FLOWNEX®
SIMULATION ENVIRONMENT

CASE STUDY

EXTERNAL HEAT TRANSFER PIPE

This case study demonstrates the implementation of a compound element with external surface heat transfer to or from an external fluid. The heat transfer includes both convection and radiation and the convection may be specified as natural (free) or forced.

Download the Flownex network

OIL & PETROCHEMICAL

Challenge:

The main challenge is to develop a useful and easy to use compound component which engineers may use when analysing heat transfer to or from a pipeline or pipe section.

Benefits:

Flownex® offers an *Insulated Pipe* element which is based on the standard Flownex® pipe element. However this element relies on the user to specify external heat transfer coefficients for convection and is also not set up to deal with radiation. Furthermore, the specification of external insulation is not as user friendly as it could be since the Composite Heat Transfer (CHT) element is designed to model pipe layers and not specifically layers of external insulation. The *External Heat Transfer Pipe* presented allows the user to simply specify the ambient conditions such as the ambient temperature and external fluid velocity (wind speed), the pipe geometry, insulation, and pipe orientation (horizontal or vertical). The associated convection coefficients will then be calculated automatically.

Solution:

The *External Heat Transfer Pipe* serves as a wrapper around the Flownex® Pipe element and tailors inputs and results to a pipe with or without insulation subjected to external surface heat transfer.

"Flownex®'s compound components enable the user to extend the standard Flownex element library with customised new components to reduce complexity and improve ease of use."

Hannes van der Walt
Principal Thermal Engineer
Gasco Pty Ltd

Introduction

The External Heat Transfer Pipe model implements the Churchill and Bernstein (1) correlations for forced convection across a cylinder and the Churchill and Chu (2, 3) correlations for natural convection over horizontal and vertical cylinders. Radiation heat transfer from the external surface is modelled using Flownex®'s built-in radiation heat transfer capability included with the Composite Heat Transfer (CHT) element. Inputs and results are simplified such that only relevant information is presented.

> "Heat loss from pipelines is a very common engineering consideration. This relatively simple compound component enables the design engineer to quickly and accurately estimate these heat losses and assists in the selection of the most cost effective insulation option."

Forced Convection Across a Cylinder

The Churchill and Bernstein (1) correlations for forced convection across a cylinder are as follows:

$$Nu = 0.3 + \frac{0.62\, Re^{1/2}\, Pr^{1/3}}{[1 + (0.4/Pr)^{2/3}]^{1/4}}\left[1 + \left(\frac{Re}{282\ 000}\right)^{5/8}\right]^{4/5} \quad \text{Eq. 1}$$

valid for $10^2 < Re < 10^7; Pe > 0.2$

where:

Nu	Nusselt number based on the pipe outside diameter, dimensionless.
Re	Reynolds numbers based on the pipe outside diameter, dimensionless.
Pr	Prandtl number evaluated at the film temperature, dimensionless.

According to Holman (4), the above correlation underpredicts the Nusselt number in the midrange of Reynolds numbers between 20 000 and 400 000. It is suggested that in this range the following correlation is used instead:

$$Nu = 0.3 + \frac{0.62\, Re^{1/2}\, Pr^{1/3}}{[1 + (0.4/Pr)^{2/3}]^{1/4}}\left[1 + \left(\frac{Re}{282\ 000}\right)^{1/2}\right] \quad \text{Eq. 2}$$

valid for $2 \times 10^4 < Re < 4 \times 10^5; Pe > 0.2$

Natural Convection from Horizontal Cylinders

For natural convection from a horizontal cylinder, Churchill and Chu (2) proposed the following correlation:

$$Nu = \left\{0.6 + \frac{0.387\, Ra^{1/6}}{[1 + (0.559/Pr)^{9/16}]^{8/27}}\right\}^2 \qquad \text{Eq. 3}$$

valid for $10^{-5} < Ra < 10^{12}$ and where

$$Ra = Gr \cdot Pr = \frac{g\, \beta\, (T_s - T_\infty) L_c^3}{v^2} \cdot Pr$$

$$\beta = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \cong \frac{1}{\rho}\frac{\Delta \rho}{\Delta T}$$

where:

Ra	Rayleigh number, dimensionless
g	Gravitational acceleration, [m/s^2]
β	Volume expansion coefficient, [1/K]
T_s	Pipe (or insulation) external surface temperature, [K]
T_∞	Freestream (bulk) fluid temperature, [K]
L_c	Characteristic length, taken as the external diameter for a horizontal pipe, and the pipe length for a vertical pipe, [m]
v	Fluid kinematic viscosity, [m^2/s]

Natural Convection from Vertical Cylinders

For vertical cylinders, it is common practice to employ the same correlations used for vertical plates. Churchill and Chu (3) proposed the following correlation:

$$Nu = \left\{0.825 + \frac{0.387\, Ra^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}}\right\}^2 \qquad \text{Eq. 4}$$

valid for

$$10^{-1} < Ra < 10^{12}$$

and

$$D \geq \frac{35\, L}{Gr^{1/4}}$$

Implementation

The *External Heat Transfer Pipe* has been implemented using a *Composite Heat Transfer* (CHT) element connected to a Flownex® *Pipe* element. In addition, six scripts were used to obtain material and fluid properties and perform the external convection coefficient calculation. Figure 1 shows the implementation:

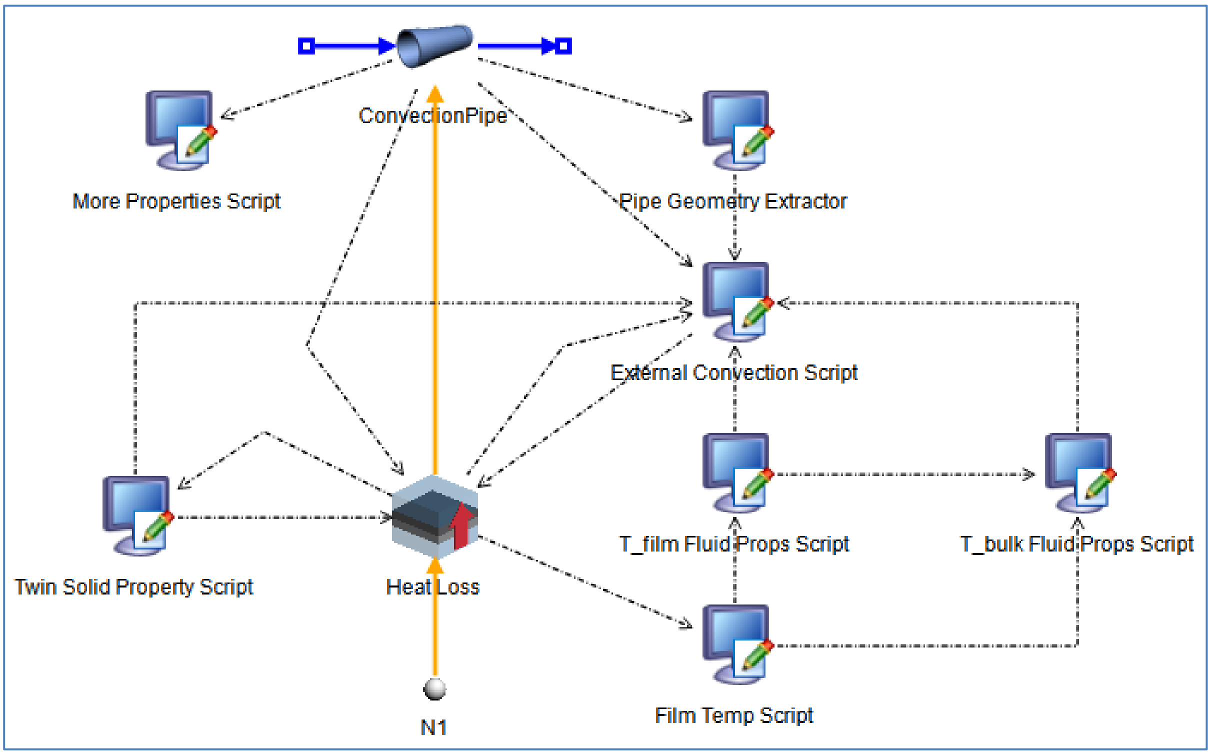

Figure 1: External Heat Transfer Pipe compound component implementation.

The scripts are as follows:

- *Twin Solid Property Script* is essentially a copy of the *Solid Properties* script in the Flownex® master database. However it handles two solid materials simultaneously so that the pipe wall and insulation material can be selected from two databases or specified locally. It also calculates the thermal capacitance for each material since Flownex®'s CHT element accepts the property of *volumetric thermal capacitance* instead of the material's density and specific heat capacity.
- *Film Temp Script* calculates the external fluid's film temperature as the average of the external surface temperature and the external fluid bulk temperature. This temperature is required since fluid properties at the film temperature are used in the above equations.
- The *T_film Fluid Props Script* and the *T_bulk Fluid Props Script* obtain the external fluid's properties at the film and bulk temperatures respectively.
- *External Convection Script* implements the above equations and populates the CHT element's external convection coefficient field.
- *More Properties Script* only serves to display additional properties in the results page.

Input and Result Pages

The input and result pages are discussed in the following figures. They have been laid out to be as straightforward and logical as possible. Figure 2 shows input and result pages when the forced convection option has been selected. It also shows the inputs when external insulation is selected. Similarly, Figure 3 shows the pages for natural (free) convection and without insulation.

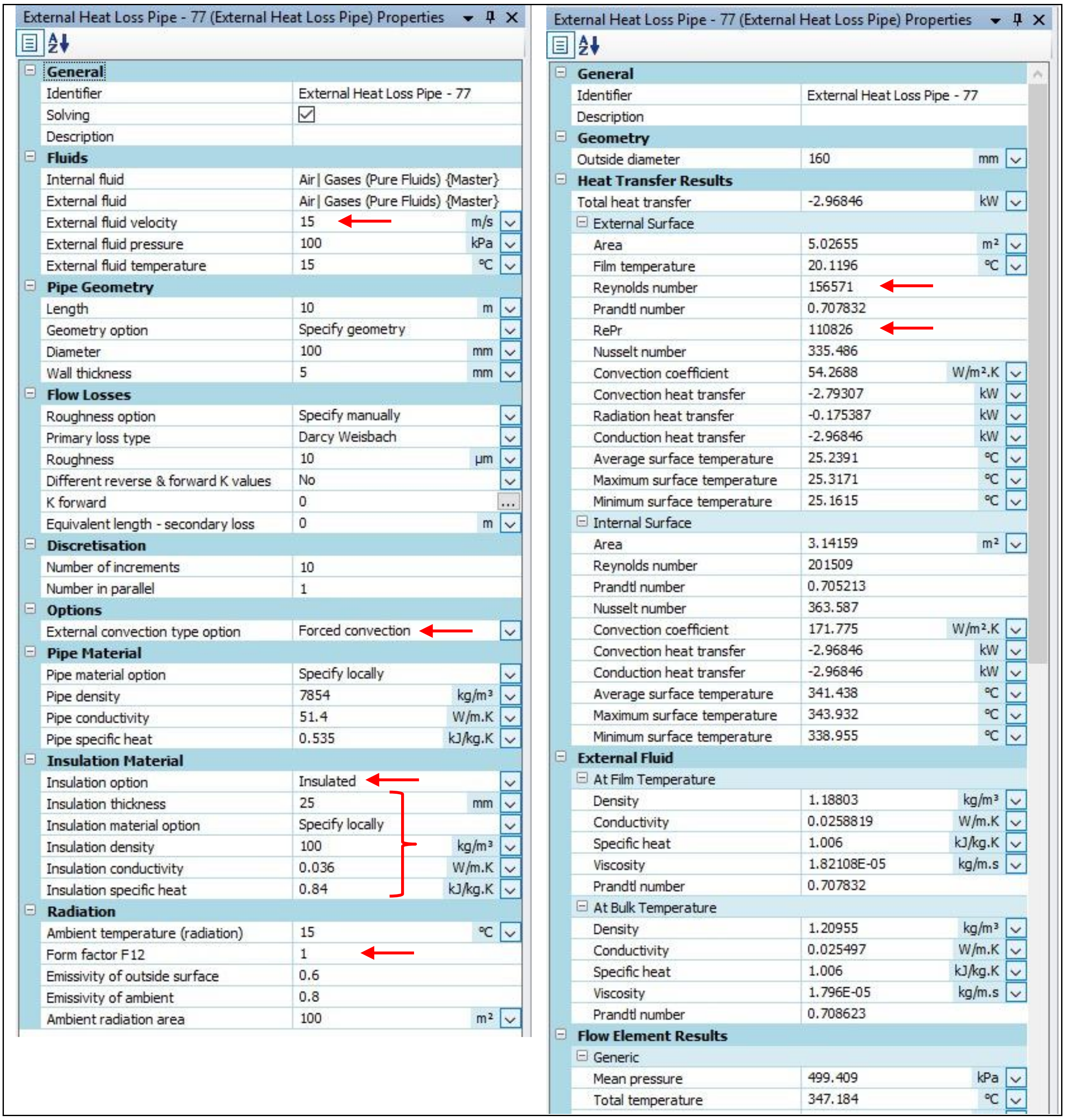

Figure 2: Input and result pages for forced convection with insulation.

As shown, when the forced convection option is selected, the external fluid velocity must be specified. When the insulation option is selected, input fields to specify the insulation material properties become available. If no radiation should be calculated, simply specify a zero radiation form factor F12. For forced convection, the calculated Reynolds number and product of Reynolds and Prandtl numbers are displayed in the results.

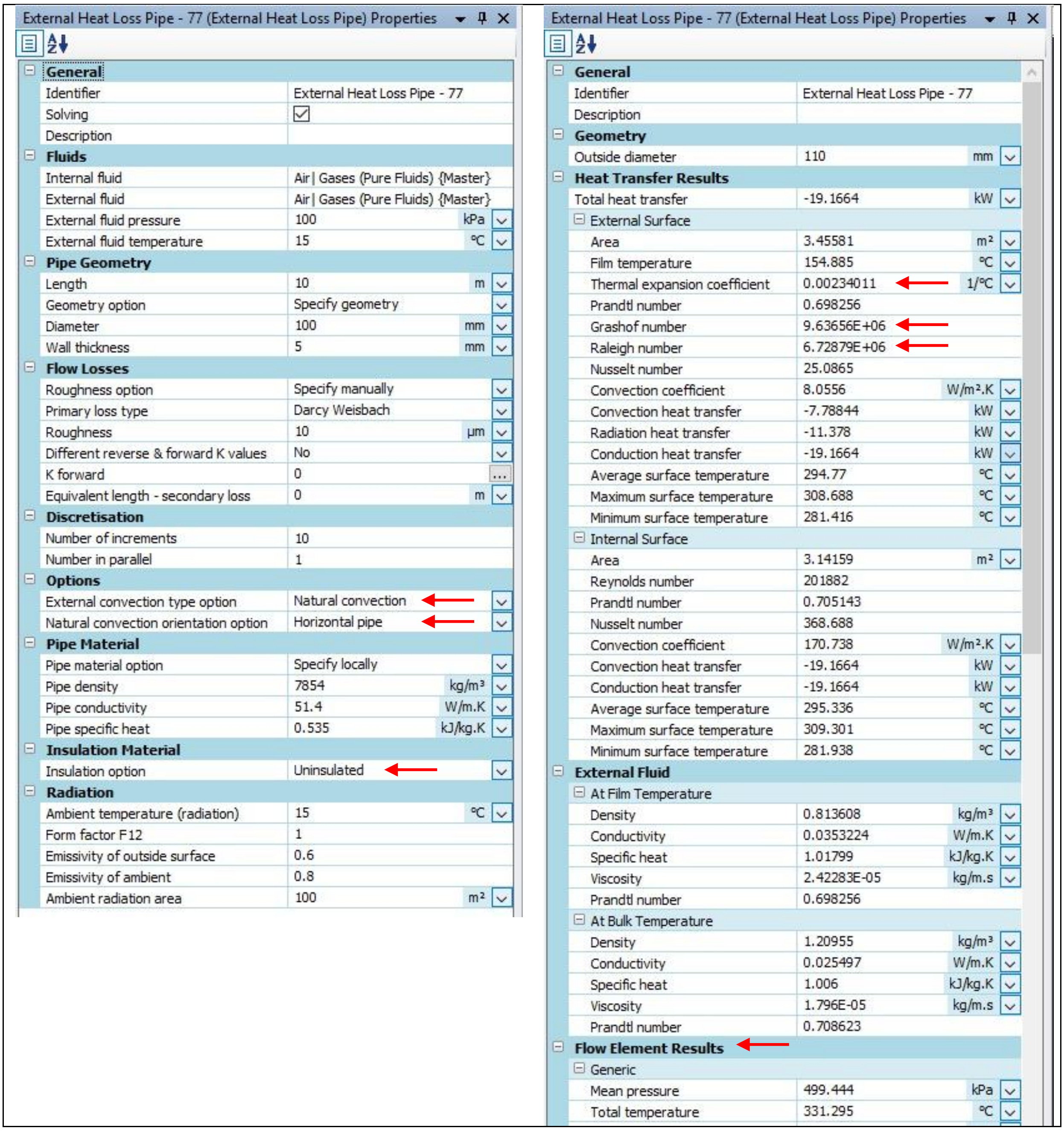

Figure 3: Input and result pages for natural (free) convection without insulation.

As shown, when the natural convection option is selected, the user must also specify the natural convection orientation of the pipe - horizontal or vertical. Furthermore, if no insulation is specified, the insulation specification fields are hidden. For natural convection, the result page shows the volumetric thermal expansion coefficient, the Grashof and Rayleigh numbers instead of the Reynolds number.

The Heat Transfer Pipe follows the standard flow element results for the Flownex® *Pipe* element.

Case Studies

A total of 8 case studies are presented to highlight several aspects of forced and natural convection:

- Forced convection; uninsulated and insulated. These two studies highlight the influence of insulation.
- Natural convection; uninsulated and insulated. As above, the effect of insulation is highlighted, but furthermore, these two cases also highlight the relative differences with forced convection.
- The next four cases investigate natural convection only and compare a horizontal pipe with an identical pipe positioned vertically. Both uninsulated and insulated cases are considered.

Case Study 1: Forced and Natural External Convection for Horizontal Pipes

The first four scenarios compare forced and natural convection of a horizontal pipe for both uninsulated and insulated pipes. Problem specification data are as follows:

Pipe:

Orientation: Horizontal (unimportant for forced convection).
Diameter: 100 mm.
Length: 10 m.
Wall thickness: 5 mm.
Material: Carbon steel.
Thermal conductivity: 51.4 W/m.K.
Density: 7854 kg/m^3
Specific heat capacity: 0.535 kJ/kg.K.

Insulation:

Thickness: 25 mm.
Material: Rockwool.
Thermal conductivity: 0.036 W/m.K.
Density: 100 kg/m^3.
Specific heat capacity: 0.84 kJ/kg.K.

External fluid: Atmospheric air.
Pressure: 100 kPa-a.
Temperature: 15°C.
Velocity: 15 m/s.

Internal fluid: Air.
Flowrate: 0.5 kg/s.
Inlet pressure: 500 kPa-a.
Inlet temperature: 350 °C.

Radiation: Ambient radiation temperature: 15°C.
Form factor F12: 1.0. It is assumed that the pipe is sufficiently exposed to a cold ambient (sky) all around to warrant a concentric cylinder form factor.
Emissivity of pipe outside surface: 0.6 (typical value).
Emissivity of ambient (sky): 0.8 (typical value).
Ambient radiation area: 100 m^2 (essentially infinity).
A more detailed discussion of the radiation specification is given in the section following the results.

Table 1: Case Study 1 Results – Forced and Natural External Convection for Horizontal Pipes.

Convection Type		Forced Convection		Natural Convection	
Heat Transfer Results / Insulation Option	Unit	Uninsulated	Insulated	Uninsulated (Horizontal)	Insulated (Horizontal)
Outside surface diameter	mm	110	160	110	160
Total HT	kW	-44.6	-1.94	-19.17	-1.76
Convection HT	kW	-38.5	-1.83	-7.79	-0.993
Radiation HT	kW	-6.1	-0.11	-11.38	-0.764
Air inlet temperature (internal)	°C	350	350	350	350
Air outlet temperature (internal)	°C	264.8	346.3	313.6	346.7
Internal surface average temperature	°C	221.0	344.3	295.3	344.8
Internal surface maximum temperature	°C	249.2	345.9	309.3	346.3
Internal surface minimum temperature	°C	194.9	342.7	281.9	343.4
External surface average temperature	°C	219.6	21.7	294.8	53.6
External surface maximum temperature	°C	247.7	21.7	308.7	53.8
External surface minimum temperature	°C	193.8	21.7	281.4	53.4
External film temperature	°C	117.3	18.4	154.9	34.3
External fluid thermal volume expansion coefficient	1/K	---	---	0.00234	0.00326
External fluid Prandtl number (at T_{film})	-	0.6996	0.7081	0.6983	0.7063
External fluid Reynolds number (at T_{film})	-	6.4983E4	1.5830E5	---	---
External fluid Grashof number (at T_{film})	-	---	---	9.6366E6	1.8203E7
External fluid Rayleigh number (at T_{film})	-	---	---	6.7288E6	1.2858E7
External fluid Nusselt number (at T_{film})	-	182.6	338.2	25.1	30.4
External convection coefficient	$W/m^2.K$	54.5	54.4	8.1	5.1

The results in Table 1 show that insulation greatly reduces the external heat loss, especially under forced convection. For the two forced convection cases, the external convection coefficients are very similar, however, due to the much lower external surface temperature, the insulated pipe loses much less heat.

The results are similar for natural convection, however as expected, the surface temperature of the insulated pipe is much higher under natural convection than under forced convection. Once again, the external convection coefficients for both natural convection cases are similar.

Lastly, the external surface temperatures are also safe to touch for both insulated pipes. Although it would be allowable to reduce the insulation thickness for the forced convection pipe (cost savings), under natural convection a reduction in insulation thickness may cause the surface temperature to be higher than allowable according to typical OH&S design standards which typically places a limit of 60°C on touchable surfaces.

Case Study 2: Comparison of Natural External Convection for Horizontal and Vertical Pipes

The problem specification data for the case of a vertical pipe under natural convection had to be modified as the equations for vertical pipes are not valid for the data given in Case 1 – refer to Eq. 4 for validity ranges. The following warnings are issued by Flownex® if the natural convection pipe in Case 1 is orientated vertically:

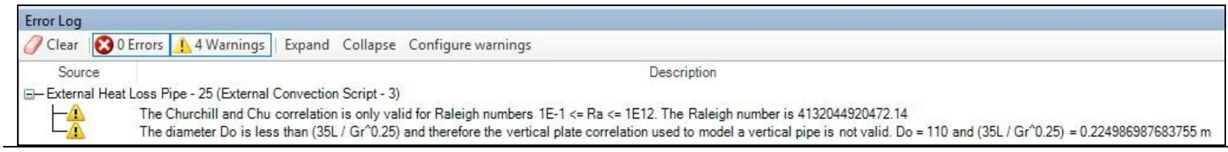

Figure 4: Flownex® warnings on correlation validity ranges.

The new problem specification data are as follows (all other data remain the same):

Pipe:

Orientation:	Horizontal and vertical.
Diameter:	150 mm.
Length:	1 m.

From the results presented in Table 2, it is shown that the insulation reduces heat loss by approximately 90% for a horizontal pipe under natural convection. It is also shown that the heat transfer of an uninsulated vertical pipe is approximately double that of a horizontal pipe in this instance, and hence insulation is even more important. The heat loss is reduced by approximately 95% by the application of insulation. It is also shown that when pipes are insulated, the orientation is much less important, as the strong natural draft created by a vertical pipe is essentially nullified by the insulation.

Table 2: Case Study 2 Results – Comparison of Natural External Convection for Horizontal and Vertical Pipes.

Pipe Orientation		Natural Convection (Horizontal)		Natural Convection (Vertical)	
Heat Transfer Results / Insulation Option	Unit	Uninsulated	Insulated	Uninsulated	Insulated
Outside surface diameter	mm	160	210	160	210
Total HT	kW	-2.54	-0.240	-5.1	-0.258
Convection HT	kW	-1.03	-0.134	-4.26	-0.215
Radiation HT	kW	-1.51	-0.106	-0.84	-0.043
Air inlet temperature (internal)	°C	350	350	350	350
Air outlet temperature (internal)	°C	345.2	349.5	340.4	349.5
Internal surface average temperature	°C	282.5	343.6	214.3	343.1
Internal surface maximum temperature	°C	284.0	343.8	216.8	343.3
Internal surface minimum temperature	°C	281.0	343.4	211.8	342.9
External surface average temperature	°C	282.0	55.2	213.3	33.0
External surface maximum temperature	°C	283.5	55.3	215.8	33.1
External surface minimum temperature	°C	280.5	55.2	210.8	33.0
External film temperature	°C	148.5	35.1	114.1	24.0
External fluid thermal volume expansion coefficient	1/K	0.00238	0.00325	0.00259	0.00338
External fluid Prandtl number (at T_{film})	-	0.6986	0.7063	0.6997	0.7072
External fluid Grashof number (at T_{film})	-	3.0264E7	4.2385E7	8.0293E9	2.4278E9
External fluid Rayleigh number (at T_{film})	-	2.1141E7	2.9935E7	5.6177E9	1.7170E9
External fluid Nusselt number (at T_{film})	-	35.2	39.2	209.9	145.2
External convection coefficient	$W/m^2.K$	7.7	5.0	42.8	18.1

Radiation Specification

Since the CHT element is capable of modelling radiation, this capability is carried over to the *External Heat Transfer Pipe*. The required input fields are shown in Figure 2 and Figure **3**.

- Ambient temperature (radiation): The external surface of the uninsulated pipe, or the cladded insulation surface, will radiate to the ambient fluid, or receive radiation from the ambient fluid. If the pipe is to radiate to/from a solid object in the line of sight, the solid object's surface temperature becomes the "ambient temperature".
- Form factor F12: This is the form factor (also known as "shape factor" or "view factor") which provides the fraction of maximum heat transfer between two objects. If radiation occurs between the pipe and the ambient air, a form factor of 1.0 may be used since the ambient envelopes the pipe like concentric cylinders. If radiation occurs with a solid object, an appropriate form factor should be selected. If the user wants to omit radiation calculations from the model, simply specify a zero form factor.
- Emissivity of outside surface: A vast archive of information is available in the literature on the emissivities of material surfaces. Some relevant surfaces are as follows:

Table 3: Emissivities for Typical Pipe and Cladded Surfaces.

Material	Temperature [°C]	Emissivity
Aluminium, polished	100	0.095
Aluminium, unoxidised	25/100/500	0.022/0.028/0.060
Aluminium, oxidised	200/600	0.11/0.19
Aluminium, heavily oxidised	93-504	0.2-0.31
Aluminium, commercial sheet	100	0.09
Aluminium, anodised sheet, chromic acid proc.	100	0.55
Chromium, polished	50/500-1000	0.10/0.28-0.38
Chromium, unoxidised	100	0.08
Chromium, oxidised	316/482/650/ 816/982	0.08/0.18/0.27/ 0.36/0.66
Copper, commercial, scoured to a shine	20	0.07
Copper, calorised	100	0.26
Copper, calorised, oxidised	200/600	0.18/0.19
Copper, oxidised	50/200/500	0.6-0.7/0.6/0.88
Copper, unoxidised	100	0.02
Copper, plate, heated a long time, covered with thick oxide layer	25/200-600	0.78/0.57
Copper, polished	50-100	0.02-0.05
Stainless steel, buffed	20-100	0.16
Stainless steel, oxidised	100-370	0.85
Stainless steel, oxidised from furnace service	200-530	0.6-0.75
Carbon steel, calorised, oxidised	200	0.52

Material	Temperature [°C]	Emissivity
Carbon steel, rough	50	0.95-0.98
Carbon steel, rolled	20	0.66
Carbon steel, ground	900-1100	0.55-0.61
Paint, aluminium	0-100	0.55
Paint, bronze	0-100	0.8
Paint, black, white, grey, green, cream	0-100	0.95

- **Emissivity of ambient:** If the ambient to/from which radiation occurs is the atmospheric air, then the ambient humidity may be important as the water content in the air plays a major role in radiation. The internet provides access to several studies on this topic such as that of Chen, Kasher, Maloney and Clark (5) which provide the following correlation:

  $$\varepsilon_{sky} = 0.73223 + 0.006349 \cdot T_{dp}$$

  where T_{dp} is the dew point temperature in °C.

  Clearly the "emissivity of ambient" may be difficult to specify precisely.

- **Ambient radiation area:** If radiation occurs to the ambient, a large area may be specified here. If radiation occurs to/from another solid object, that object's surface area must be specified.

Summary

Heat loss from pipelines is a very common engineering consideration. This relatively simple compound component enables the design engineer to quickly and accurately estimate these heat losses and assists in the selection of the most cost-effective insulation option.

Flownex®'s compound components enable the user to extend the standard Flownex® element library with customised new components to reduce complexity and improve ease of use. This ease of extendibility sets Flownex® apart from the competition and its ability to model even the temperature profiles through an insulated pipe wall subjected to heat transfer is unmatched.

References

1. Churchill, S.W. and Bernstein, M. "A Correlating Equation for Forced Convection from Gases and Liquids to a Circular Cylinder in Crossflow", *J. Heat Transfer*, vol. 99, pp. 300-306, 1977.
2. Churchill, S.W. and Chu, H.H.S., "Correlating Equations for Laminar and Turbulent Free Convection from a Horizontal Cylinder", *Int. J. Heat Mass Transfer*, vol. 18, p. 1049, 1975.
3. Churchill, S.W. and Chu, H.H.S., "Correlating Equations for Laminar and Turbulent Free Convection from a Vertical Plate", *Int. J. Heat Mass Transfer*, vol. 18, p. 1323, 1975.
4. Holman, J.P., Heat Transfer, 9th Ed., McGraw-Hill, p. 285 eq. 6-22.
5. Chen, B., Kasher, J., Maloney, J., Girgis, G.A. and Clark, D. "Determination of the Clear Sky Emissivity for use in Cool Storage Roof and Roof Pond Applications", *Passive Solar Research Group*, University of Nebraska-Lincoln, University of Nebraska at Omaha.