FIRE EXPOSED DUCT SYSTEM

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FEDS fire exposed duct system program

The FEDS program calculates temperatures in parts of interest in a ventilation systems exposed to fire. The letter S could also be interpreted as sections. The scenarios can be internal or external fire exposure of a ventilation duct system part. The calculation is static with fixed stated temperatures as input data. The fire is described with high temperatures that influences the duct system parts of interest. An internal heat release inside a duct can also be introduced to a part of the duct. The duct model is limited to a single straight circular duct, but bends, sharp bends and rectangular ducts can be treated with some simplification.

Ventilation system fire scenarios

A fire can influence a part of a ventilation system from a fire outside or by a ventilation flow containing hot fire gases inside. These influences can cause spread of fire to other parts of the ventilation system both upstream through heat radiation and downstream through both heat radiation and flow. Inside and outside fire combined with upstream and downstream gives four basic fire scenarios denoted $A_>$, $A_<$, $B_>$ and $B_<$, as also shown in Figure 1. The inside fire and upstream case $B_<$ is somewhat rearranged to a branch connected downstream to a main ventilation duct with hot fire gases. The $B_<$ case might be regarded as harmless, but the radiation can have a large influence upstream and certainly when no flow is present.

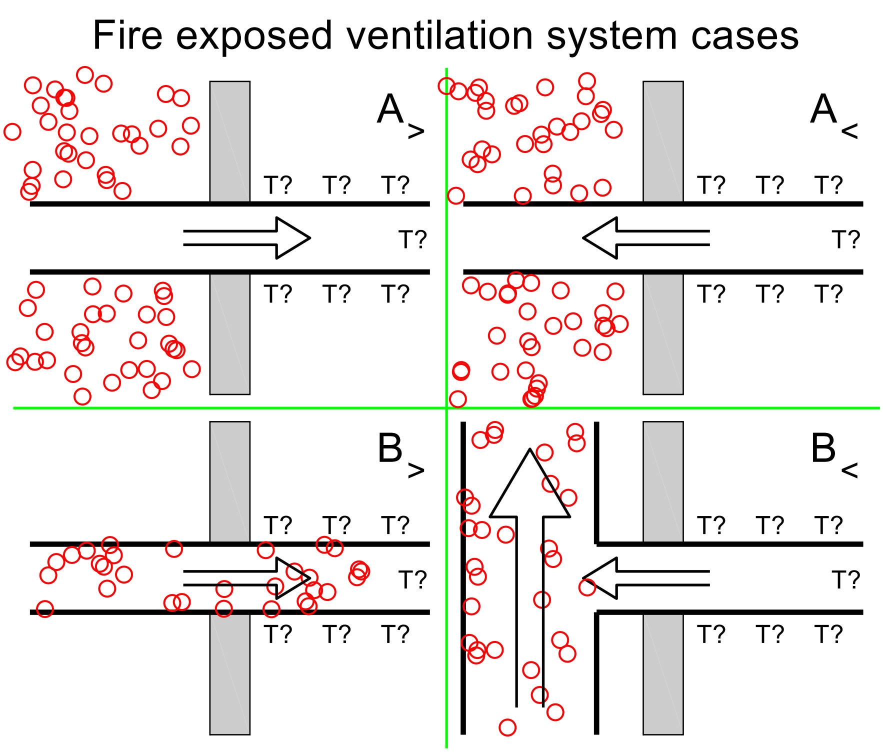

Figure 1 Four fire exposed ventilation system cases.

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Supply and extract systems

The duct calculated can be a part of a supply or extract air ventilation system as shown in Figure 2. External fires can cause high supply branch temperatures and high main return extract temperature that could damage the fan. The user has to state the mass flow split for all sections with branches for supply or extract air and also the extract temperatures that can be fire influenced or normal.

A branch is located in the right end of a section if the mass flow split parameter a_{io} is larger than zero. The supply system main flow enters at the main ducts left end. The supply branch temperatures are equal to the duct air temperatures at the section right end.

The extract system main flow leaves at the main ducts left end. The extract branch temperatures at the section right ends are set by the user.

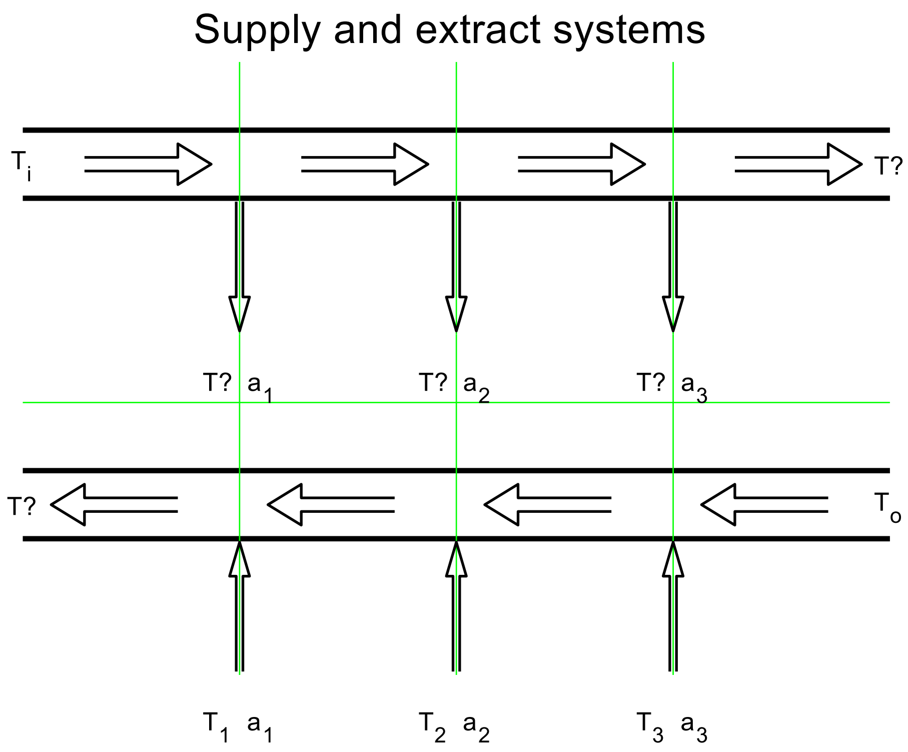

Figure 2 Necessary data to defined supply or extract systems.

Duct heat radiation

Heat radiation in ducts can reach far compared with the duct diameter. Duct systems with large diameters compared with lengths are the most critical ones. The opposite case with diameters small in comparison with large lengths are far from critical. This long range effect also means that a model might be extended beyond the borders of primary interest to cope and cover duct heat radiation well. A long duct locked in either end without heat losses will have the same temperature inside as at the open end as shown in Figure 3. A long duct with open ends without any flow will have a decreasing or increasing temperature depending on the outside temperatures as also shown in Figure 3. The heat radiation through the open duct is a function of the length/diameter quotient and also equal to *n* parallel sheets as shown in Figure 4 and accordingly to (1).

$$P = \sigma \, (T_h^4 - T_c^4) \, / \, (n + 1) \qquad \text{(W/m}^2\text{)} \qquad (1)$$

A single sheet corresponds to a duct length/diameter parameter *k*, which is equal to 1.35 for a circular duct and up to 1.5 for rectangular ducts. The heat transfer in ducts can be compared with free heat radiation between circular sheets parallel and perpendicular. The distances are equal to 1, 2 and 5 characteristic lengths as shown in Figure 5. Duct heat radiation can be transferred into heat radiation between a number of parallel sheets. The number is equal to the duct length in characteristic length *kd*, where *d* is the duct diameter. The parameter *k* is equal to 1.35 for circular ducts and up to 1.5 for rectangular ducts.

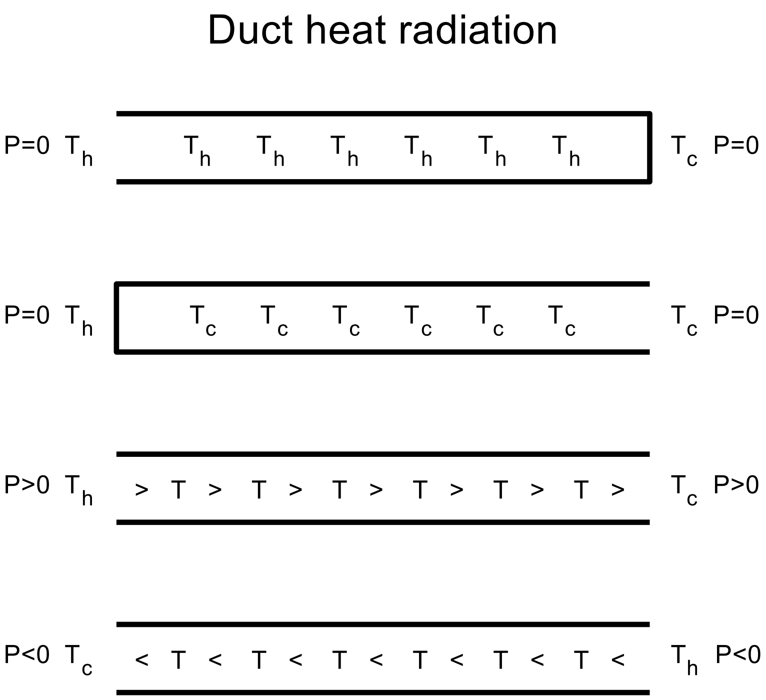

Figure 3 Duct heat radiation in duct system without heat losses.

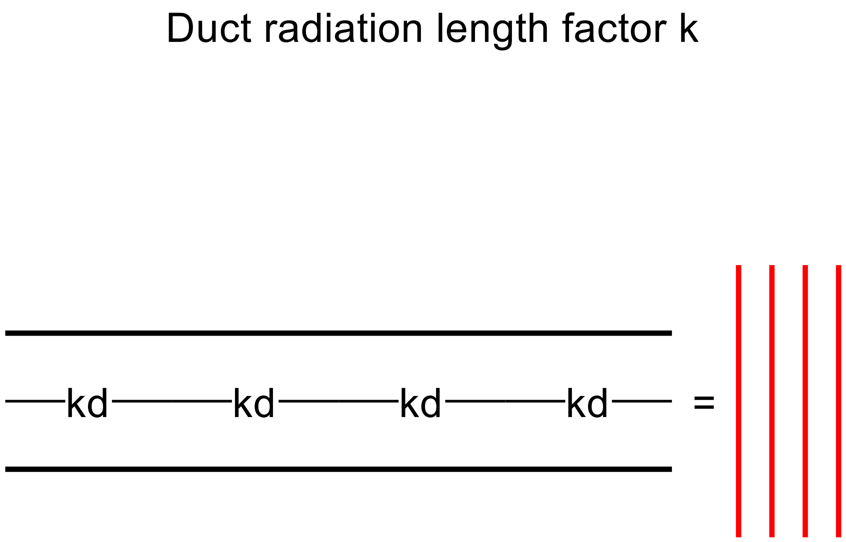

Figure 4 Conversion of duct radiation from duct length *kd* into parallel sheets.

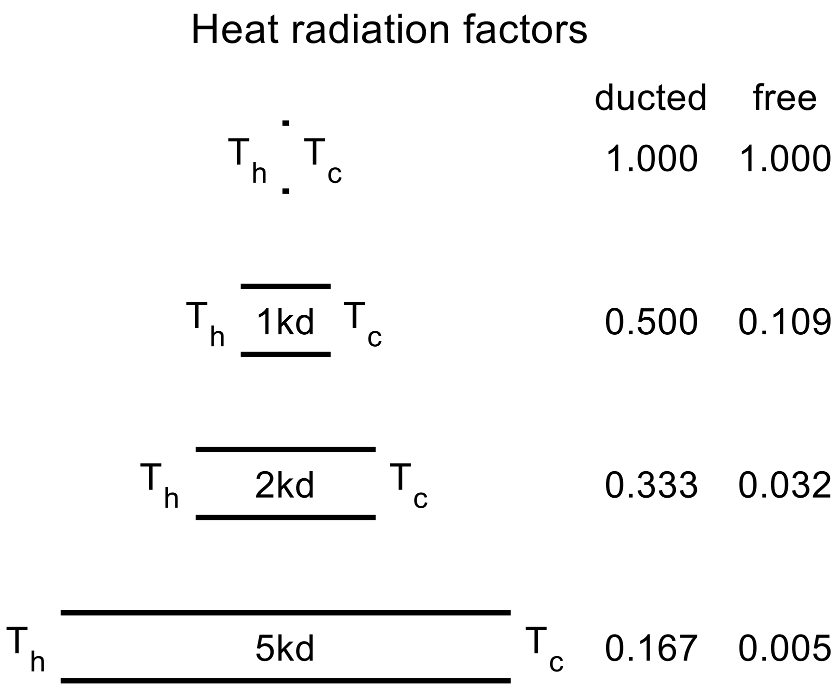

Figure 5 Comparison between ducted and free heat radiation for different *kd* lengths.

FEDS model and duct ring concept

The calculation is limited to a straight circular duct with the same diameter throughout the total length. The duct is divided into rings with a standard module 10, 20, 50 and 100 mm according to Figure 7 or by a user input. All lengths and positions has to be modular as shown in Figure 6. The maximum duct length is a direct function of the chosen length module as shown in Figure 8. A number of identical rings regarding insulation and external temperature can be grouped into a section to facilitate model description to a number of sections instead of a vast number of single rings. A number of sections describes the model. Several sections can also be identical.

The calculation model takes into account internal and external heat radiation, duct axial heat conduction along the duct, duct radial heat conduction through insulation if any, surface heat convection between duct and air and flow heat transfer. Temperatures calculated for each ring are the air inside the ring, the ring inside surface or duct and the ring insulation outside sur-face. The axial heat conduction is small compared with heat radiation, heat convection and heat transfer by flow. The axial heat conduction only averages the temperature differences to some extent. This effect is more pronounced in duct systems with small dimensions.

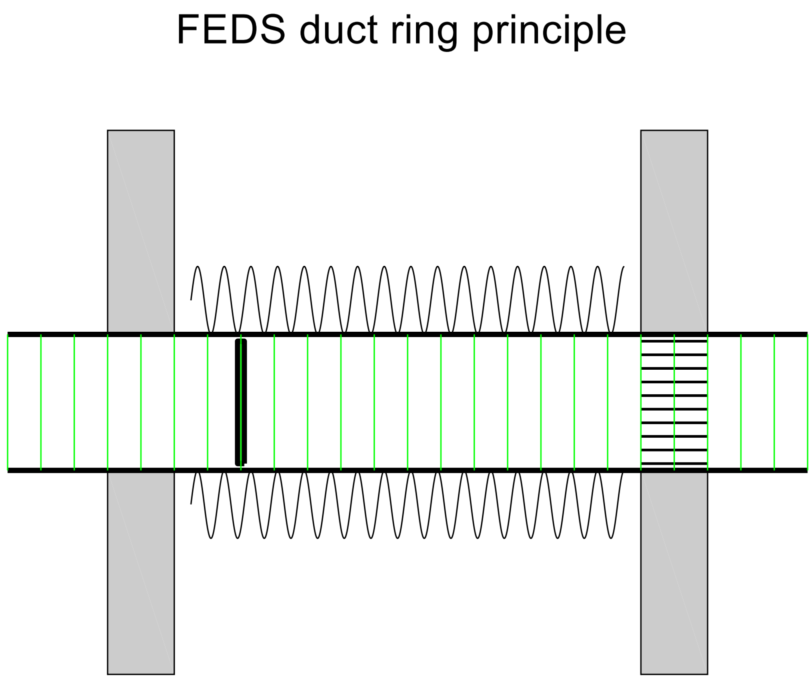

Figure 6 FEDS duct ring principle.

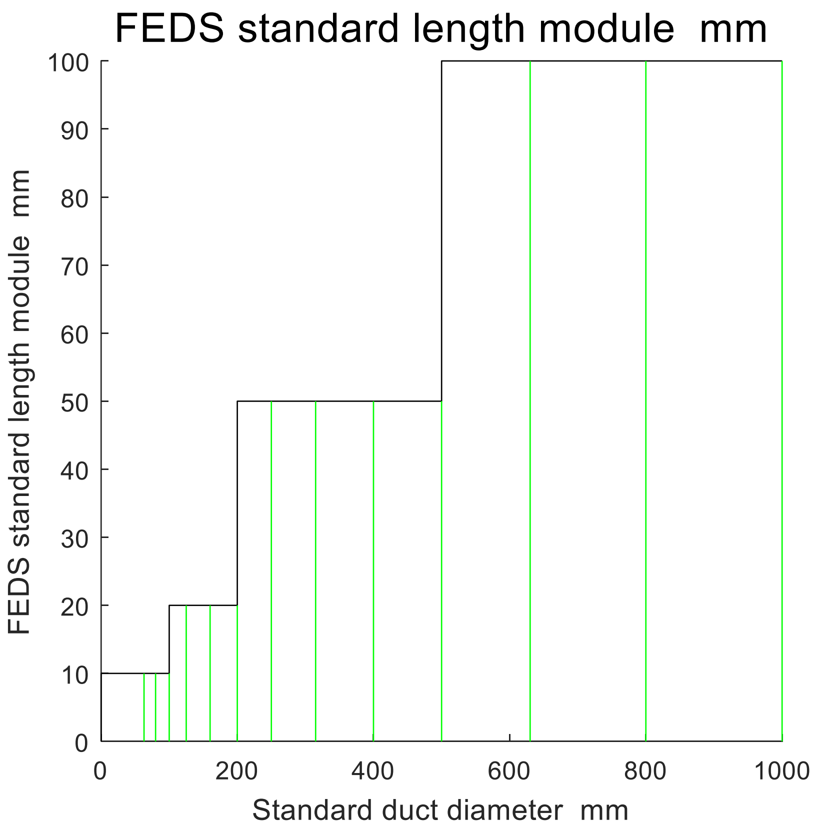

Figure 7 FEDS standard length module as a function of duct diameter.

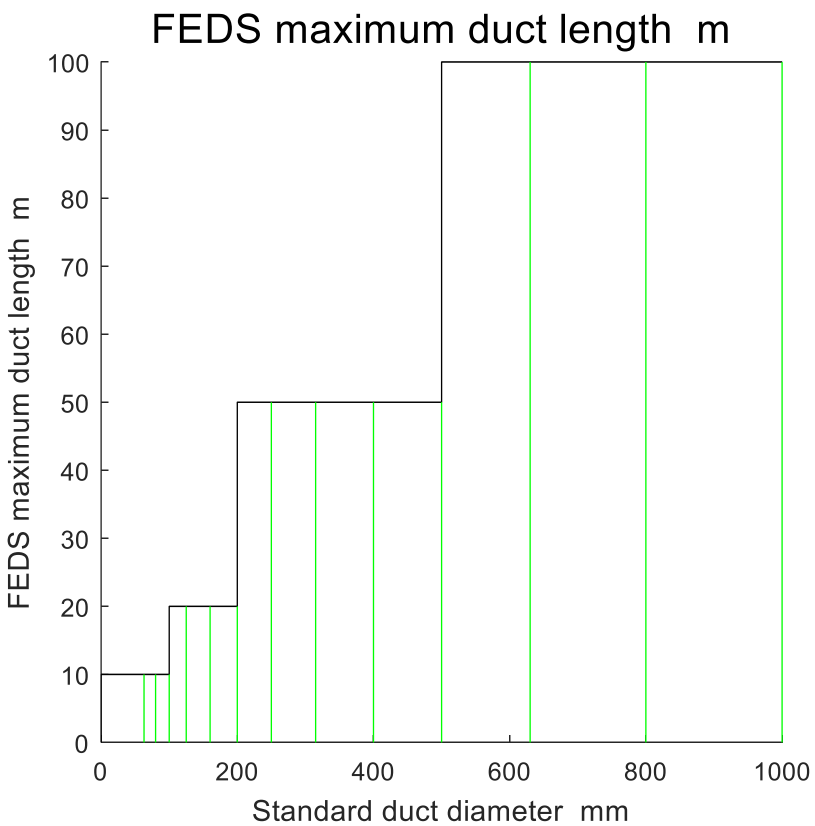

Figure 8 FEDS maximum duct length as a function of duct diameter.

The total duct length is limited to 1000 rings. At first glance the maximum number of unknowns seems to be 3000 due to the fact that each ring contains three temperatures for air, duct inside surface and duct insulation outside surface. However all air temperatures can be calculated in sequence with assumed duct inside temperatures and inflow and its temperatures. All duct insulation outside temperatures can be estimated with the duct inside temperature and the external temperature.

The FEDS model is built by six parts such as section with insulation, fire damper **FD**, radiation brake **RB,** shaft/coverings **SC,** internal heat release **HR** and duct ends **E$_i$** and **E$_o$** as shown in Figure 9 with three sections for a uninsulated, insulated and concrete slab passage. An example of a five section model based on above parts is shown in Figure 8 including the ring division.

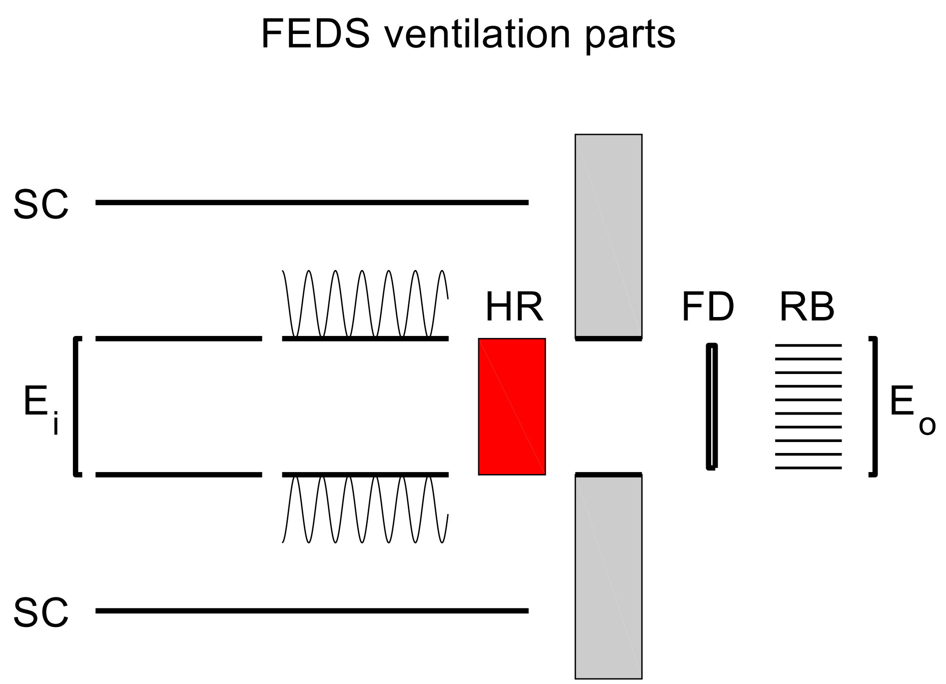

Figure 9 FEDS ventilation parts.

A bend can be treated as a straight duct with the length equal to the bend centreline length and radiation correction, which gives a total equivalent length close to 4 diameters. A sharp 90° bend has a centreline length of one diameter and with radiation correction the equivalent length becomes close to 2 diameters. The conversion from bend/angle to a straight duct are shown in Figure 10.

A rectangular duct can be treated as a circular duct with the same cross section. The cross section of a duct determines the amount of heat radiation transferred. What this conversion means is shown in Figure 11.

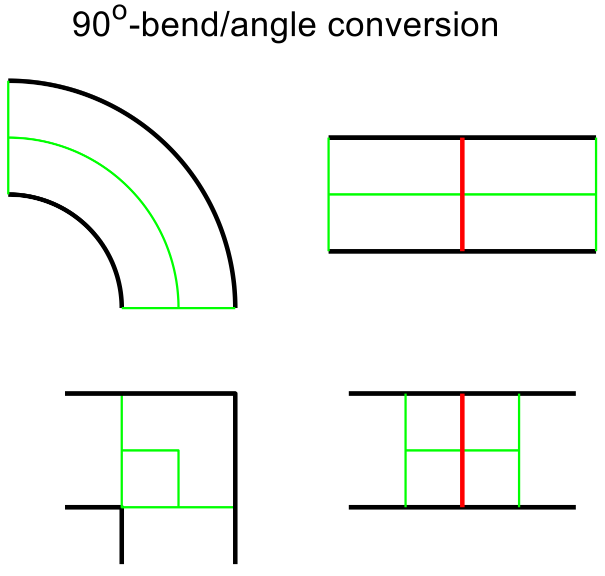

Figure 10 Conversion of 90°-bend/angle to a straight duct.

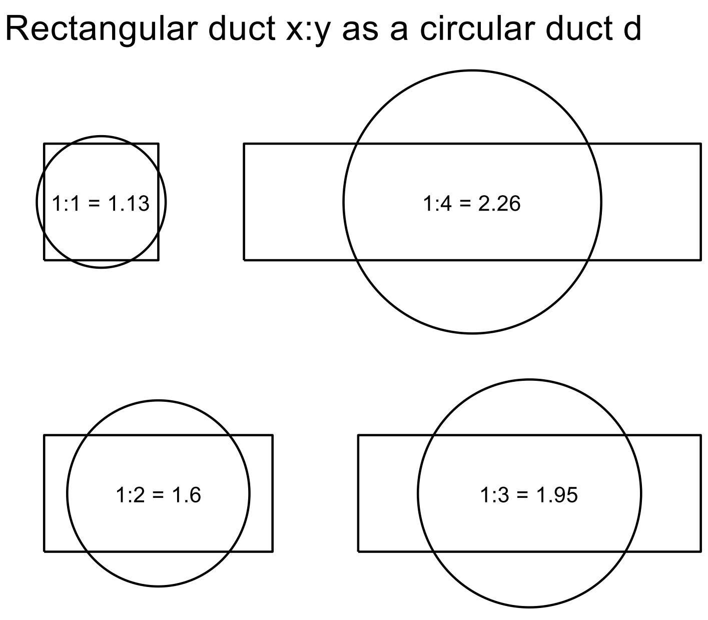

Figure 11 Conversion of a rectangular duct to a circular duct.

FEDS insulation

A duct insulation layer is stated by the user with type and thickness. Several layers can be combined into an equivalent single layer with the same total thickness. Calculation of insulation heat losses is far from easy, but can be tampered with. Insulation materials heat conductivity is a function of temperature can be stated in four ways. One method is polynomial functions for different insulation materials from manufactures. The other methods are based heat radiation screening area m^2/m^3 and the air heat conductivity.

The heat conductivity in porous materials can be described by air heat conductivity and heat radiation between screening areas determined by the insulation material. This model makes possible to combine several different materials into a single equivalent one with the same total thickness and a weighted screening area with the same total screening area.

The density can together with assumed material diameter d_m m be calculated to radiation screening area S m^2/m^3 as shown in (2). A simplified rule gives the screening area m^2/m^3 as 4π m^2/kg times the density ρ_i kg/m^3 as shown in (3). That is valid for insulation material diameter of 0.04 mm or 40 µm and material density ρ_m 2500 kg/m^3. The insulation material surface O m^2/m^3 gives another most simple method to calculate the screening area as material surface divided by π changing perimeter to diameter as in (4). The most obvious method is to describe insulation materials with the screening area m^2/m^3 directly and not by the density.

$$S = 4\,\rho_i / (\pi\,\rho_m\,d_m) \qquad (m^2/m^3) \qquad (2)$$

$$S = 4\,\pi\,\rho_i \qquad (m^2/m^3) \qquad (3)$$

$$S = O / \pi \qquad (m^2/m^3) \qquad (4)$$

The insulation heat conductivity is calculated as shown in (5) as function of absolute temperature T K, screening area S m^2/m^3 and air heat conductivity.

$$\lambda(T) = \lambda_{air}(T) + 4\,\sigma\,T^3 / S \qquad (W/Km) \qquad (5)$$

A ventilation duct section can be uninsulated, which simplifies the data input, modelling and calculation. The internal heat radiation model has only to take into account heat radiation to external surfaces with known temperatures. The insulation material type and thickness for this case are stated as 0 and 0 mm. A ventilation duct section can also have zero heat loss, which simplifies the modelling and calculation. The insulation material type and thickness for this case are stated as -1 and 0 mm.

The heat conduction through the insulation is purely radial for each ring. There is no heat exchange through the insulation between rings. There can be temperature differences in external temperatures between rings belonging to different duct sections.

FEDS fire damper FD

A single fire damper FD shall be placed between two duct sections/parts and consists of several steel sheets with heat radiation in between. The fire damper has no length in the calculation model and is treated as plane between two rings. The general air velocity is set to zero for an activated fire damper or to a value to describe axial leakage.

A standard fire damper consists of two metal sheets with some suitable material in between to limit the axial leakage between the damper and the duct, when the fire damper is activate and closed. A single sheet fire damper reduces the radiation exchange by half.

The fire damper heat radiation *P* W between the temperatures T_h K and *T* K through *n* parallel sheets with area *A* m^2 and its reduction factor *r* can be stated as below.

$$P = \sigma A\,(T_h^4 - T_c^4) / (n + 1) \qquad \text{(W)} \qquad (6)$$

$$r = 1 / (n + 1) \qquad \text{(-)} \qquad (7)$$

Notice that the transferred heat and the reduction factor *r* decrease more and more slowly with increasing number of sheets. The reduction factor *r* becomes 0.50, 0.33, 0.25 and 0.20 for the first four sheets. The fire damper main objective is to block spread of smoke and fire gases.

The temperatures for *n* parallel sheets can be calculated for the hottest sheet as T_{max} K and the coldest sheet as T_{min} K as shown below in (8-9) and simplified in (10-11) when $T_h >> T_c$.

$$T_{max}^4 = (nT_h^4 + T_c^4) / (n + 1) \qquad (\text{K}^4) \qquad (8)$$

$$T_{min}^4 = (T_h^4 + nT_c^4) / (n + 1) \qquad (\text{K}^4) \qquad (9)$$

$$T_{max} = T_h\,(n / (1 + n\,))^{0.25} \qquad \text{(K)} \qquad (10)$$

$$T_{min} = T_h / (n + 1)^{0.25} \qquad \text{(K)} \qquad (11)$$

The coldest sheet out of 15 or 80 sheets when $T_h >> T_c$ is far from cold and (11) gives $T_{min} = T_h /2$ respectively $T_{min} = T_h /3$.

The fire damper FD values 1-3 corresponds to a single sheet, a double sheet with no insulation in between and two sheets insulated in between. In the program 1-2 is available.

FEDS radiation brake RB

Not available in this version

The radiation brake RB protects the upstream part of a duct from intense radiation from the downstream part of a duct. The flow transfers the radiation heat collected in the radiation brake downstream. The radiation brake is a device that has a large surface area in a small volume that allows the air to pass with a minor pressure drop. The radiation brake has no moving parts. The main principle is that the ventilation system is running.

A radiation brake has a length of one diameter and can be placed between two duct sections/parts. The effect is determined by the given equivalent length in diameters, which gives the same duct surface area as the radiation brake. An equivalent length of one diameter means just a piece of duct of that length.

An application of radiation brake is an extract air branch connected to a fire exposed main duct as shown in Figure 1 as case A<. The extract air branch can be short and with a single extract air device. The radiation from the main duct can create high surface temperatures in the short extract branch.

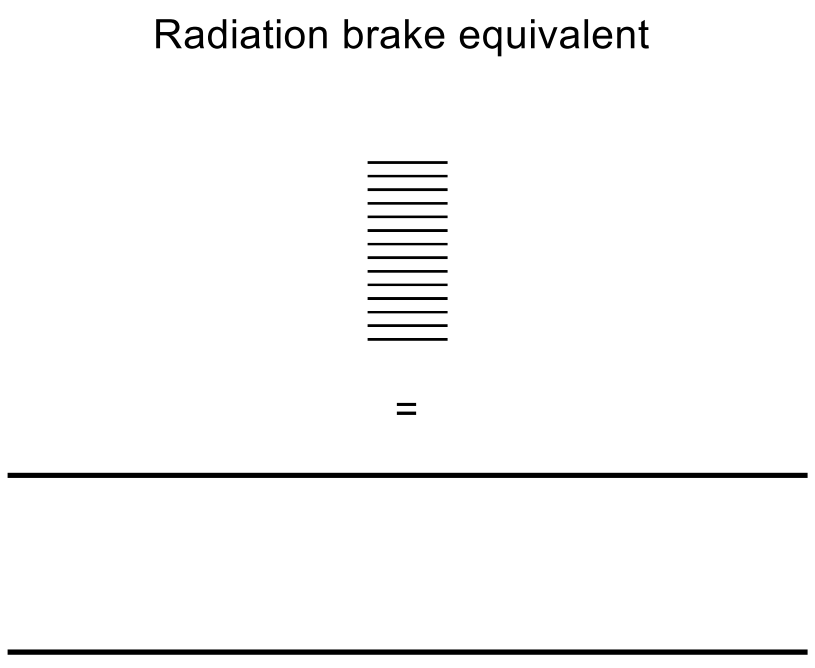

Figure 12 Radiation brake conversion.

Internal heat release HR

The internal heat release HR gives a possibility to calculate a fire in an extract duct of some kind. The total heat release is limited by the air mass flow together with oxygen depletion < 0.5 or by the maximum surface area heat release together with given area on fire. The maximum heat release is distributed with fixed proportions between air and duct surface.

The heat release from an air mass flow of 1 kg/s is 6.6 MW if all oxygen is utilized. Normal fires are extinguished, when the relative oxygen level is less than 0.5.

The internal heat release HR is defined by five parameters begin and end positions as shown in Figure 13, oxygen depletion 0-1 (less than 0.5), heat part to air 0-1 (greater than 0.8) and maximum surface heat release 1 MW/m^2 (or less).

One remark about internal heat release is that the duct surface temperature can reach very high temperatures. This is due to the fact that both the radiative and the convective heat transfer is modest compared with the possible internal heat release.

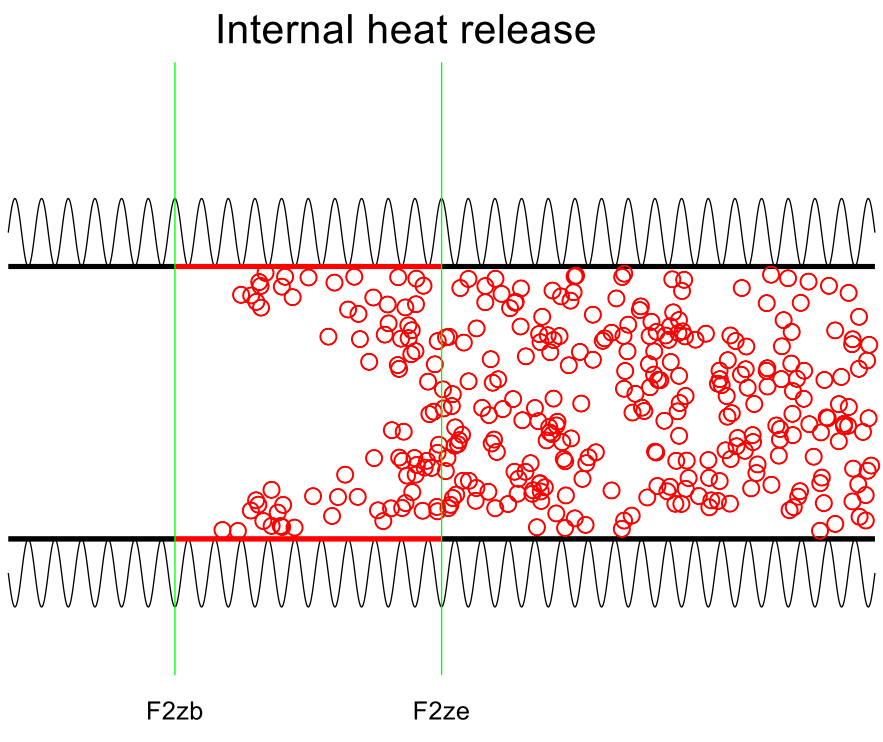

Figure 13 Internal heat release HR positions F2zb and F2ze.

FEDS model data input

The user data input is modest in the minimum case with 5 main items such as velocity, diameter, duct ends temperature, number of sections and for each section 4 items length, insulation type, insulation thickness and external temperature. The total duct length is the sum of the duct section lengths.

The main data input in the maximum case contains additional duct heat conductivity, duct thickness, fire damper type/value and position, radiation brake type/value and position, duct ends open or blocked and duct section data contains length, insulation type and thickness, shaft/coverings, inside and outside emissivities and additional branch inflow temperature and relative mass flow. This gives for *n* sections a minimum and maximum data input of 5+4*n* respectively 13+9*n*. The duct heat conductivity and duct thickness are known for standard duct dimensions and can be default values depending of the diameter. The amount of input data is shown for minimum and medium case with a single section in Figure 14 respectively 15.

The number of main data increases with five when an internal fire is included in the calculation. The total duct length can be stated as a checksum for all stated duct sections/parts. The length module can also be stated if the standard length module limits the total length of interest.

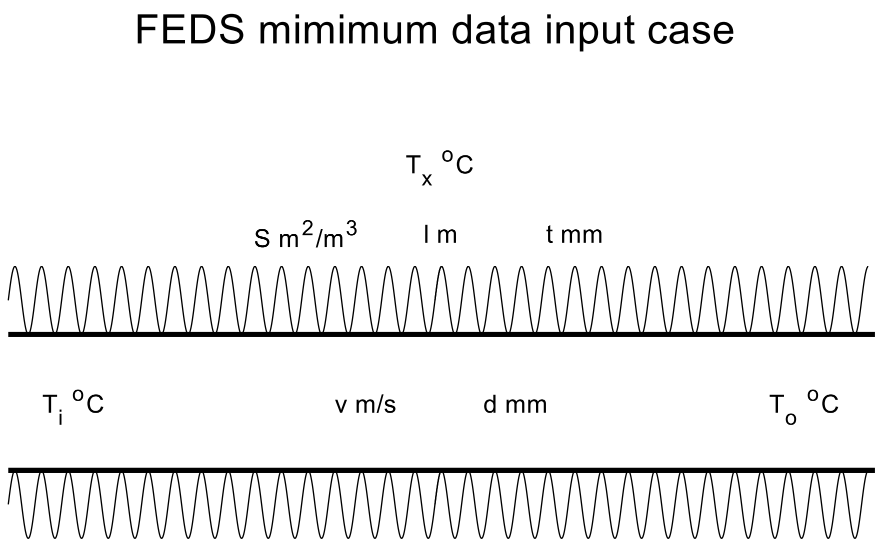

Figure 14 Minimum data input for model with a single section.

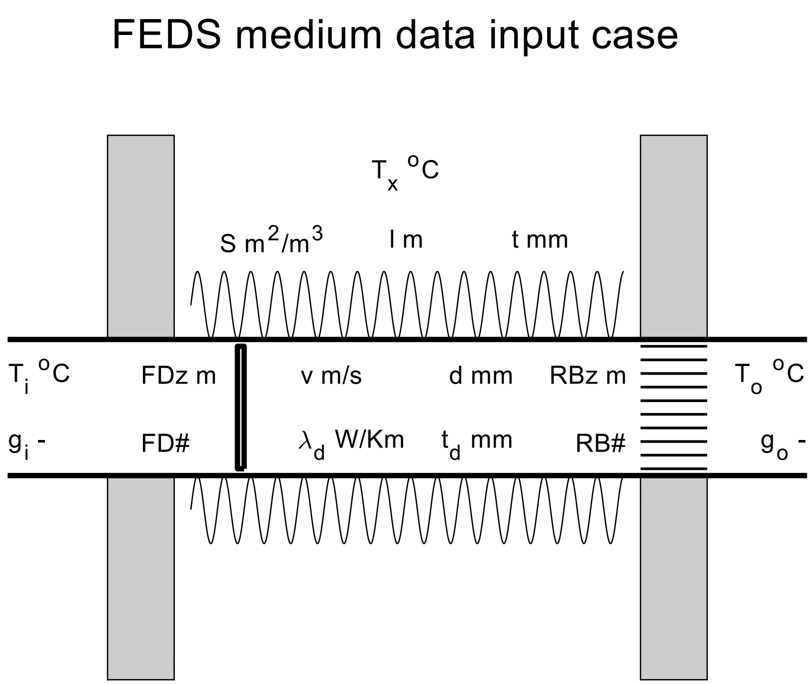

Figure 15 Medium data input for model with a single section.

FEDS calculation

The solution principle is to fulfil static heat balances for all rings temperatures by iterating a start solution for zero flow further. A matlab version of the FEDS program has been run with 100 test cases on a laptop computer Dell Latitude E5440. The iteration time interval as a function of number of rings for 100 test cases is shown in Figure 16. The iteration time has been estimated as a cubic function of the number of rings *n* equal to $8(n/1000)^3$.

The convergence is checked with a test quotient between the heat balance error equal to the heat balances itself versus the sum of the positive or the negative part of the heat balance terms. The convergence is also checked with a test quotient between the temperature changes and the so far calculated temperatures. These selected test quotients are independent of units and problem size. The two test quantities are shown as ^{10}log in Figure 17 for a case with an extract ventilation system solved in Figure 18. The test limit was set to 10^{-18}.

How the solution progresses for a single case is shown in Figure 17 in ^{10}log-scale by the standard deviation of dT, the standard deviation of T almost constant in red and the quotient in black. Notice that test quotient flattens out after 8 iterations and that test limit could be less than 10^{-12}. The numeric precision cannot go any further. The number of iterations if limited to 20 (default). The number of iterations is seldom above 10. The number of iterations should always be inspected and if the limit 20 is reached that might indicate that the solution is far from complete.

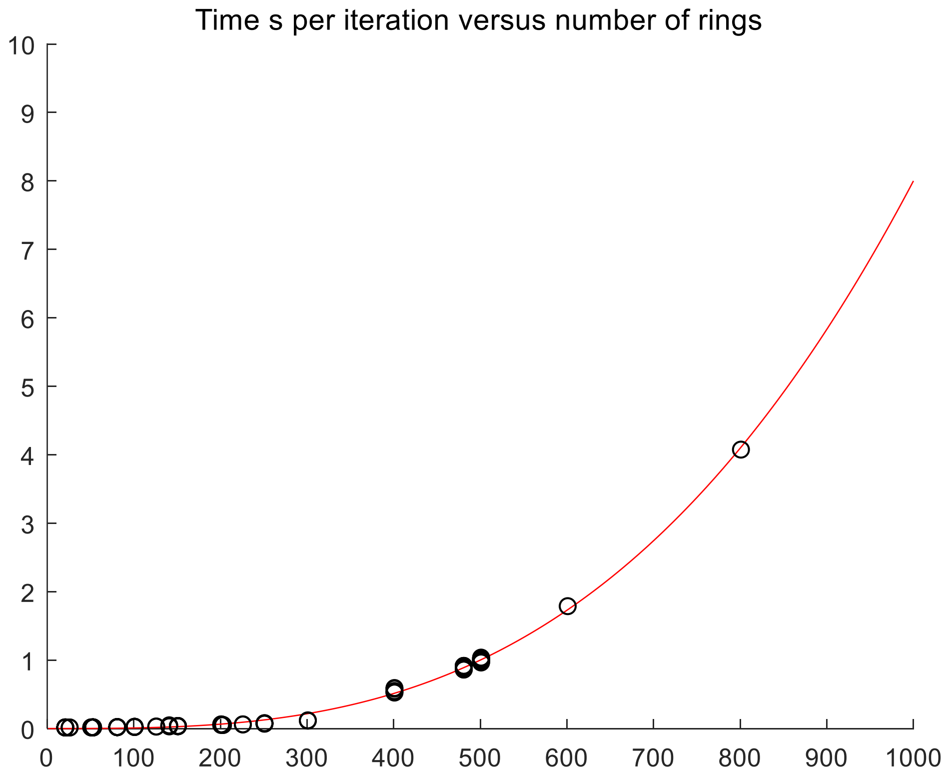

Figure 16 Iteration time interval as a function of number of rings for 100 test cases.

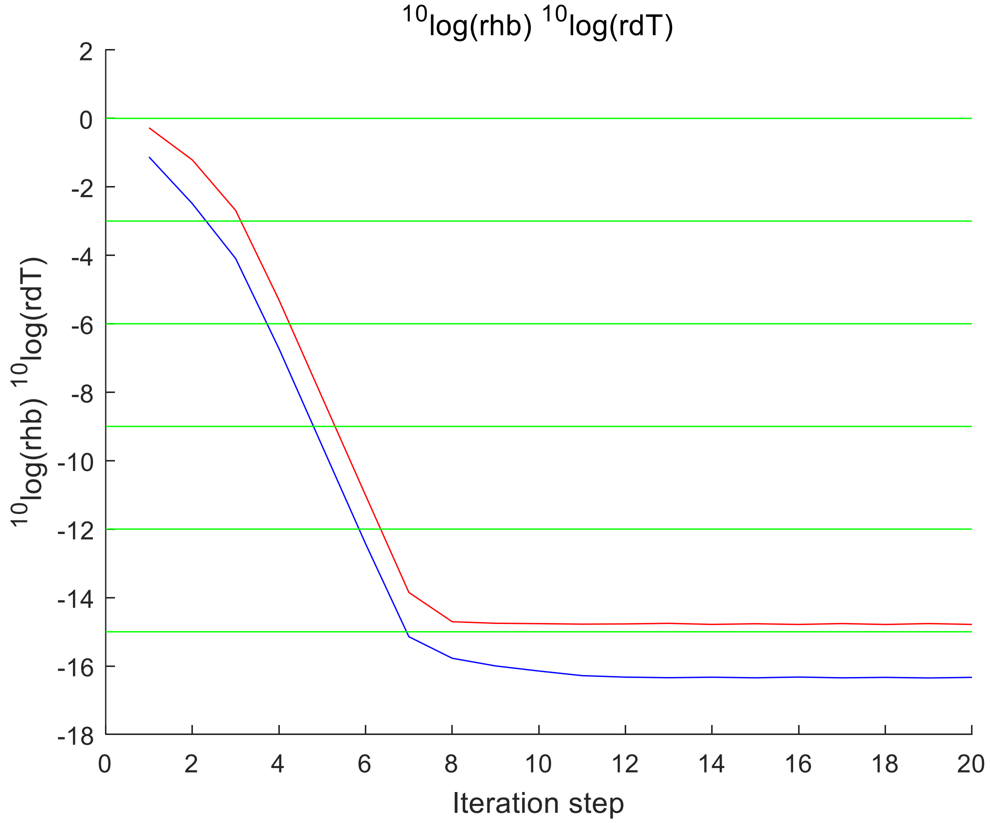

Figure 17 Iteration history for test quantities heat balance and temperature changes.

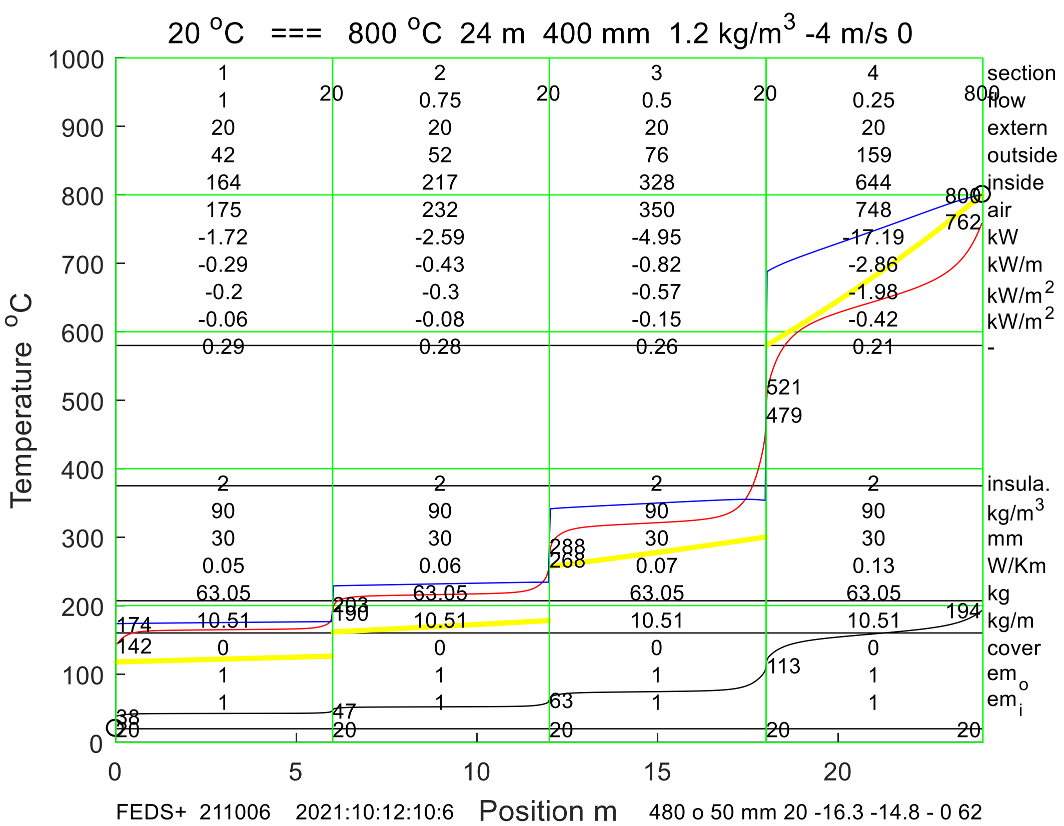

Figure 18 Example with iteration history in Figure 17.

References in Swedish

Lars Jensen	(2017)	TVIT-7102	Värmestrålning i en luftkanal.
Lars Jensen	(2020)	TVIT-7120	Värmetransport i porösa material.