FLOWNEX® SIMULATION ENVIRONMENT

CASE STUDY

FOULING FACTORS IN FLOWNEX HEAT TRANSFER MODELS

This case study demonstrates the implementation of two methods to account for thermal fouling factors in heat transfer piping and tubing in a simple way.

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Challenge:

The main challenge is the incorporation of thermal fouling factors in heat transfer applications such as fired heaters and heat exchangers.

Benefits:

Flownex® allows the user to model heat transfer through piping walls in a simple manner. However the effect of fouling is not incorporated. This case study offers two simple methods to account for the overall heat transfer reduction that will result from fouling. The calculation of tube wall temperatures are also investigated and the two methods compared.

Solution:

Two simple scripts have been developed and are used in conjunction with the materials library to account for the effects of fouling in Flownex® heat transfer models.

"What sets Flownex® apart from the competition is its ability to model even the temperature profiles through a multi-layered pipe wall subjected to heat transfer."

Hannes van der Walt
Principal Thermal Engineer
Gasco Pty Ltd

Introduction

Fouling can have a significant influence on heat transfer processes by reducing the actual heat transfer rate and may, therefore, need to be taken into account in some cases. In addition, fouling may also influence flow properties such as velocities and pressure drop due to changes in the coil pipe inside diameter and roughness. However this case study only focusses on the influence on heat transfer. Flownex® offers impressive heat transfer capabilities as standard,. but does not currently account for fouling in heat transfer problems. Fortunately, due to Flownex®'s scripting capabilities and extensive materials library, fouling can be integrated with relative ease.

"Two methods to account for thermal fouling are presented. Both may provide results of acceptable accuracy; however it was shown that in extreme cases with high fouling and high heat fluxes, it may be necessary to model the physical fouling layers to improve accuracy. Fortunately, Flownex® is perfectly suited to performing this task."

There are several different types of fouling that may occur in practice. Some examples are:

- Sedimentation fouling.
- Inverse solubility fouling.
- Chemical reaction fouling.
- Corrosion product fouling.
- Biological fouling.
- Combination of several of these.

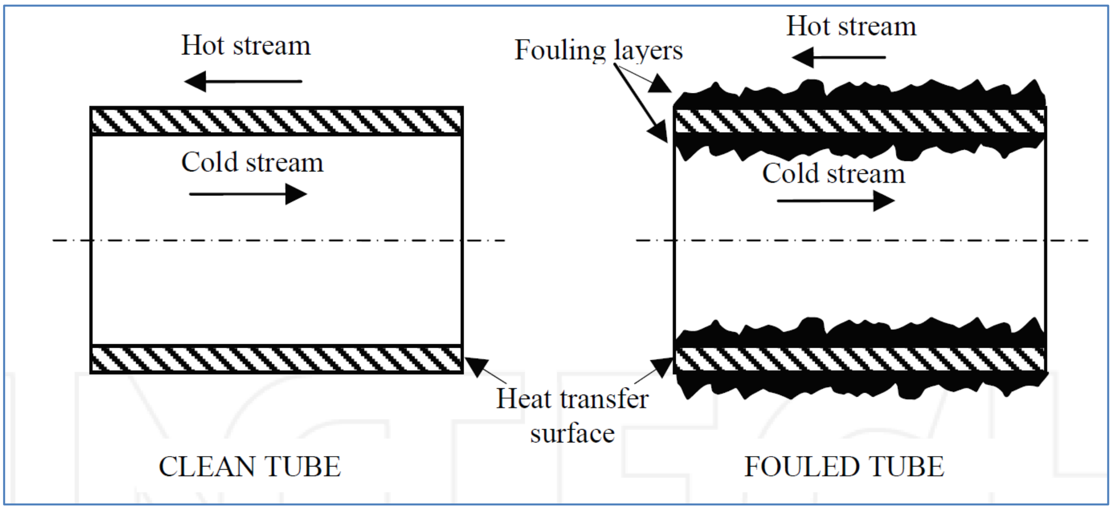

Figure 1: Fouling of heat transfer piping and tubing.

These different fouling mechanisms will result in different fouling effects on a specific heat transfer application. Engineers normally account for fouling by adding an additional thermal resistance to the heat transfer process. The magnitude of this additional thermal resistance depends on the fouling mechanism, the fluids involved, temperatures, pressures, flow velocities, etc. TEMA specifies a broad range of fouling factors to be used in tubular exchangers for example and engineers have often been using these values without further consideration. While the TEMA fouling factors are based on conservative observations in industry, much of these values originated more than half a century ago when fouling was not well understood. Therefore, designs based on these are often overly conservative and result in heat exchangers significantly larger than necessary. Aspen and HTRI, the well-known thermal rating suite software makers, are continuing to perform extensive research into the mechanisms of fouling to improve thermal calculations through the implementation of more realistic fouling resistance models.

Nevertheless, currently used fouling factors such as those from TEMA are seen as being based on conservative estimates calculated from observed effects on heat transfer equipment and are mostly not based on measurements of actual fouling layer thicknesses and chemical composition. It is not surprising then that little exists in open literature on specific foulant thicknesses and thermal properties such as conductivity.

Modelling Thermal Fouling

This case study assumes a heat transfer process which involves cylindrical surfaces such as heat transfer coil pipes or tubing used in heat exchangers or fired heaters. As with many engineering problems, there is a simple, but less accurate method to account for fouling, and then there is a more comprehensive, but more accurate approach.

The simple approach to account for thermal fouling is to calculate a reduced, equivalent "fouled" material conductivity (for the tube or coil material) which presents the same thermal resistance as the actual process. This method will necessarily result in accurate heat transfer rates, but the temperature profile through the pipe or tube wall will not be precise due to the absence of the fouled layer(s) with very low conductivity and consequently large temperature gradients, and also because the actual pipe material will have a higher conductivity, and consequently a lower temperature gradient. Furthermore, depending on the thickness of the actual fouling layer, the exposed surface area is also increased for the outer surface and decreased for the inner surface. This effect is not accounted for in the simple approach.

The more elaborate approach is to model the actual physical fouling layers, using Flownex®'s ability to model pipe layers. The actual pipe or tube material will have an unmodified actual conductivity, but the fouling layer conductivities must also be known. Since the foulant is usually of known origin (for example calcium carbonate in the case of water, or carbon in the case of flue gas), the actual physical fouling layer heat transfer may be modelled as thin layers either side of the pipe or tube wall. This, however, would imply knowledge of the thickness and the conductivity of the physical fouling layer which clearly makes this approach more complex.

Both methods will result in the same overall heat transfer rate through the pipe or tube wall, and both methods may yield very similar temperatures in the centre of the pipe or tube wall except for extreme cases. However the simple solution will not yield an entirely accurate temperature profile through the solid. This variation may or may not be important to the design engineer.

Fouling is typically accounted for in engineering calculations using a thermal resistance method based on the equivalent electrical analogy. The convection and conduction heat transfer through the fluid film, the fouling layer and the pipe material layer(s) may be modelled in terms of an electrical analogy as shown in Figure 2 below.

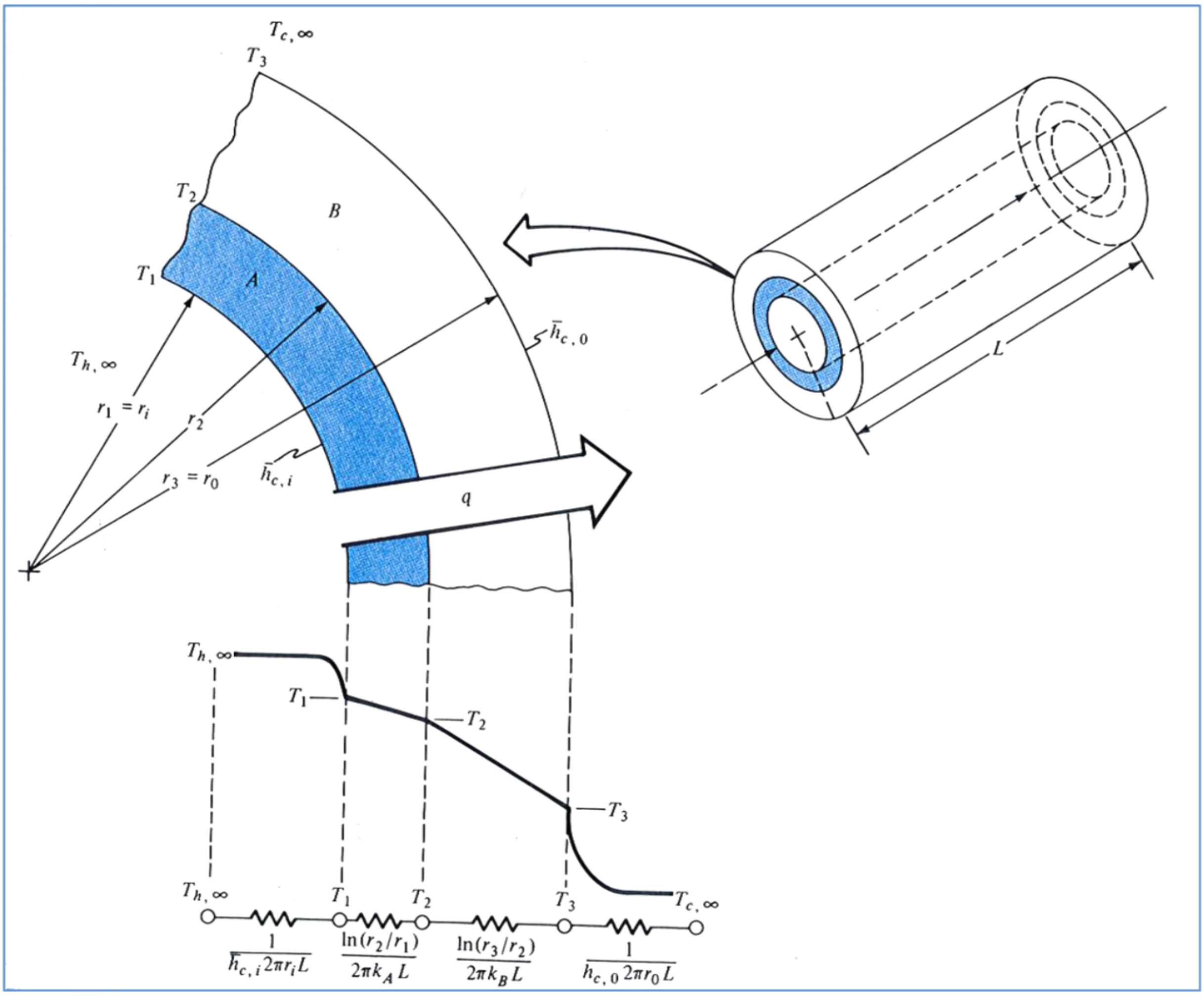

Figure 2: Typical thermal resistance model for heat transfer through a multi-layered cylinder with convection boundaries

This thermal resistance model is used in the case study to account for fouling by implementing related equations in a Flownex® script which would assign appropriate conductivity values (in the case of the simple approach) or fouling layer thicknesses (in the case of the more complex approach) to the Flownex® Composite Heat Transfer (CHT) element used in the model. The following two sections briefly develop the theory required for implementation in Flownex®'s scripting feature to achieve these objectives.

Equivalent "Fouled" Conductivity (Simple Approach)

For a general heat transfer process, the following may be written:

$$\dot{Q}=UA\Delta T_{ln} \tag{1}$$

Where:

U is the overall heat transfer coefficient [W/m^2.K].
A is the surface area subjected to heat transfer [m^2].
ΔT_{ln} is the log-mean temperature difference driving the heat transfer [K].

The same heat transfer may also be written in terms of thermal resistance as follows:

$$\dot{Q}=\frac{\Delta T_{ln}}{R} \tag{2}$$

Where:

R is the thermal resistance [K/W].

Fouling factors are commonly written in terms of thermal resistances and are simply added in series to the other thermal resistance components in the heat transfer problem as shown in Figure 2:

$$R=\frac{1}{h_i\,A_i}+\frac{R_{f,i}}{A_i}+\frac{\ln(\frac{D_o}{D_i})}{2\,\pi\,k\,L}+\frac{R_{f,o}}{A_o}+\frac{1}{h_oA_o} \tag{3}$$

Where:

h_i and h_o are the inside and outside surface convection coefficients [W/m^2.K].
A_i and A_o are the inside and outside surface areas subjected to convection heat transfer [m^2].
$R_{f,i}$ and $R_{f,o}$ are the inside and outside surface fouling factors respectively [m^2.K/W].
D_i and D_o are the inside and outside pipe diameters [m].
k is the pipe material thermal conductivity [W/m.K].
L is the length of the pipe [m].

As shown, fouling simply adds two additional thermal resistance terms to the total resistance equation. To determine an equivalent "fouled" material thermal conductivity, Eq.(3) may be written on both sides of the equality, the left side without the fouling terms but with an equivalent "fouled" thermal conductivity while the right-hand side is written with the fouling resistance terms and a "clean" actual thermal conductivity:

$$\frac{1}{h_i\,A_i}+\frac{\ln(\frac{D_o}{D_i})}{2\,\pi\,k_{fouled}L}+\frac{1}{h_oA_o}=\frac{1}{h_iA_i}+\frac{R_{f,i}}{A_i}+\frac{\ln(\frac{D_o}{D_i})}{2\,\pi k_{clean}\,L}+\frac{R_{f,o}}{A_o}+\frac{1}{h_oA_o} \tag{4}$$

Where:

k_{fouled} is the equivalent "fouled" material thermal conductivity [W/m.K].

k_{clean} is the actual material thermal conductivity [W/m.K].

Reorganising and solving for the equivalent "fouled" conductivity:

$$k_{fouled} = \frac{\ln\left(\frac{D_o}{D_i}\right)}{2\left(\frac{R_{f,i}}{D_i} + \frac{\ln(\frac{D_o}{D_i})}{2\,k_{clean}} + \frac{R_{f,o}}{D_o}\right)} \quad (5)$$

The above equation may now be used to calculate an "equivalent" material thermal conductivity to account for the additional thermal resistance due to fouling.

Modelling the Actual Fouling Layers (More Comprehensive Approach)

As explained before, fouling factors used in industry have not necessarily been derived from measurements of fouling layer thicknesses although some thickness values may be obtained from the internet.

However developing a Flownex® model to predict the pipe wall temperature gradients accurately will require the use of actual physical fouling layers with finite thicknesses. The approach is to model a fouled coil or tube using a Flownex® model with three layers; the outer and inner layers representing the fouling and the centre layer representing the actual pipe or tube wall. A two-layer pipe wall is shown in Figure 2 above.

As stated, the actual thickness of the fouling layer is not normally known but can be calculated based on knowledge of the fouling resistance (factor) and a known value or a good estimate of the foulant conductivity. Fouling layers are usually quite thin and should not have a noticeable influence on the flow through or over the pipes or tubes. However, significant temperature gradients may exist across them, and this is the area of interest from a heat transfer point of view.

With a known fouling factor as specified for Eq.(3), together with a known foulant and thus a known or estimated thermal conductivity for the fouling layer, the thickness can be calculated. This can be done by equating the fouling resistance on the left in the following equation to the resistance presented by an equivalent solid cylindrical fouling layer as shown by the right-hand term:

$$\frac{R_f}{A} = \frac{\ln\left(\frac{D_o}{D_i}\right)}{(2\,\pi\,k\,L)} \quad (6)$$

Noting that the diameters in the equation above relate to fouling layer and not the pipe or tube wall in this instance, they may be written in terms of the fouling laying thickness t. Inside and outside fouling thickness may then be written as:

$$\frac{R_{f,i}}{\pi D_i L} = \frac{\ln\left(\frac{D_i}{D_i - 2t}\right)}{2 \pi k L} \quad (7)$$

and similarly:

$$\frac{R_{f,o}}{\pi D_o L} = \frac{\ln\left(\frac{D_o + 2t}{D_o}\right)}{2 \pi k L} \quad (8)$$

Solving for the fouling thicknesses, it can be shown that:

$$t_i = \frac{D_i}{2}\left[1 - e^{-\left(\frac{2kR_{f,i}}{D_i}\right)}\right] \quad (9)$$

$$t_o = \frac{D_o}{2}\left[e^{\left(\frac{2kR_{f,o}}{D_o}\right)} - 1\right] \quad (10)$$

Where:

t_i is the inside fouling layer thickness.

t_o is the outside fouling layer thickness.

With a given fouling factor and known values or best estimates of the foulant conductivity, the above equations may be used to calculate a fouling layer thickness that will present the same thermal resistance as the given fouling factor. Eq.(9) and Eq.(10) may be implemented in a Flownex® script to assist with the calculation of the inner and outer fouling layer thicknesses.

Typical Fouling Factors

Some common fouling factors used in the industry are listed below. Several comprehensive sources also exist on the internet such as

http://www.engineeringpage.com/technology/thermal/fouling_factors.html
http://www.wlv.com/wp-content/uploads/2014/06/databook/ch1_6.pdf

It is shown that common fouling factors range from 9E-5 to 1.7E-3. This represents quite a large range and clearly can have a significant influence on heat transfer equipment performance.

Table 1: Typical fouling factors used in industry

Foulant	Fouling Factor	Foulant	Fouling Factor
	[m^2.K/W]		[m^2.K/W]
Acid gas (min)	0.00035	Heavy fuel oil	0.00088
Acid gas (max)	0.00053	Hydraulic oil	0.00018
Asphalt	0.00176	Hydrogen	0.00176
Carbon dioxide vapour	0.00018	Industrial air	0.0004
Caustics	0.00035	Kerosene (min)	0.00035
Compressed air	0.00035	Kerosene (max)	0.00053
Crude oil (dry, min)	0.00035	Natural gas	0.00018
Crude oil (dry, max)	0.00088	Natural gas flue gas	0.00088
Crude oil (wet, min)	0.00035	Nitrogen	0.00009
Crude oil (wet, max)	0.00123	Refrigerant liquid	0.0002
Engine exhaust	0.00176	Salts	0.00009
Fuel oil (min)	0.00035	Steam (clean)	0.00009
Fuel oil (max)	0.0009	Treated boiler feed water	0.0002
Glycols (MEG, DEG, TEG)	0.00035	Vegetable oils	0.00053
Heat transfer oil	0.00018	Quenching oil	0.0007

Modelling Heat Transfer With Fouling Through Pipe Walls In Flownex®

Implementing the two different approaches to modelling fouling in Flownex® requires an understanding of the Flownex® Composite Heat Transfer (CHT) element. When connected to a pipe element, the CHT element allows the user to specify the pipe wall geometry (thickness) or to obtain it from the connected pipe element. The latter approach is often easier and is used in this case study. Furthermore, Flownex® gives the user the ability to specify the number of nodes used through the pipe wall. This offers the possibility to determine temperatures on the pipe surfaces and at specific positions inside the pipe wall. For steady state calculations, the temperature gradient through a solid of uniform conductivity is constant, i.e. the temperature distribution is linear, so only the surface temperatures are required to determine the temperature gradient. For transients, however, more nodes are needed as the temperature distribution is non-linear.

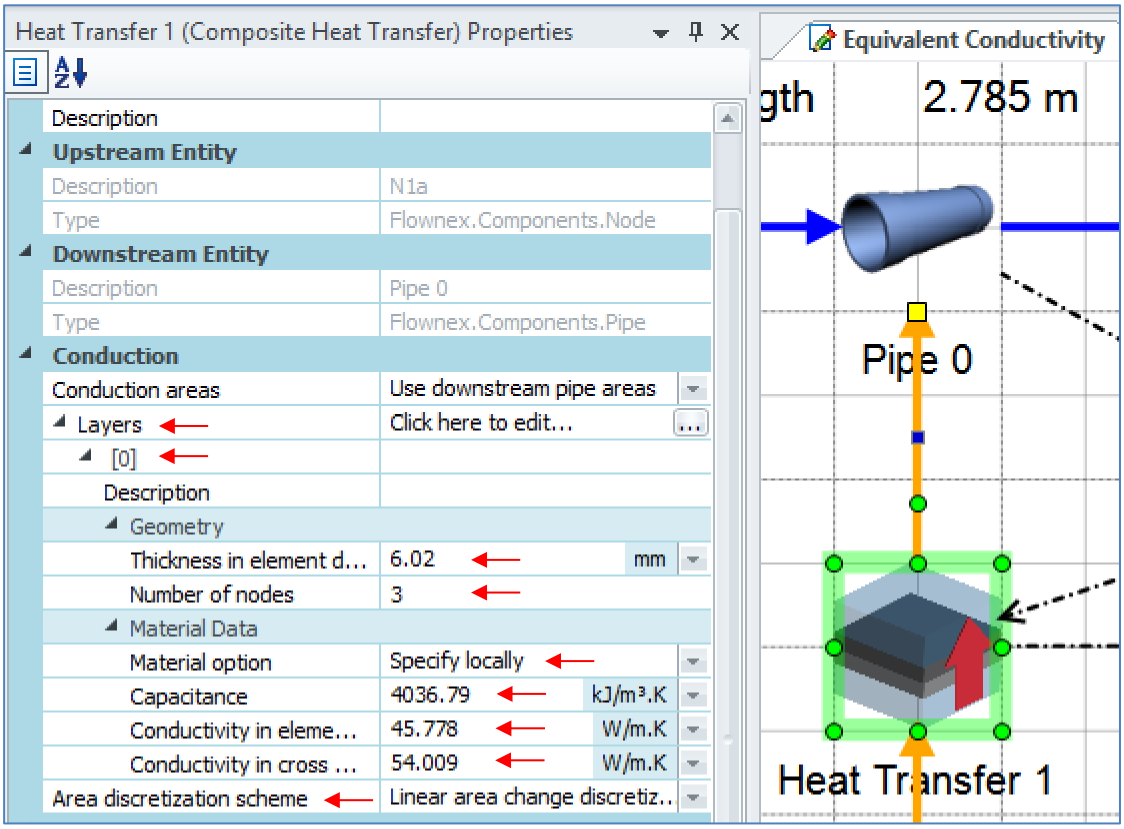

Figure 3: The Flownex® CHT element connected to a Pipe element, specifying a single layer pipe wall of 6.02 mm wall thickness and with three nodes.

Indicated by the red arrows in Figure 3 above are the important input fields. Note that there is only one layer (Layer [0]). The script will supply the geometry as will the materials data as long as the material option has been set to *Specify locally*. For steady state calculations, the capacitance has no influence. Pipe surface areas change linearly with diameter, and hence the *Area discretisation scheme* has been set to linear.

When simulating heat transfer through an insulated pipe wall, for instance, one would use two layers, the outer layer representing the insulation material, similar to the layers shown in Figure 2. Each layer requires the specification of its thickness, the number of nodes and material properties. Fouling may also be modelled as additional layers in Flownex®. An example is shown in Figure 4.

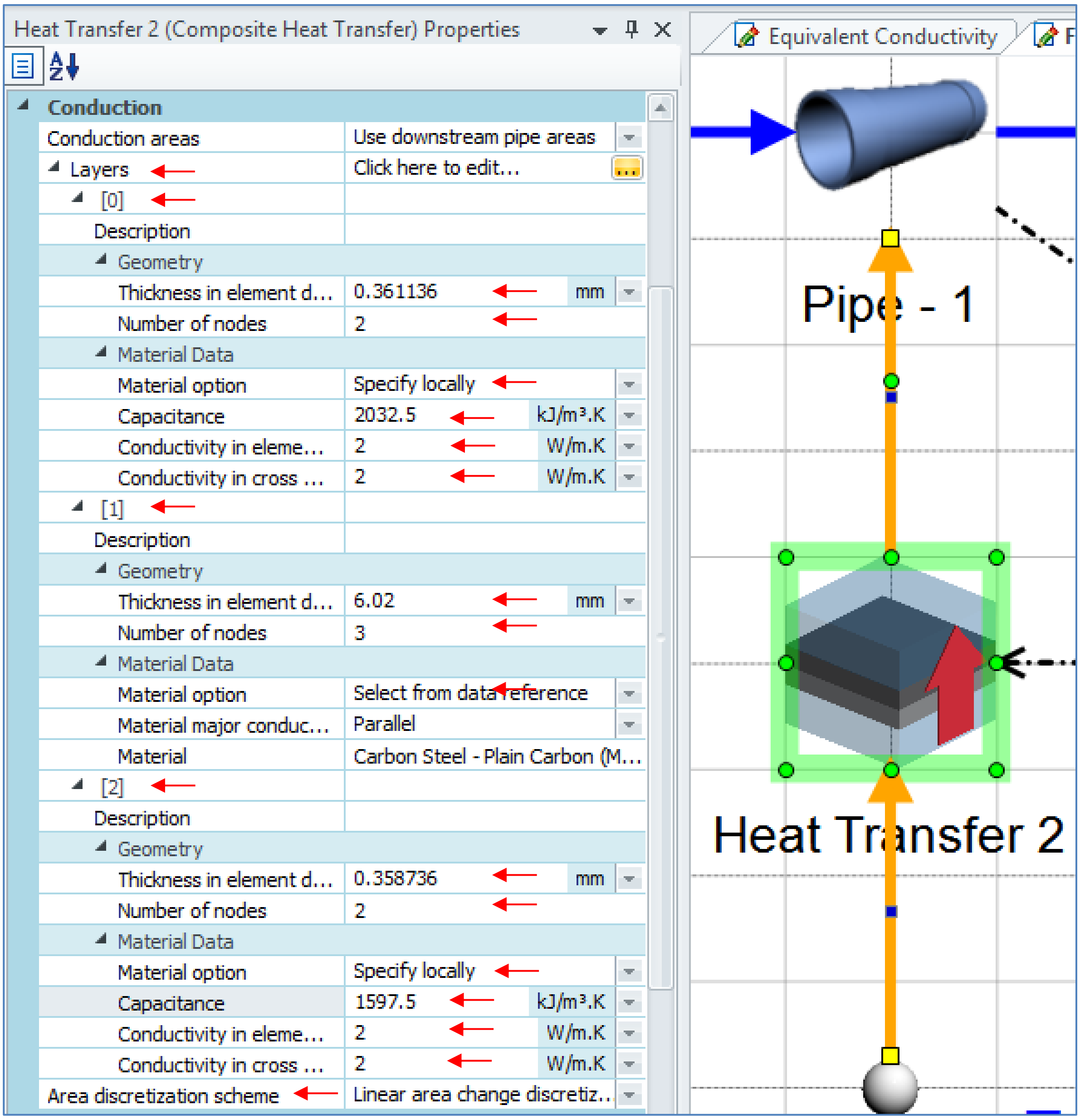

Figure 4: The Flownex® CHT element connected to a Pipe element, specifying a three layer pipe wall with seven nodes in total.

The above two examples (single layer pipe wall and 3-layer pipe wall) are used to implement the two approaches to fouling resistance implementation in Flownex® and is discussed next.

The Flownex Single Layer Pipe Wall Model

A single layer pipe wall will be used to implement the equivalent "fouled" conductivity approach discussed earlier. In this example, a 3-node single layer as shown in Figure 3 is implemented in the Flownex® CHT element, and its inner workings are explained in Figure 5. Flownex® uses a finite volume calculation method where the temperature and all other thermal properties are considered constant for a particular volume. Note that Flownex® uses a node-centric approach where nodes are positioned at the centre of each volume with volume boundaries indicated by dashed lines. This is so because the elements between the nodes act as the thermal resistances between the temperature differences represented by the bounding nodes in the electrical analogy. As a result, the nodes at the surfaces represent half volumes.

When modelling a 6.02 mm thick pipe wall and specifying three nodes, the pipe wall is divided into 25%-50%-25% relative thicknesses as shown. Flownex®'s results offer temperatures at the nodes as well as the elements. However the element temperatures are interpolated between the nodes and may be misleading, especially when relatively few nodes are used as will be highlighted in the next section.

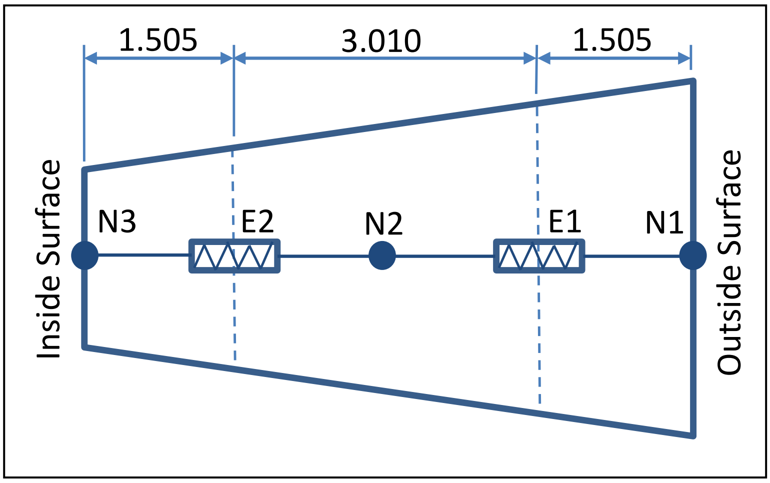

Figure 5: The Flownex® resistance model for a single layer pipe wall of 6.02 mm wall thickness and with three nodes.

Flownex® Model for the Multi-Layer Pipe Wall Simulating Layers of Fouling

When implementing multi-layered pipe walls in Flownex®'s CHT element, the layer layout is slightly different to that of a single layer. Nodes are still present at the surfaces and still represent half control volumes, but elements represent the interfaces between material layers. Of course, if for example, the inside fouling layer was absent in Figure 6, then the inside pipe wall surface would be represented by a node and the actual pipe wall material would be divided into two and a half control volumes instead of three equal volumes as shown here.

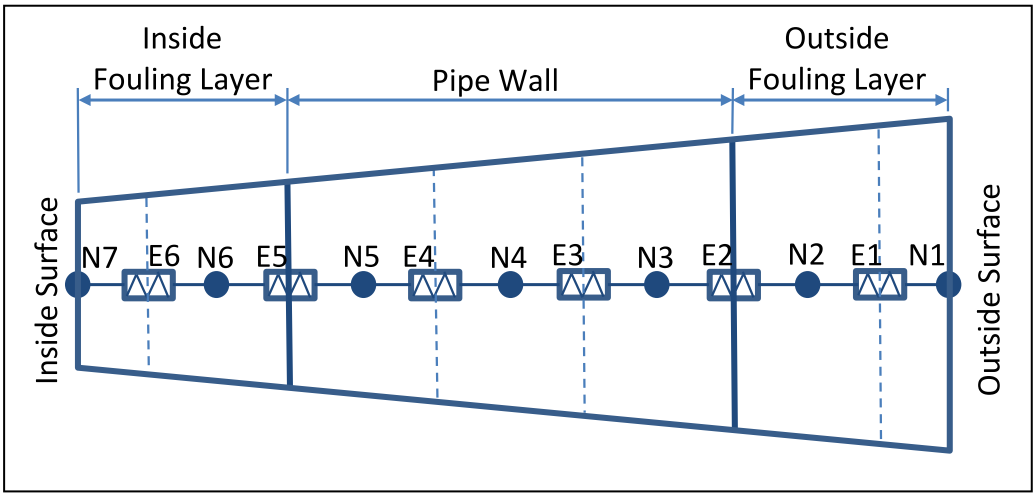

Figure 6: The Flownex resistance model for a 3-layer pipe wall with seven nodes in total. The outer layers represent physical fouling layers.

As discussed before, during a steady state simulation, the temperature gradient through any one material will be constant. However the slope may change between different layers due to the different conductivities. Since elements are placed on the boundaries between layers (the dotted lines), plotting the element temperatures as a function of radial position will appear to be non-linear. This is due to the elements on the interfaces (E2 and E5 in Figure 6) being affected by both layer conductivities and representing an interpolated temperature of its two bounding nodes.

Case Study – Equivalent "Fouled" Conductivity

This section discusses the modelling of heat transfer through a fouled pipe wall using the simpler equivalent "fouled" conductivity approach.

A Flownex® model is presented in Figure 7 showing results of heat transfer through a DN100 Schedule 40 pipe with flowing water. The length is set to 2.785 m to ensure a 1 m² outside surface area. In this example, the CHT element was set up for outside surface convection. The outside ambient (flue gas) temperature was arbitrarily chosen as 800°C (a typical flue gas temperature), and then the convection coefficient was selected to ensure 100 kW of heat transfer, i.e. the outside surface flux rate is also 100 kW/m² with no fouling present.

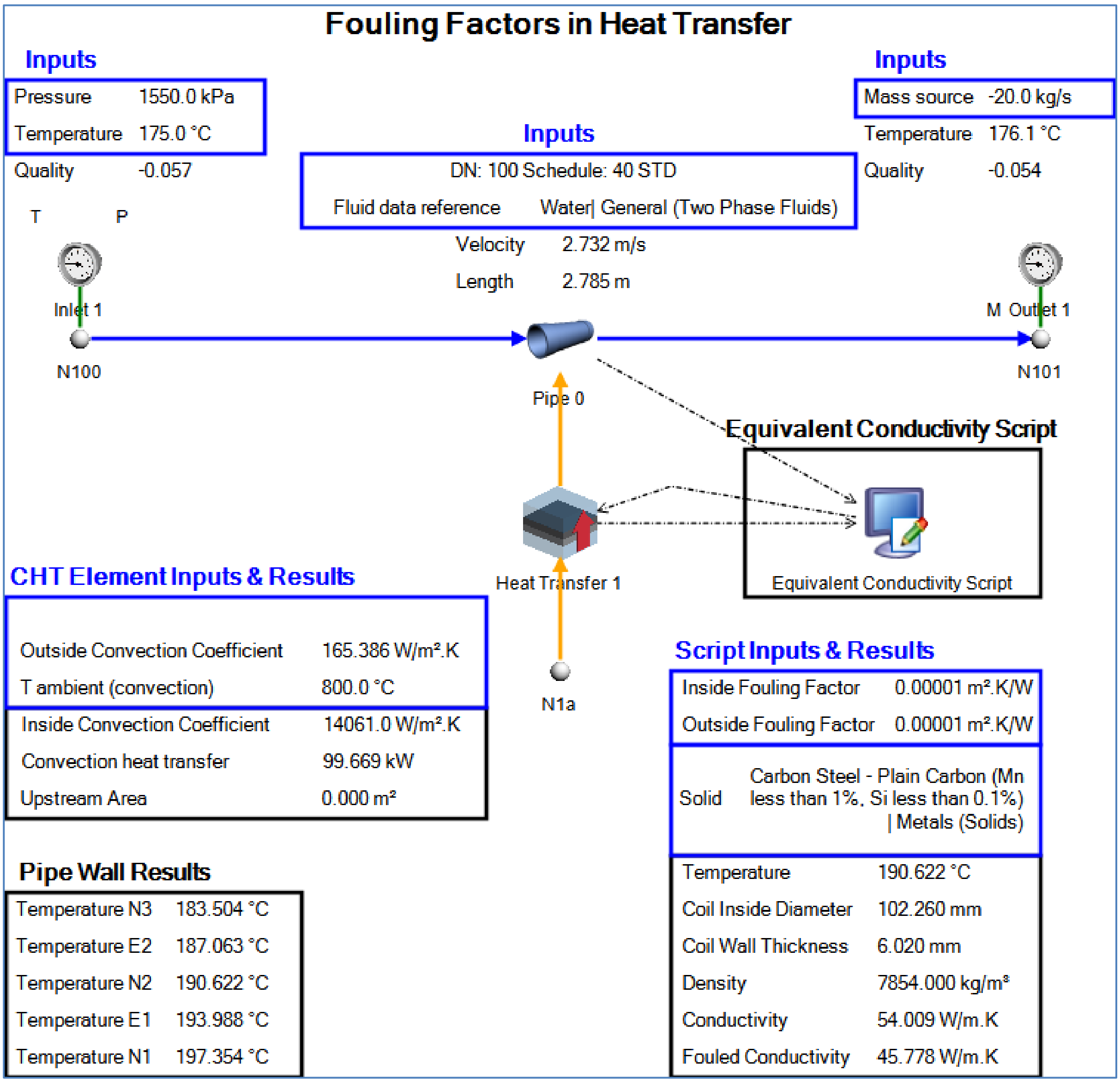

Figure 7: Flownex® model of fouled pipe heat transfer using the equivalent "fouled" conductivity model. The CHT element has three nodes (Figure 5) and inputs are as per Figure 3.

The case shown has inside and outside fouling factors of 0.00001 m^2.K/W and shows a reduced heat transfer of 99.67 kW. It also indicates that the fouled conductivity is reduced to 45.778 W/m.K from the original value of 54.009 W/m.K.

Increasingly higher fouling factors were then applied to the model to observe changes in the pipe wall material thermal conductivity and the heat transfer rate while keeping the outside surface flue gas temperature and convection coefficient constant. The results are shown in Figure 8.

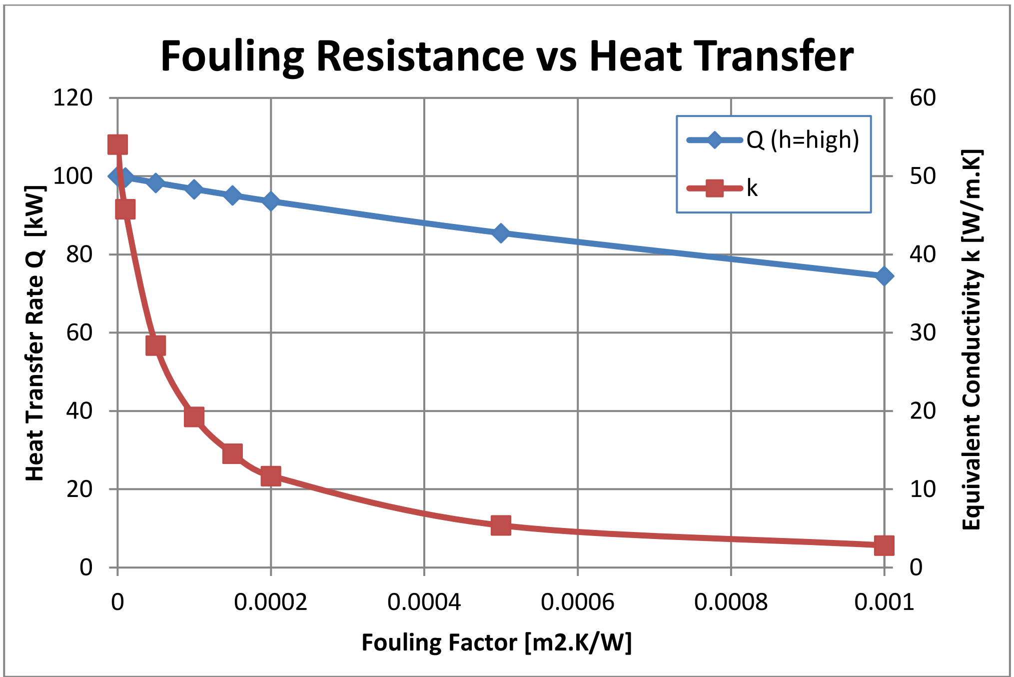

Figure 8: Flownex® results illustrating the influence of fouling resistance on the equivalent conductivity and heat transfer rate.

The above figure shows the calculated equivalent "fouled" material conductivity as a function of fouling. It also indicates that the heat transfer has reduced to 75% of the original value over the indicated span. The relationship between the two curves follows Eq.(5) where the conductivity (which itself is directly proportional to the heat transfer rate) is inversely proportional to the fouling factor.

A second case was tested with much lower outside surface convection of 50 W/m^2.K to investigate the influence of fouling for cases where fouling is an order of magnitude less than another significant thermal resistance such as convection. For this case:

$$R_{convection} = \frac{1}{h_o A_o} = \frac{1}{50 \times 1} \frac{K}{W} = 0.02 \frac{K}{W} \quad (11)$$

$$R_{fouling} = \frac{R_{f,o}}{A_o} + \frac{R_{f,i}}{A_i} \approx 2 \frac{R_{f,o}}{A_o} = 2 \times 0.001 \frac{K}{W} = 0.002 \frac{K}{W} \quad (12)$$

To achieve this, an artificial flue gas temperature of 2195.3°C was used to achieve 100 kW heat transfer with no fouling. It is shown in Figure 9 that for the case where a high outside convection coefficient was used (low convection resistance), fouling has a large influence on the heat transfer rate. When fouling is an order of magnitude smaller than convection resistance for example, the heat transfer rate is much less influenced.

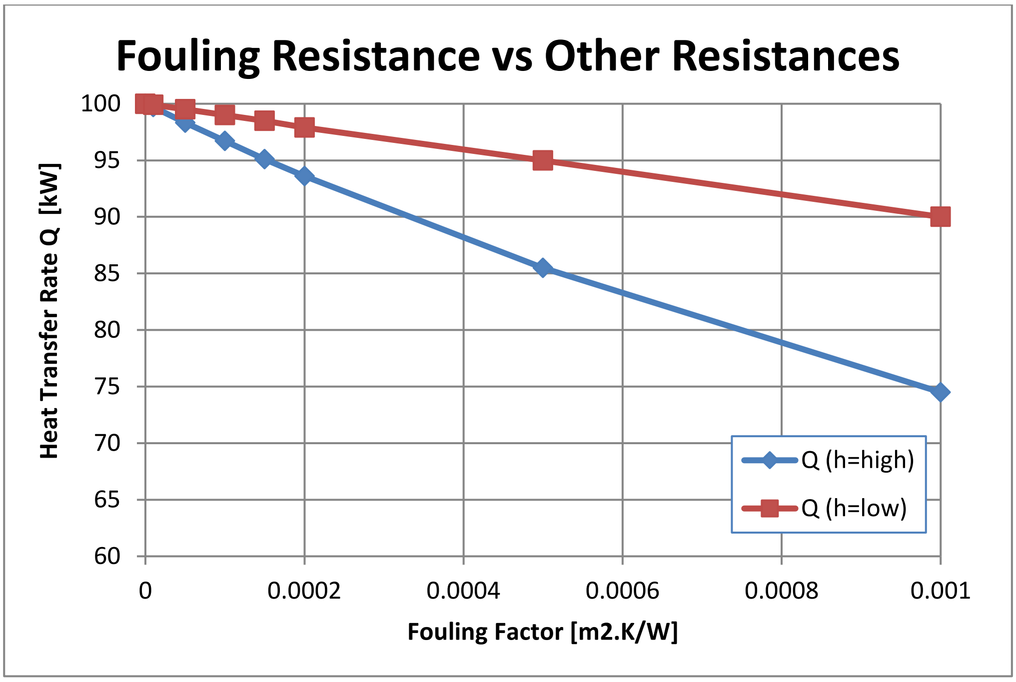

Figure 9: Flownex® results illustrating the influence of outside surface convection and fouling resistance on the heat transfer rate.

Case Study – Modelling Actual Fouling Layers

This section discusses the modelling of actual fouling layers and compares results with the previous method of equivalent "fouled" conductivity. Flownex®'s CHT element allows the specification of several different heat transfer mechanisms on both surfaces of the pipe wall. For this case study, a constant outside surface heat flux of 50 - 100 kW/m^2 will be specified. In applications such as fired heaters, fouling causes the burners to fire harder to achieve the same duty and hence the same flux rate is typically achieved. The result is that fouling will cause higher outside surface temperatures assuming the inside surface heat transfer remains unaffected.

In the first example, common but moderate fouling factors such as those used in natural gas processes of 0.00018 m^2.K/W are used on both surfaces with a thermal conductivity of 2 W/m.K for the foulant. A heat transfer flux of 50 kW/m^2 is typical for fired heater applications and is applied to the pipe outside surface.

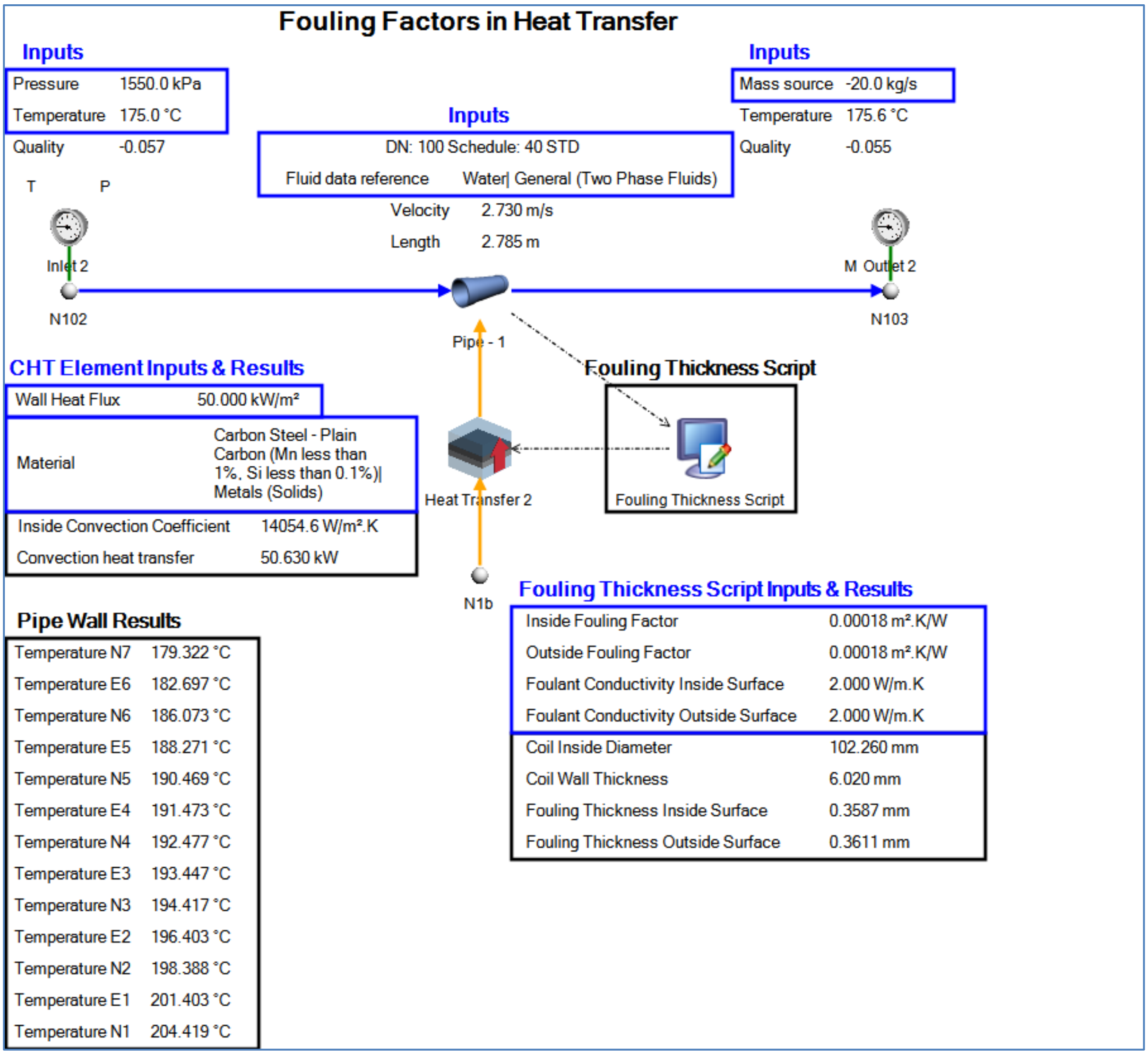

Figure 10: Flownex® model of fouled pipe heat transfer modelling the actual fouling layers in a 3-layer pipe model. The CHT element has seven nodes (Figure 6) and inputs are as per Figure 4.

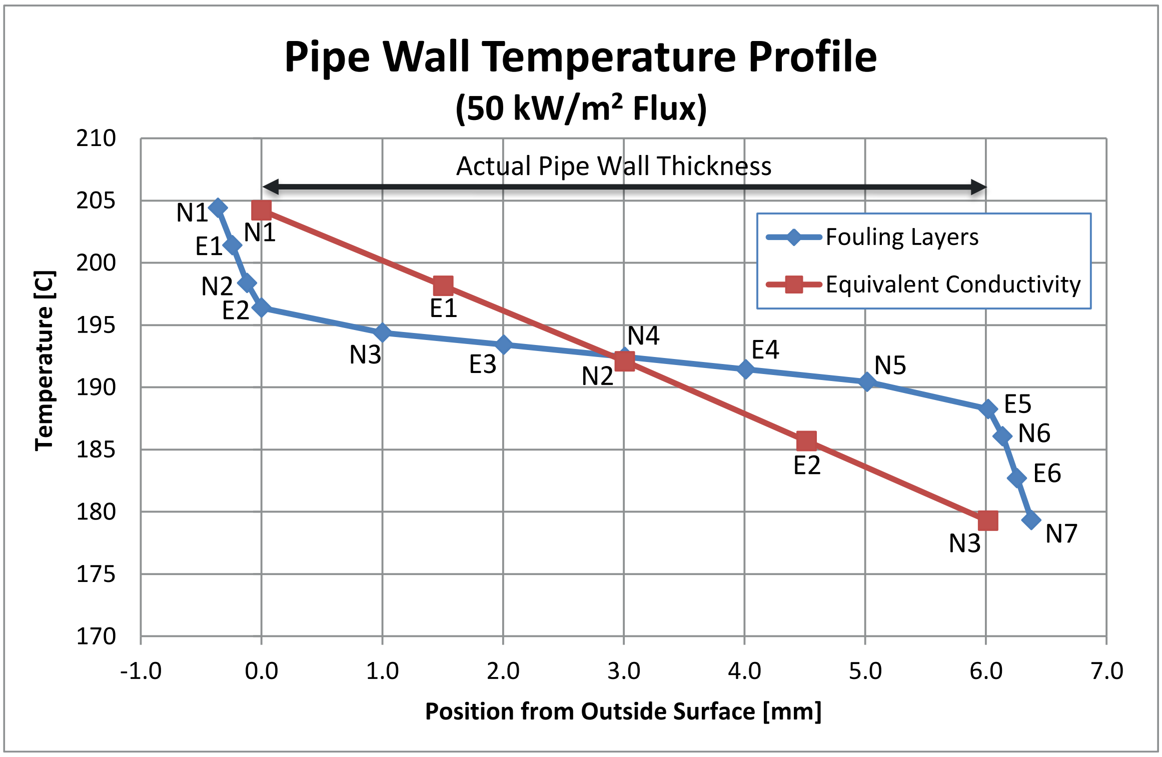

Figure 11: Flownex® results comparing the equivalent "fouled" conductivity method to modelling the actual fouling layers for moderate fouling factors.

It is shown that the temperature gradient for the actual pipe wall (blue series) is lower than that of the equivalent "fouled" conductivity (red series) due to its higher (unaltered) conductivity. As expected, the surface temperatures (N1 vs. N1 and N3 vs. N7) are very similar, and the centre pipe wall temperatures are essentially the same. The steep temperature gradients across the fouling layers (N1 to E2 and N7 to E5 in the blue series) cause maximum discrepancies of only approximately 6 °C at the actual pipe surfaces. Under most design circumstances a discrepancy of this magnitude would be acceptable. Note that there appears to be a change of slope between E2 to N3 to E3 in the blue series. As explained before, element temperatures (E2) are interpolated between its two neighbouring nodes (N2 and N3) and may, therefore, be misleading, especially if the calculation domain is not discretised into small volumes.

For the second example, the two methods are compared when much higher fouling and a much higher flux are present. It is assumed that the pipe carries treated boiler feed water with a fouling factor of 0.0002 m^2.K/W and that the outside surface is exposed to engine exhaust gases with a fouling factor of 0.00176 m^2.K/W. These are relatively high fouling factors and will serve to highlight differences between the two approaches for extreme cases. Furthermore, the heat transfer flux is increased to 100 kW/m^2. The results are shown in the following figure.

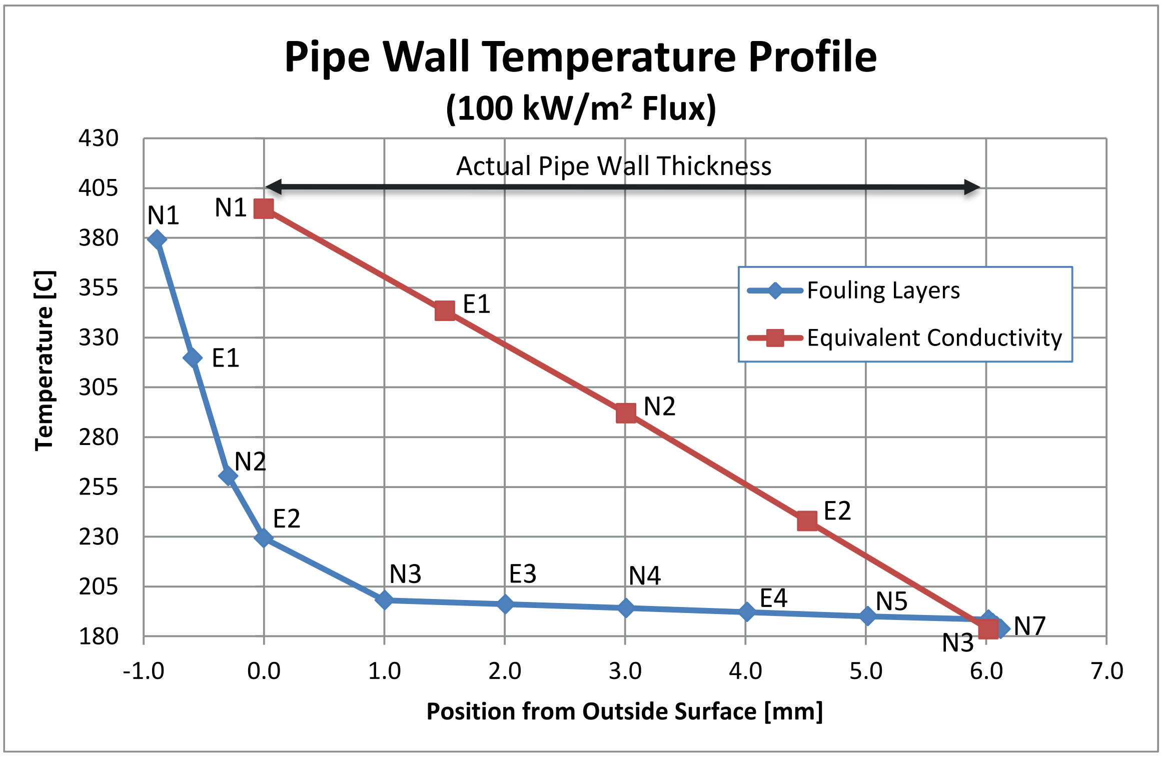

Figure 12: Flownex® results comparing the equivalent "fouled" conductivity method to modelling the actual fouling layers for high fouling factors.

It is illustratedthat while the surface temperatures (inside and outside pipe wall surfaces) are very similar, the temperature distribution through the pipe wall is very different. This is to be expected as the actual pipe conductivity (blue series) is much higher and consequently, has a much lower temperature drop from the pipe outside surface to inside surface as shown by node N3 to N5 in the blue series. It is also illustrated that the comparatively thick outside fouling layer has a very steep gradient from N1 to N2 owing to its much lower conductivity.

The red-series represent the equivalent "fouled" conductivity model with a much lower hypothetical conductivity than the real pipe material. Consequently, the temperature gradient from N1 to N3 (N3 being the last red marker in the series) is much steeper than the corresponding blue series represented by N3 to N5.

Using ordinary carbon steel piping in a fired heater, temperatures should typically remain below approximately 300°C. It is shown that in reality, the pipe temperature will not even quite reach 200°C in this example, however when the equivalent "fouled" conductivity model is used, calculated temperatures rise to 395°C, which is clearly unacceptable for plain carbon steel piping.

It is shown then that when significant fouling is present, the equivalent "fouled" conductivity model may not predict pipe wall temperatures with sufficient accuracy.

Summary

Two methods to account for thermal fouling have been presented. Both may provide results of acceptable accuracy, however, it was shown that in extreme cases with high fouling and high heat fluxes, it may be necessary to model the physical fouling layers to improve accuracy. Fortunately, Flownex® is perfectly suited to performing this task.

Flownex® offers the user the ability to implement calculations which form part of the solution network. In this way, it is relatively straightforward to implement the equations required to account for the influence of thermal fouling. What sets Flownex® apart from the competition is its ability to model even the temperature profiles through a multi-layered pipe wall subjected to heat transfer.