_n)$ is the heat conduction coefficient at T_n (middle of the grid), m is a grid step (the amount of steps the distance x is divided into), n is the point in the middle of one grid step, $T_{n+1/2}$ is the temperature point between grid n and grid n+1, $T_{n-1/2}$ is the temperature point between grid n and grid n-1 and Δx_n is the thickness of the grid.

In order to be able to calculate other geometries, the *shape factor* S in the total heat rate equation $q = q_x^{''} A = Sk\Delta T$ is defined for different geometries according to equations [10] to [12].

For one-dimensional plane *walls* and for *cube* walls, S is defined as

$$S = A / x,$$ [10]

where A is the unit area for the layer and x is the thickness of the layer.

For c*ylindrical walls* (cylindrical coordinates), S is defined as

$$S = \frac{2\pi h}{\ln(x_o / x_i)},$$ [11]

Peter Bjorklund
August 10, 2006   06120-ORC-T

where h is the height of the cylinder, x_o the outer radius of the layer and x_i the inner radius of the layer.

For *spherical walls* (spherical coordinates), S is defined as

$$S = \frac{4\pi x_i x_o}{x_o - x_i} \cdot$$

[12]

Outotec

HSC Chemistry® 6.0

12 - 29

Peter Bjorklund

August 10, 2006

06120-ORC-T

12.4.2   Convection

Heat transfer due to convection occurs between two points, where one is on a surface and the other in a fluid/gas. Convection cannot normally be solved mathematically except for some laminar cases. Therefore convection calculations are mostly based on empirical equations or correlations and the uncertainty, or the margin of error in these calculations can be as high as ±20%. In the literature these correlations can also vary and the validity of the result is mostly limited to some range of one or more thermophysical properties of the fluid/gas. The correlation equations used in the program are taken from references /1/ and /2/.

The heat flux due to convection is calculated as

$$q'' = h_c (T_s - T_\infty),$$ [13]

where h_c is the convection coefficient, T_s is the surface temperature and T_∞ is the fluid/gas temperature. The mathematical models for h_c, based on experimental data, are given in dimensionless form using the Nusselt number, which is defined as

$$\overline{Nu}_L = \frac{h_c L}{k},$$ [14]

where L is the *characteristic length* for the prescribed geometry.

The Nusselt number can be related through empirical data to other properties of the convective gas/fluid. These properties are normally temperature and pressure dependent, hence the film temperature, $T_f = (T_s + T_\infty)/2$, should be used when determining these properties. The task is then simply to describe the problem as accurately as possible and to select the appropriate correlation. Using equation [14] and the appropriate correlation equation the value of h_c can be calculated. The correlations depend on whether *forced* or *free (natural) convection* is studied. In forced convection the motion of the fluid is due to an external pressure gradient caused by a fan or a pump. In free convection the fluid motion is due to buoyancy forces only, such as gravitational or centrifugal forces. In some forced convection cases when the speed of the fluid is low there is a mixture of forced and free convection called *mixed convection*, however this is not taken into account in this work. See *3.11 Limitations* for a more detailed description of when mixed convection conditions are noticeable.

Convection can also be subdivided into *internal* and *external* flow, which means that the fluid is either contained inside an enclosure or flowing freely outside a geometry. Flow in pipes is an example of a forced internal flow that has been studied thoroughly. Forced internal flow is more difficult to examine due to, for instance, the influence of centrifugal forces inside reactors. The convection coefficient are also dependent on the way the fluid is put into motion, for example, different types of propellers give different coefficients. In some cases simple experimental correlations for the convection coefficient in the form $h_c = h_c(u_\infty)$ may be used. External flow has also been studied extensively and listed below are the different correlations, which may be used for different cases. Note that for a plane wall the internal convection is equivalent to the external convection.

Free convection

The correlation describing the nature of the flow for free convection is called the *Rayleigh number* and is defined according to

$$Ra_L = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha},$$ [15]

where g is the acceleration due to gravity and β the thermal expansion coefficient.

Sometimes the *Grashof number,* which describes the ratio of buoyancy forces to viscous forces, is used in correlations and is defined as

$$Gr_L = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2} = \frac{Ra_L}{Pr}$$ [16]

A description of how to calculate the free convection Nusselt number, defined in equation 14, for different geometries is explained below.

Wall, vertical position $\theta_V = 0°$ /1/:

- Surface:
  - Characteristic length: L = z
  - Laminar flow ($Ra_L < 10^9$):

$$\overline{Nu}_L = 0.68 + \frac{0.670 Ra_L^{1/4}}{\left[1 + (0.492/Pr)^{9/16}\right]^{4/9}}$$ [17]

  - Turbulent flow ($Ra_L \geq 10^9$):

$$\overline{Nu}_L = \left\{ 0.825 + \frac{0.387\, Ra_L^{1/6}}{\left[1 + (0.492/Pr)^{9/16}\right]^{8/27}} \right\}^2$$ [18]

- Enclosure:
  - Characteristic length: L = thickness of wall enclosure
  - H = z (height of enclosure)
  - H/L ≤ 2:

$$\overline{Nu}_L = 0.18\left(\frac{Pr}{0.2 + Pr}Ra_L\right)^{0.29}$$ [19]

    - Valid when:
      1 < H/L < 2
      $10^{-3} < Pr < 10^5$
      $10^3 < (Ra_L Pr)/(0.2+Pr)$

  - 2 < H/L < 10:

$$\overline{Nu}_L = 0.22\left(\frac{Pr}{0.2 + Pr}Ra_L\right)^{0.28}\left(\frac{H}{L}\right)^{-1/4}$$ [20]

    - Valid when:
      2 < H/L < 10

$$Pr < 10^5$$
$$10^3 < Ra_L < 10^{10}$$

- H/L ≥ 10:

$$\overline{Nu}_L = 0.42 Ra_L^{1/4}\, Pr^{0.012}\left(\frac{H}{L}\right)^{-0.3}$$
[21]

  - Valid when:
    $$10 < H/L < 40$$
    $$1 < Pr < 2\cdot10^4$$
    $$10^4 < Ra_L < 10^7$$

Wall, horizontal position $\theta_V = 90°$ /1/, /2/:

- Surface:
  - Characteristic length: L = A/P, i.e. the surface area divided by the perimeter
  - Hot upper surface or cold lower surface:
    $$\overline{Nu}_L = 0.27 Ra_L^{1/4}$$
    [22]
  - Cold upper surface or hot upper surface:
    - $Ra_L < 10^7$:
      $$\overline{Nu}_L = 0.54 Ra_L^{1/4}$$
      [23]

    - $Ra_L \geq 10^7$:
      $$\overline{Nu}_L = 0.15 Ra_L^{1/3}$$
      [24]
- Enclosure:
  - Characteristic length: L = thickness of wall enclosure
  - Hot lower surface:
    - $Ra_L \leq 1708$:
      $$\overline{Nu}_L = 1 \,(\text{pure conduction})$$
    - $Ra_L > 1708$:
      $$\overline{Nu}_L = 0.069 Ra_L^{1/3}\, Pr^{0.074}$$
      [25]
      - Valid when:
        $$3\cdot10^5 < Ra_L < 7\cdot10^9$$
  - Cold lower surface:
    - $$\overline{Nu}_L = 1\,(\text{pure conduction})$$

Cube /1/:

- Surface:
  - Internal flow:
    - Characteristic length: L = z_i
    - Nusselt number according to equation [17] or [18] for all walls
    - The flow is assumed to cool down at the walls (downflow), thus creating a circulating flow with an upflow through the center of the cube.
    - Not valid for small cubes
  - External flow:
    - Cube walls:
      - Characteristic length: L = z_o

- Nusselt number according to equation [17] or [18]
  - Roof and bottom:
    - Characteristic length: L = A/P, i.e. the roof/bottom surface area divided by the perimeter
    - Nu_{roof} and Nu_{bottom} according to equation [22], [23] or [24]
- Enclosure:
  - Same as for wall depending on horizontal or vertical cube enclosure

Cylinder, vertical $\theta_v = 0°$ /1/:

- Surface:
  - Internal flow:
    - Characteristic length: $L = z_i$
    - Nusselt number according to equation [17] or [18] for wall, roof and bottom
    - The flow is assumed to cool down at the walls (downflow), thus creating a circulating flow with an upflow through the center of the cylinder
    - Not valid for small cylinders
  - External flow:
    - Cylinder wall:
      - Characteristic length: $L = z_o$
      - Nusselt number according to equation [17] or [18]
        - Valid when:
          $$D/L \geq 35/(Ra_L/\mathrm{Pr})^{1/4}$$
    - Roof and bottom:
      - Characteristic length: L = A/P = D/4, i.e. the surface area divided by the perimeter
      - Nu_{wall} according to equation [17] or [18]
      - Nu_{roof} and Nu_{bottom} according to equation [22], [23] or [24]
- Enclosure:
  - *Approximated* as vertical wall enclosure

Cylinder, horizontal $\theta_v = 90°$ /1/:

- Surface:
  - Internal flow:
    - Characteristic length: $L = D_i$
    - Nusselt number calculated according to equation [17] or [18]
    - The flow is assumed to cool down at the walls (downflow), thus creating a circulating flow with an upflow through the center of the cylinder
    - Not valid for small cylinders
  - External flow:
    - Cylinder wall:
      - Characteristic length: $L = D_o$

$$\overline{Nu}_D = \left\{ 0.60 + \frac{0.387 Ra_D^{1/6}}{\left[1 + (0.559/\mathrm{Pr})^{9/16} \right]^{8/27}} \right\}^2 \qquad [26]$$

- Valid when:
  $\mathrm{Ra_D} \leq 10^{12}$
- Roof and bottom:
  - Characteristic length: $L = r_o \sqrt{\pi}$, i.e. square with same area
  - Nu_{roof} and Nu_{bottom} according to equation [17] or [18]
- Enclosure:
  - Characteristic length L = thickness of cylinder enclosure
  - h_c calculated directly, not through the Nusselt number (Nu_L)

$$Ra_c^* = \frac{\left[ln(D_o/D_i) \right]^4}{L^3 \left(D_i^{-3/5} + D_o^{-3/5} \right)^5} Ra_L \qquad [27]$$

- $Ra_c^* < 100$:

$$h_c = \frac{k}{ln(D_o/D_i) \cdot D_i/2} \qquad [28]$$

- $Ra_c^* \geq 100$:

$$k_{eff} = 0.386 \left(\frac{\mathrm{Pr}}{0.861 + \mathrm{Pr}} \right)^{1/4} \left(Ra_c^* \right)^{1/4} \cdot k \qquad [29]$$

$$h_c = \frac{k_{eff}}{ln(D_o/D_i) \cdot D_i/2} \qquad [30]$$

- valid when:
  $10^2 \leq \mathrm{Ra_c^*} \leq 10^7$

Sphere /1/:

- Surface:
  - Internal flow:
    - Characteristic length: $L = z_i$
    - Nusselt number according to equation [17] or [18]
    - The flow is assumed to cool down at the walls (downflow), thus creating a circulating flow with an upflow through the center of the sphere
    - Not valid for small spheres
  - External flow:
    - Characteristic length: $L = D_o$

$$\overline{Nu}_D = 2 + \frac{0.589 Ra_D^{1/4}}{\left[1 + (0.469/\mathrm{Pr})^{9/16} \right]^{4/9}} \qquad [31]$$

  - Valid when:
    $\mathrm{Ra_D} \leq 10^{11}$
    $\mathrm{Pr} \geq 0.7$
- Enclosure:
  - Characteristic length: L = thickness of the sphere enclosure
  - h_c calculated directly, not through the Nusselt number (Nu_L)

$$Ra_s^* = \frac{L}{(D_o D_i)^4} \frac{Ra_L}{\left(D_i^{-7/5} + D_o^{-7/5}\right)^5} \qquad [32]$$

- $Ra_s^* < 100$:

$$h_c = k\pi \frac{D_i D_o}{L} \qquad [33]$$

- $Ra_s^* \geq 100$:

$$k_{eff} = 0.74 \left(\frac{Pr}{0.861 + Pr}\right)^{1/4} \left(Ra_s^*\right)^{1/4} \cdot k \qquad [34]$$

$$h_c = k_{eff} \pi \frac{D_i D_o}{L} \qquad [35]$$

- Valid when:
  $10^2 \leq Ra_s^* \leq 10^4$

Outotec

HSC Chemistry® 6.0

12 - 35

Peter Bjorklund

August 10, 2006

06120-ORC-T

Forced convection

Forced convection is here assumed to be *external* only. The correlation number describing the nature of the flow for forced convection is called the *Reynolds number*, which describes the ratio of inertia forces to viscous forces of a flow and is defined as

$$\text{Re}_L = \frac{u_\infty L}{\nu} \qquad [36]$$

where u_∞ is the speed of the fluid/gas. Note that the direction of the flow is assumed to be *horizontal* in this program and that forced convection inside enclosures is not taken into consideration.

Wall /1/:

- Laminar flow, $\text{Re}_L \leq 5 \cdot 10^5$:
$$\overline{Nu}_L = 0.664\,\text{Re}_L^{1/2}\,\text{Pr}^{1/3} \qquad [37]$$
  - Valid when:
    $\text{Pr} \geq 0.6$
- Turbulent flow (flow separation), $\text{Re}_L \geq 5 \cdot 10^5$:
$$\overline{Nu}_L = (0.037\,\text{Re}_L^{4/5} - 871)\,\text{Pr}^{1/3} \qquad [38]$$
  - Valid when:
    $0.6 \leq \text{Pr} \leq 60$
    $5 \cdot 10^5 \leq \text{Re}_L \leq 10^8$

Cube /1/:

- Tangential horizontal flow on *all* sides assumed
- Cube walls:
  - Characteristic length front and back wall: $L = x_o$
  - Characteristic length left and right wall: $L = y_o$
  - Nusselt number calculated as [37] or [38]
- Roof and bottom:
  - Characteristic length: $L = y_o$
  - Nusselt number calculated as [37] or [38]

Cylinder /1/:

- Cylinder wall:
  - Characteristic length: $L = D_o$

$$\overline{Nu}_D = 0.3 + \frac{0.62\,Re_D^{1/2}\,Pr^{1/3}}{\left[1 + (0.4/Pr)^{2/3}\right]^{1/4}} \left[1 + \left(\frac{Re_D}{282000}\right)^{5/8}\right]^{4/5} \qquad [39]$$

  - Valid when:
    $\text{Re}_D \cdot \text{Pr} \geq 0.2$
- Roof and bottom:

- Characteristic length: $L = r_o \sqrt{\pi}$, i.e. square with same area
- Nusselt number calculated as [37] or [38]

Sphere /1/, /2/:

- Characteristic length: $L = D_O$

$$\overline{Nu}_D = 2 + (0.4\,\mathrm{Re}_D^{1/2} + 0.06\,\mathrm{Re}_D^{2/3})\,\mathrm{Pr}^{0.4}\left(\frac{\mu_\infty}{\mu_s}\right)^{1/4} ,$$ [40]

where μ_∞ is the dynamic viscosity at the fluid/gas temperature and μ_s is the dynamic viscosity at the surface temperature.
- valid when:

$0.71 \leq \mathrm{Pr} \leq 380$

$3.5 \leq \mathrm{Re}_D \leq 7.6 \cdot 10^4$

$1.0 \leq (\mu_\infty/\mu_s) \leq 3.2$

12.4.3   Radiation

Heat transfer due to radiation occurs in the range of approximately 0.4 μm to 1000 μm of the electromagnetic wavelength spectrum /3/. This spectrum includes both visible light as well as infrared radiation. Radiation heat transfer between two points occurs when waves are *emitted* at one point and *absorbed* at another. Sometimes the wave is *reflected* or *transmitted* and thus there is no radiation heat transfer between these two points. However, the wave can be absorbed at another point thus creating a heat flow between these new points instead. Since radiation consists of electromagnetic waves it is therefore not dependent on the medium, in fact radiation heat transfer through a vacuum is higher than through other mediums since almost no radiation is absorbed there. Radiation plays a significant role at high temperatures and radiation heat transfer is in this instance much higher than convection heat transfer. This can be seen from equations [41], [44] and [52], with temperatures raised to a power of four.

Radiation heat transfer can be subdivided into three types: S*urface radiation*, *gas radiation* and *combined gas and particle radiation*. These are described more closely below.

Surface radiation

Surface radiation means that the heat flux is due to a surface (at temperature T_s) that radiates to the outside environment (at temperature T_∞), which is assumed to be very large compared to the radiating surface. A typical case could be the walls of a big room. The net heat flux is calculated according to

$$q'' = \varepsilon_s \sigma \left(T_s^4 - T_\infty^4 \right), \tag{41}$$

where ε_s is the surface emissivity, which is a function of the surface temperature, $\varepsilon_s = \varepsilon_s (T_s)$ and σ is the Stefan-Boltzmann constant. The surface is assumed to be gray, which means that the surface absorptivity is equal to the surface emissivity $(\alpha_s(T) = \varepsilon_s (T))$.

For easier comparison with the convection heat rate, we can define the heat radiation coefficient as

$$h_r = \varepsilon_s \sigma \left(T_s + T_\infty \right)\left(T_s^2 + T_\infty^2 \right) \tag{42}$$

and by using equations [41] and [42] the heat rate can be expressed as

$$q'' = h_r \left(T_s - T_\infty \right) \tag{43}$$

which is of the same form as equation [13]. The surface emissivity can be found from tables in the literature. The *normal emissivity* (ε_n) or the *hemispherical* or *total emissivity* (ε_h) may be listed depending on the material. The normal emissivity is the normal directional emissivity while the hemispherical emissivity is the averaged value for all solid angles passing through a hemisphere centered over the surface element /3/.

Gas radiation

The heat flux due to radiation from a gas to a surface is calculated as /4/

$$q'' = \frac{\varepsilon_s + 1}{2}\sigma\left(\varepsilon_g T_g^4 - \alpha_g T_s^4\right), \qquad\qquad [44]$$

where ε_s is the surface emissivity, $\varepsilon_g = \varepsilon_g(T_g)$ is the gas emissivity at the *gas* temperature and $\alpha_g = \alpha_g(T_g, T_s)$ is the gas absorptivity as a function of both the *gas and surface* temperatures. It is natural that α_g also depends on T_s as this defines the spectrum of incoming radiation and this is clear because T_g defines the state of the gas and therefore its thermal properties. The surface is also here assumed to be gray. The coefficient $(\varepsilon_s+1)/2$ is an approximation for the effective emissivity of the solid.

The heat radiation coefficient is now

$$h_r = \frac{(\varepsilon_s + 1)\sigma\left(\varepsilon_g T_g^4 - \alpha_g T_s^4\right)}{2(T_g - T_s)}. \qquad\qquad [45]$$

In order to calculate ε_g and α_g the *exponential wide band model* proposed in /5/ can be used. This model has been optimized and made more efficient computationally in /6/. The model can treat mixtures containing H_2O, CO_2, CO, NO, SO_2 and CH_4 in, for example, a non-radiating nitrogen gas. The model also takes into account the pressure and the optical depth of the geometry. The gas emissivity function is

$$\varepsilon_g = \varepsilon_g(T_g, p, L, x_{H2O}, x_{CO2}, x_{CO}, x_{NO}, x_{SO2}, x_{CH4}), \qquad\qquad [46]$$

where p is the pressure, L is the optical depth and x is the molar fraction of the individual gas species. Note that the sum of the radiating gases can be smaller than one, $\sum x_{sp} \leq 1$, since the rest of the mixture can consist of non-radiating gases.

This model is applicable for the temperature range T = 300 K to 2500-3000 K and the pressure range p = 0.5 to 20 bar. The optical depth L depends on the geometry and is listed in the following table for the most common geometries /7/. All surfaces are assumed to be able to absorb radiation.

Geometry	Characteristic dimension	Optical depth (L)
1. Sphere	Diameter (D)	0.63D
2.1 Cylinder (h = 0.5D)	Diameter (D)	0.45D
2.2 Cylinder (h = D)	Diameter (D)	0.6D
2.3 Cylinder (h = 2D)	Diameter (D)	0.73D
3.1 Cube (1x1x1)	Any side (x)	0.6x
3.2 Cube (1x1x4)	Shortest side (x)	0.81x
3.3 Cube (1x2x6)	Shortest side (x)	1.06x

Table 1: *Examples of optical depths for simple geometries*

For dimensions not listed in Table 1 the optical depth coefficient can be interpolated or extrapolated. A simple example is:

Calculate the optical depth for a cube with the dimensions 1x4x7.
1. Extrapolated as a 1x1x7 cube using geometries 3.1 and 3.2 gives
   L_{1x1x7} = 0.6+(0.81-0.6)·[(7-1)/(4-1)] = 1.02
2. Extrapolated as a 1x2.5x7 cube using geometries 3.2 and 3.3 gives
   $L_{1x2.5x7}$ = 0.81+(1.06-0.81) ·[(2.5-1)/(2-1)] = 1.185.
3. These two results can then be used again to extrapolate into the 1x4x7 cube which gives L_{1x4x7} = 1.02+(1.185-1.02)·[(4-1)/(2.5-1)] = 1.35. This is the answer since the shortest side is x = 1.

The gas absorptivity at the surface temperature can be calculated using the same model if two temperature correction factors are introduced. The function then becomes

$$\alpha_g = \varepsilon_g (T_g, p, L \cdot \left(\frac{T_s}{T_g}\right)^{1.5}, x_{H2O}, x_{CO2}, x_{CO}, x_{NO}, x_{SO2}, x_{CH4}) \cdot \left(\frac{T_g}{T_s}\right)^{0.5} \qquad [47]$$

and as seen from the correction factors, the surface temperature T_s is now also needed as an input. For further information and detail on this model references /5/ and /6/ should be consulted. The gas radiation calculation code used by HSC is based on code made by *Tapio Ahokaine*n.

Combined gas and particle radiation

A particle cloud emissivity can be calculated when the mean size of the particles and the particle cloud geometry are known, according to /4/

$$\varepsilon_c = 1 - e^{-\varepsilon_p n_p L A_p} , \qquad [48]$$

where ε_p is the emissivity of a single particle, n_p is the number of particles per unit volume of cloud, L is the thickness of the cloud and A_p is the average cross-sectional area of the particle. If the particles in the cloud are not uniform in size, then the surface mean diameter can be used according to

$$A = \frac{\pi d_s^2}{4} = \frac{\pi}{4} \frac{\sum_{i=1}^{n} n_i d_i^2}{\sum_{i=1}^{n} n_i} , \qquad [49]$$

where d_s is the surface mean diameter and n_i is the number of particles of the same diameter d_i. The total gas and particle cloud emissivity can then be approximated as /7/

$$\varepsilon_{g+c} = \varepsilon_g + \varepsilon_c - \varepsilon_g \varepsilon_c , \qquad [50]$$

where ε_c is the particle cloud emissivity and ε_g is the gas emissivity calculated according to the model behind equation [46]. The total gas and particle cloud absorptivity can be approximated as

$$\alpha_{g+c} = \alpha_g + \varepsilon_c - \alpha_g \varepsilon_c , \qquad [51]$$

where α_g is the gas absorptivity calculated according to the model behind equation [47].

Finally, the heat flux due to radiation from a gas and particle cloud to a surface is then calculated according to /7/

$$q'' = \frac{\varepsilon_s}{\alpha_{g+c} + \varepsilon_s - \alpha_{g+c}\varepsilon_s} \sigma\left(\varepsilon_{g+c}T_g^4 - \alpha_{g+c}T_s^4\right)$$

[52]

and the heat radiation coefficient as

$$h_r = \frac{\varepsilon_s \sigma\left(\varepsilon_{g+c}T_g^4 - \alpha_{g+c}T_s^4\right)}{\left(\alpha_{g+c} + \varepsilon_s - \alpha_{g+c}\varepsilon_s\right)\left(T_g - T_s\right)}.$$

[53]

References

1. Incropera, F.P. & DeWitt, D.P.: Fundamentals of Heat and Mass Transfer, Fourth Edition. John Wiley & Sons, New York, 1996. ISBN 0-471-30460-3.

2. Taine J. & Petit J-P.: Heat Transfer. Prentice Hall, Hempstead, 1993. ISBN 0-13-387994-1.

3. Siegel R. & Howell J.R.: Thermal Radiation Heat Transfer, Second Edition. Hemisphere Publishing Corporation, 1972. ISBN 0-07-057316-6.

4. Themelis N.J.: Transport and Chemical Rate Phenomena. Gordon and Breach Science Publishers SA, 1995. ISBN 2-88449-127-9.

5. Edwards, D.K., Balakrishnan A. Thermal Radiation by Combustion Gases. Int. J. Heat Mass Transfer, vol. 16, pp. 25-40, 1973.

6. Lallemant N. & Weber R.: A computationally efficient procedure for calculating gas radiative properties using the exponential wide band model. Int. J. Heat Mass Transfer, vol. 39, No.15, pp. 3273-3286, 1996.

7. VDI Heat Atlas. Düsseldorf VDI-Verlag, 1993.

8. Haar L. & Gallagher J.S. & Kell G.S.: NBS/NRC Steam Tables: Thermodynamic and Transport Properties and Computer Programs for Vapor and Liquid States of Water in SI Units. Hemisphere Publishing Corporation, 1984. ISBN 0-89116-353-0.

9. Jokilaakso A.: Virtaustekniikan, lämmönsiirron ja aineensiirron perusteet. Technical University of Helsinki, Otakustantamo, 1987. ISBN 951-672-015-3.

10. Edwards, D.K. Gas radiation properties. Heat Exhanger Design Handbook, No. 5 Physical Properties. VDI-Verlag GmbH, Hemisphere Publishing Corp. 1983 (about 250 p.)