Example:
Tubular element for a broiler application
Element power rating: 2,000 W (P)
Voltage: 230 V (U)
Final tube diameter 8 mm
Final tube length 1,000 mm

As a first step it is of importance to find out the actual heating zone length.
If the terminal length inside the element tube is 2 × 50 mm the total coil length (L_e) will be:

$$L_e = 1{,}000 - (2 * 50) = 900\ mm$$

Coil hot resistance (R_T) can be calculated using the following equation:

$$R = \frac{U^2}{P} = \frac{230^2}{2{,}000} = 26.45\ \Omega$$

Tube surface load (p_{tube}) can be defined by:

$$P_{y,tube} = \frac{P}{A_{tube}} = \frac{P}{(\pi * d_{tube} * L_e * 0.01)} =$$

$$\frac{2{,}000}{(\pi * 10 * 900 * 0.01)} = 7.07\ W/cm^2$$

For wire surface load (p_{wire}) inside tube, factor 3 is used as general rule of thumb:

$$p_{y,wire} = 3 * p_{y,tube} = 3 * 7.07 = 21.21 \ \approx 22\ \mathrm{W}/cm^2$$

Wire surface (A_C) can be calculated using the following equation:

$$p_{y,wire} = \frac{P}{A_c} => A_c = \frac{P}{p_{y,wire}} = \frac{2{,}000}{21.21} = 94.29 \ \approx \ 94\ cm^2$$

Kanthal's alloy Nikrothal® TE specifically designed for use in tubular elements is an excellent choice for this application and an average wire temperature of 900°C is expected. Due to temperature factor of resistance (Ct = 1,06 for Nikrothal® TE at 900°C) resistance at room temperature can be calculated by using the following equation:

$$R_T = C_t * R_{20} => R_{20} = \frac{R_T}{C_T} = \frac{26.45}{1.06} = 24.95 \ \approx \ 25\Omega$$

The ratio between wire surface area and resistance is:

$$\frac{A_c}{R_{20}} = \frac{94}{25} = 3.76\ cm^2/\Omega$$

The value 3.44 (cm2/Ω) for Nikrothal® TE is corresponding to a wire size of about 0.55 mm. We assume that a steel tube of initially 10 mm diameter is being used and can then expect a resistance reduction of about 30 % upon rolling. The resistance of the coil should therefore be close to 35 Ω.

The wire surface prior to compression is normally up to 7 % bigger, or 100 cm^2, and the ratio between wire surface and resistance 2.85 cm^2/Ω. The corresponding wire size is 0.50 mm.

Performing tests using calculated wire size is recommended aiming to verify element properties and influence from both coiling and reduction as a result of compression.

Example:
Suspended coil element for convection heater
Element power rating: 3,000 W (P)
Voltage: 230 V (U)
Coil length: 850 mm (L_e)

For a suspended element in a forced convection application the recommended wire surface load is normally ranging from 7 to 8 W/cm^2. For this element calculation example a suitable surface load at 8 W/cm^2 will be used.

The first thing to calculate is the total wire resistance needed. This is done in two steps by using the following calculations:

1. Coil hot resistance (R_T):

$$R = \frac{U^2}{P} = \frac{230^2}{300} = 17.63\ \Omega$$

Coil resistance at room temperature can be calculated by dividing the hot resistance (R_T) using the temperature factor (C_t). For this application design Nikrothal® 60 is a well proven alloy and at the expected temperature level 900°C the defined Ct value is 1.10.

2. Coil cold resistance (R_{20}):

$$R_{20} = \frac{R_T}{C_T} = \frac{17.63}{1.10} = 16.03\Omega$$

Wire surface area (A_C) is given by dividing element Power with the wire surface load:
$A_C = P / p = 3{,}000 / 8 = 375\ cm^2$

By using the result from surface area calculation, a suitable wire dimension can be found by calculating the surface area to cold resistance ratio, resistivity at room temperature (cm^2/Ω).

The ratio between wire surface and resistance is:

$$R_{20} = \frac{R_T}{C_T} = \frac{17.63}{1.10} = 16.03\Omega$$

Comparing the calculated value for resistivity at room temperature (cm^2/Ω) in the table for Nikrtohal® 60 shows that wire dimension Ø 1.0 mm is the closest match at 22.2 cm^2/Ω.

When wire dimension has been set the information on resistance per meter wire (Ω/m) is available from the Nikrothal® 60 table, hence total wire length can be calculated:

$$\frac{A_c}{R_{20}} = \frac{375}{16.03} = 23.39\ cm^2/\Omega$$

Wire surface load with selected wire dimension Ø 1.0 mm can be verified by the following calculation, as value surface area per meter (cm2/m) can be found in the Nikrothal® 60 table:

$$p_{y,wire} = \frac{P}{(cm^2/m) * L} = \frac{3{,}000}{31.4 * 11.6} = 8.21\ W/cm^2$$

The ratio between coil diameter and wire diameter (D/d) depends greatly on element design and wire temperature. For suspended element in this calculation outer coil diameter 15 mm is selected. This gives the following ratio:

$$\frac{D}{d} = \frac{15}{1} = 15$$

Coil pitch (s) can be found by using equation:

$$s = \frac{\pi * (D - d) * L_e}{L} = \frac{\pi * (15 - 1) * 850}{11.63} = 3.21mm$$

Use the following calculation to find out the number of element coil turns (W):

$$W = \frac{(1{,}000 * L)}{\pi * (D - d)} = \frac{(1{,}000 * 11.63)}{\pi * (15 - 1)} = 264\ turns$$

Close wound coil length (Lw) is given by number of coil turns times wire dimension:

$$L_w = W * d = 264 * 1 = 264$$

The streched coil length (Le) can now be calculated:

$$L = \frac{s}{d} * L_w = \frac{3.21}{1} * 264 = 847\ mm$$

Application tests to adjust and verify appropriate air flow settings is recommended and should always be considered in order to confirm element coil calculation and heating element properties in forced convection.

FURNACE CALCULATIONS

Designers of equipment using electric resistance heating materials must determine what material and form will satisfy specific heating requirements. The general approach is to start with the required operating temperature and power, the available voltage, and the space for the heating elements. A suitable material and element type is then selected (see 'Physical and Mechanical Properties,' page 15, and 'Design Factors,' page 19), followed by calculations for element parameters.

This section describes the relevant design calculations for spiral wire elements and corrugated strip and wire elements. (See the Appendix for detailed symbols, definitions, and formulas.)

ELEMENT SURFACE LOAD

Increased surface load results in a higher element temperature compared to its surroundings. Thus, the maximum permissible element temperature imposes a limit on surface load. The maximum permissible surface load decreases with increasing furnace temperature and depends on factors such as maximum element temperature, element deformation, and current limits.

Surface load affects element design in two opposing ways. If surface loading is reduced, a larger and more expensive element is required; however, such an element experiences slower material consumption, resulting in a longer life. The goal is to select a surface load that provides an optimal balance between service life and element cost.

The surface load of a heating element, p, is equal to its power, P, divided by its surface area, A:

$$p = P/A$$

In the metric system, surface load is usually expressed in W/cm^2, and the imperial system, in W/in^2. Element temperature is the major factor in the life of an element and is determined by its surrounding temperature and surface load. Since Kanthal® alloys can be operated at higher temperatures than Nikrothal® alloys, they can achieve higher surface loading with an equivalent or longer life than Nikrothal®.

There are three criteria for determining the maximum surface load:

- Element temperature
- Form stability (especially for Kanthal® alloys)
- Current

The more freely radiating the element form, the higher the maximum surface load. Therefore, the ROB (Rod Over Bend) type element can handle the highest load, followed by the corrugated strip element. The spiral type, being more concealed, has a lower maximum surface load. Spirals on tubes can carry a higher load than spirals in grooves.

The graphs in page 51, shows the recommended surface loads for Kanthal® and Nikrothal® alloys in industrial furnaces. Since Kanthal® alloys can be operated at higher temperatures than Nikrothal® alloys, a higher surface load can be accepted without jeopardizing element life. Element design is also crucial. The more freely radiating the element form, the higher the maximum surface load. Therefore, the ROB type element (corrugated heavy wire, mounted on the surface) can handle the highest load, followed by the corrugated strip element.

Coil elements on ceramic tubes can handle a higher load than coil elements in grooves. The values in the diagrams on page 51 are given for the following design conditions:

ELEMENT TYPES A (HEAVY WIRE) AND B (STRIP):
- Minimum strip thickness: 2.5 mm
- Minimum wire diameter: 5 mm
- Minimum pitch: 50 mm at maximum loop length and maximum surface load

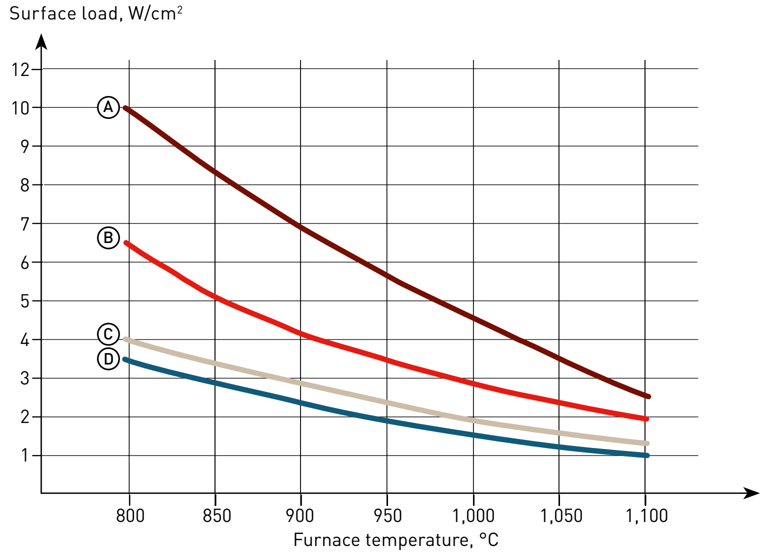
Maximum recommended loop length:
- < 900°C: 300 mm
- 1,000°C: 250 mm
- 1,100°C: 200 mm
- 1,200°C: 150 mm
- 1,300°C: 100 mm

For finer wire diameters and smaller strip thicknesses, lower surface loads and shorter loop lengths must be chosen to avoid element deformation and subsequent shorter element life.

ELEMENT TYPE C:
- Wire element on ceramic tube
- Minimum wire diameter: 3 mm

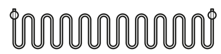
ELEMENT TYPE D:
- Wire and strip element in grooves
- Minimum wire diameter: 3 mm
- Minimum strip thickness: 2 mm

MAXIMUM RECOMMENDED SURFACE LOADS FOR NIKROTHAL® ALLOYS IN INDUSTRIAL FURNACES

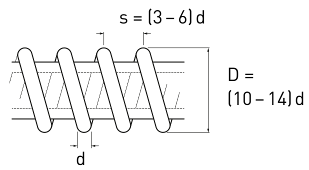


Ⓐ Freely radiating corrugated wire elements

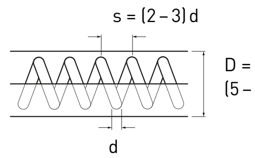
Ⓑ Freely radiating corrugated strip elements



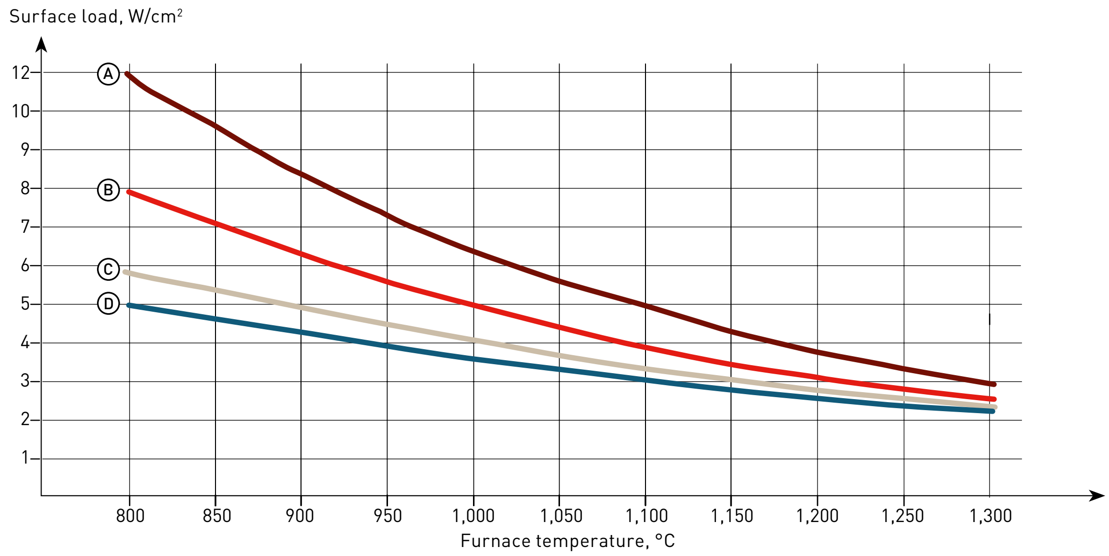
Ⓒ Spiral elements on ceramic tubes



Ⓓ Heating elements in grooves



MAXIMUM RECOMMENDED SURFACE LOADS FOR KANTHAL® A-1, KANTHAL® AF AND KANTHAL® APM ALLOYS IN INDUSTRIAL FURNACES



Note: The diagrams are valid for thyristor control. For on-off control lower surface loads should be chosen (about - 20%).

DESIGN OF WIRE ELEMENTS

CALCULATION OF WIRE DIAMETER

DIRECT CALCULATION METHOD

The diameter that will result in the desired surface load, given the electrical input data, can be calculated as:

$$d = \frac{1}{k_d} \sqrt[3]{I^2 \frac{\rho C_t}{p_s}}$$

where:
I = Current
ρ = Resistivity
C_t = Temperature factor
p_s = Surface load of heating element
k_d = Wire diameter form factor

For metric units, with ρ in Ω mm²/m and p_s in W/cm², k_d = 2.91, and d will be in mm.
For imperial units, with ρ in Ω circ. mil/ft and p_s in W/in², k_d = 335, and d will be in inch.

Example:
Power, W = 20 kW
Voltage, U = 220 V
Target surface load, ps = 4.0 W/cm2 (26 W/in²)
Wire temperature = 1,200°C (2,190°F)
Material = Kanthal® AF
Resistivity, ρ = 1.39 Ω mm²/m (836 Ω circ. mil/ft)
Temperature factor, Ct (1,200°C) = 1.06

First determine the current, I:

$$I = \frac{P}{U} = \frac{20{,}000}{220} = 90.9 \text{ A}$$

The diameter can then be calculated:

$$d = \frac{1}{2.91} \sqrt[3]{90.9^2 \frac{1.39 \times 1.06}{4.0}} = 4.98 \text{ mm (0.196 in)}$$

The nearest standard size is 5.0 mm (0.197 in). The actual surface load at this power and voltage will then be 3.95 W/cm² (25.5 W/in²).

TABLE LOOKUP METHOD

Wire diameter can alternatively be chosen using the ratio η, i.e. surface area, Ac, to cold resistance, R20. The ratio is presented as in the tables section, page 73.

Given the electrical data, element temperature, and target surface load, η can be calculated as:

$$\eta = \frac{A_c}{R_{20}} = I^2 \frac{C_t}{p_s}$$

where:
A_c = Surface area of the conducting wire
R_{20} = Cold resistance
I = Current
C_t = Temperature factor
p_s = Surface load of heating element

Having determined the target η, a suitable wire diameter can be selected from the tables. Whether this size actually suits the element concerned should be considered in relation to the operating conditions.

Example:

$$\eta = \frac{90.9^2 \times 1.06}{4.0} = 2{,}194 \frac{\text{cm}^2}{\Omega} \left(340 \; \frac{\text{in}^2}{\Omega}\right)$$

Under the η column in the table, the nearest value is 2,220 cm²/Ω (344 in²/Ω), giving a diameter of 5.0 mm (0.197 in). The actual surface load at this power and voltage will then be 3.95 W/cm² (25.5 W/in²).

CALCULATION OF WIRE LENGTH

Having determined wire type and diameter, the next stage in arriving at a spiral element is to calculate wire length. The first step is to determine the cold resistance, R_{20}, of the selected wire:

$$R_{20} = \frac{R_T}{C_t} = \frac{U^2}{PC_t}$$

where:

R_{20} = Cold resistance
R_T = Hot resistance
C_t = Temperature coefficient
U = Voltage
P = Power

The resistance per unit length, $R_{20/m}$, can be calculated as:

$$R_{20/m} = \frac{4\rho}{\pi d^2}$$

Alternatively, the resistance per meter (or per ft) has been precalculated for material and diameter combinations and can be found in the tables. From this, the wire length, ℓ, can be calculated as:

$$\ell = \frac{R_{20}}{R_{20/m}}$$

Example:
Wire diameter, d = 5.0 mm (0.197 in)
Power, P = 20 kW
Voltage, U = 220 V
Wire temperature = 1,200°C (2,190°F)
Material = Kanthal® AF
Resistivity, ρ = 1.39 Ω mm²/m (836 Ω circ. mil/ft)
Temperature factor, Ct (1,200°C) = 1.06

$$R_T = \frac{U^2}{P} = \frac{220^2}{20{,}000} = 2.42\ \Omega$$

$$R_{20} = \frac{R_T}{C_t} = \frac{2.42}{1.06} = 2.28\ \Omega$$

The resistance per unit length, $R_{20/m}$ is:

$$R_{20/m} = \frac{4 \times 1.39}{3.14 \times 5.0^2} = 0.0708\,\frac{\Omega}{m}\ \left(0.0216\ \frac{\Omega}{ft}\right)$$

The total wire length is:

$$\ell = \frac{2.28}{0.0708} = 32.2\ \mathrm{m}\ (106\ \mathrm{ft})$$

COIL ELEMENT DIMENSIONS

Having determined the wire diameter and length, the next step is to select the external diameter of the coil. Regarding values for the ratio of coil external diameter, D to wire diameter, d, see page 51.

Smaller ratios cause too great a winding strain on the wire; larger ratios produce a weaker, more flimsy coil.

For a given wire length, ℓ, the number of turns, w is:

$$w = \frac{\ell}{\pi(D - d)}$$

where the length should be converted to the same unit as diameter, e.g. from m to mm (multiply ℓ by 1,000) or ft to in (multiply ℓ by 12).

The close-wound coil length, L_w, is:

$$L_w = wd$$

Recommended values for the pitch, s, see page 51.

Stretched coil length can finally be calculated as:

$$L = \frac{s}{d}\,L_w$$

Example:
Wire diameter, d = 5.0 mm (0.197 in)
Wire length, ℓ = 32.2 m (106 ft)
Coil outer diameter, D = 27.5 mm (1.08 in)
Pitch, s = between 10 mm (0.394 in) and 20 mm (0.787 in)

$$w = \frac{32{,}200}{3.14 \times (27.5 - 5.0)} \approx 456$$

Close-wound coil length,

$$L_w = 456 \times 5.0 = 2{,}280 \text{ mm } (89.8 \text{ in})$$

Stretched length,

$$\text{min: } L = 2 \times 2{,}280 = 4{,}560 \text{ mm } (180 \text{ in})$$
$$\text{max: } L = 4 \times 2{,}280 = 9{,}120 \text{ mm } (359 \text{ in})$$

DESIGN OF CORRUGATED STRIP ELEMENTS

In designing corrugated strip elements, the procedure is first to determine the width, thickness, and length of the strip and then the corrugation parameters: pitch, depth (or height) of corrugation, etc. Instructions are given for both parallel and stretched corrugated elements.

Strip size depends on operating conditions centered around surface loading and on the type of alloy selected. In turn, selection of an alloy is based on the same parameters plus furnace atmosphere, heating/cooling cycles, and element temperature. For recommended values of surface load, see graphs in page 51.

Example:
Power, W = 12 kW
Voltage, U = 110 V
Target surface load, p_s = 1.0 W/cm² (6.45 W/in²)
Material = Kanthal® A-1
Resistivity, ρ = 1.45 Ω mm²/m (872 Ω circ. mil/ft)
Temperature factor, C_t (1,200°C) = 1.04

Table lookup method
An alternative method of calculating the strip section is calculate the surface area to cold resistance ratio and find a suitable strip dimension in the tables:

$$\eta = \frac{A_c}{R_{20}} = I^2 \frac{C_t}{p_s}$$

Example

$$\eta = \frac{109.1^2 \times 1.04}{1.0} = 12{,}400 \frac{\text{cm}^2}{\Omega} \left(1{,}920 \ \frac{\text{in}^2}{\Omega}\right)$$

The nearest standard size is 2.0 × 20 mm (0.079 × 0.79 in) with η = 12,100 cm²/Ω (1875 in²/Ω). The actual surface load at this power and voltage will then be 1.02 W/cm² (6.6 W/in²). Note that a 0.7 × 35 mm (0.028 × 1.4 in) strip also has η = 12,100 cm²/Ω (1875 in²/Ω), but is much less appropriate since the thickness ideally should be at least 1.5 mm (0.06 in).

CALCULATION OF STRIP LENGTH
Having determined the strip width and thickness, the strip length, l, must be calculated. This requires an initial calculation of cold resistance, R_{20}:

$$R_{20} = \frac{R_T}{C_t} = \frac{U^2}{PC_t}$$

The resistance per unit length, $R_{20/m}$, can be calculated as:

$$\ell = \frac{R_{20}}{R_{20/m}}$$

Alternatively, the resistance per meter (or per ft) has been precalculated for material and diameter combinations and can be found in the tables. From this, the strip length, ℓ, can be calculated as:

$$R_{20/m} = \frac{\rho}{tb}$$

Example:
Strip dimensions, t × b = 2.0 × 20 mm (0.079 × 0.79 in)
Power, P = 12 kW
Voltage, U = 110 V
Material = Kanthal® A-1
Resistivity, ρ = 1.45 Ω mm²/m (872 Ω circ. mil/ft)
Temperature factor, Ct (1,200 °C) = 1.04

$$R_T = \frac{U^2}{P} = \frac{110^2}{12{,}000} = 1.01\ \Omega$$

$$R_{20} = \frac{R_T}{C_t} = \frac{1.01}{1.04} = 0.97\ \Omega$$

The resistance per unit length, $R_{20/m}$ is:

$$R_{20/m} = \frac{1.39}{2 \times 20} = 0.0363 \frac{\Omega}{m} \left(0.0110\ \frac{\Omega}{ft}\right)$$

The total wire length is:

$$\ell = \frac{0.97}{0.0363} = 26.7\ \text{m (88 ft)}$$

CORRUGATED ELEMENT DIMENSIONS

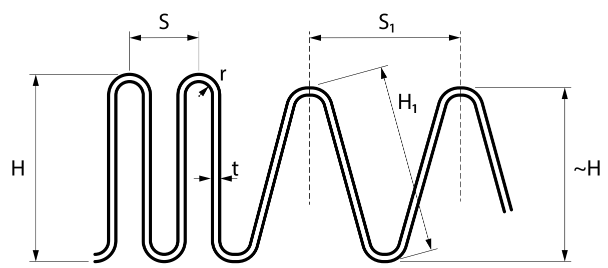
A corrugated element, with a parallel section and a stretched section, is shown in Fig. 1. As illustrated, the key design parameters for the element are the element (or corrugation) height, H, pitch, s, and bending radius, r. Other values necessary for element calculations are: Total element length, Le (given by the furnace design), and strip thickness, t, width, b, and length, ℓ.

Parallel Corrugated Element

When the loops are parallel, there is a geometrical relationship between r and s:

$$r = \frac{s - 2t}{4}; \quad s = 4r + 2t$$

FIGURE 1



The element length, L_e, after parallel corrugation is then:

$$L_e = \frac{\ell(2r + t)}{H + 1.14r - 0.43t}$$

Alternatively, if the element length is pre-determined, the element height can be calculated as:

$$H = \frac{\ell}{L_e}(2r + t) - 1.14r + 0.43t$$

Stretched Elements

Stretching a corrugated element so that the loops are no longer parallel reduces the danger of deformation. A stretched element may be calculated by the same method as a parallel element. That is: the total (stretched) element length, L_1, is given by the furnace design; t, b, and ℓ are determined by calculation. Element height, H, must be selected.

The pitch after stretching, s_1, (center-to-center distance between hooks for hanging elements) is:

$$s_1 = \frac{sL_1}{L}$$

The element height can be calculated by:

$$H = \frac{\ell}{L_e}(2r + t) - 1.14r + 0.43t$$

The height of a stretched element, H, will be somewhat lower than that with parallel loops.

$$H \simeq \sqrt{H_1 - \left(\frac{s_1}{2}\right)^2}$$

The difference in height will in most cases be small and may be neglected.

Example:
Strip dimensions, t × b = 2.0 × 20 mm (0.079 × 0.79 in)
Strip length: 26.7 m (88 ft)
Element length, L_e: 3.00 m (9.84 ft)
Ceramic support diameter, d_{sup}: 28 mm (1.1 in)
Ceramic support max permissible width: 33 mm (1.3 in)

A bending radius, r, of at least 14 mm (0.55 in) is needed for the strip to fit around the Ø28 mm (Ø1.1 in) ceramic supports. A slight clearance of 0.5 mm (0.02 in) should be added in addition to this.

$$r = \frac{d_{sup}}{2} + 0.5 = \frac{28}{2} + 0.5 = 14.5\ \text{mm}\ (0.57\ \text{in})$$

For parallel loops, the pitch, s, will then be:

$$s = 4r + 2t = 62\ \text{mm}\ (2.44\ \text{in})$$

The element height is then:

$$H = \frac{26.7}{3.00}(2 \times 14.5 + 2) - 1.14 \times 14.5 + 0.43 \times 2 =$$
$$260\ \text{mm}\ (10.2\ \text{in})$$

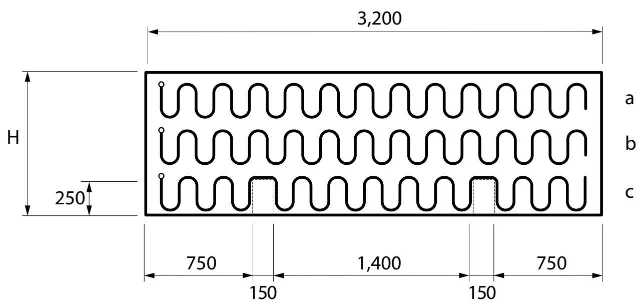
Check the dimensions:
t = 2 mm (0.079 in)
b = 20 mm (0.79 in) = 10 t
s = 62 mm (2.44 in) = 3.1 b
r = 14.5 mm (0.57 in) = 7.25 t
H = 260 mm (10.2 in)
>1.5 mm (>0.06 in)
(8–12) t
≤33 mm (1.3 in)
min. 50 mm (2.0 in)
min. (4–5) t
max. 150–400 mm (5.9–15.8 in)

All dimensions are within the recommended limits.

DESIGN OF FREELY RADIATING STRIP AND WIRE ELEMENTS

In order to show the element calculation methods for freely radiating wire and strip elements, a 200 kW fiber-lined furnace is chosen as a calculation example (see Fig. 2). The furnace is equipped with deep-corrugated elements mounted on ceramic hangers. In the first case, wire elements are used, and in the second case, strip elements. A comparison has been made at the end with strip elements of NiCr elements to show weight and cost savings by using Kanthal® AF.

FIGURE 2

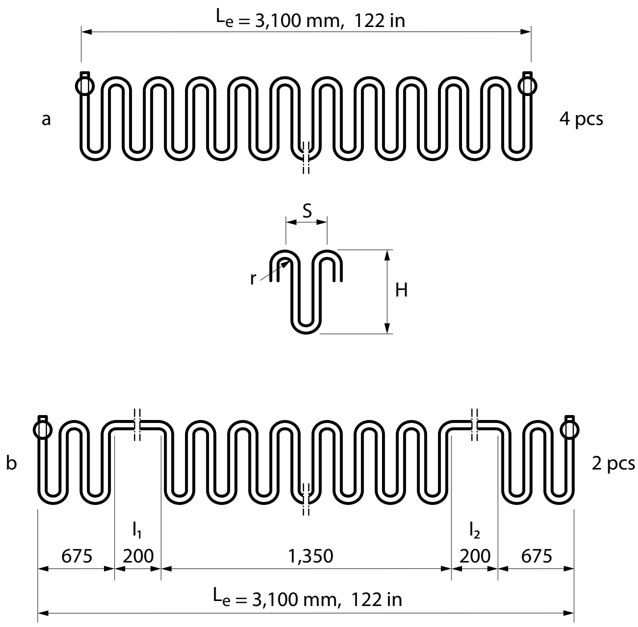


DEEP-CORRUGATED KANTHAL® AF WIRE ELEMENT

The element design is shown in Fig. 3. The furnace is equipped with four elements of type "a" and two elements of type "b".

FURNACE DATA
Power (total): 200 kW
Furnace temperature, T_f: 1,100°C (2,010°F)
Assumed element temperature, T_e (for calculations): 1,200°C (2,190 °F)
Number of 3-phase groups: 1
Power per phase: 66.67 kW
Voltage: 380 V
Current: 175.4 A
Resistance: 2.166 Ω
Number of elements in series: 2
Element length, L_e: 3.1 m (10.2 ft)

FIGURE 3



DATA PER ELEMENT
Power, P: 33.33 kW
Voltage, U: 190 V
Current, I: 175.4 A
Max surface load, p_s: 6.0 W/cm² (38.7 W/in²)
Resistance, hot, R_T: 1.083 Ω
Material: Kanthal® AF
Resistivity, ρ: 1.39 Ω mm²/m
Temperature factor, C_t (1,200°C): 1.06
Terminals: Round, ℓ_u, length 350 mm (13.8 in)

CALCULATION OF TERMINALS
Determine the appropriate terminal diameter to handle the current and maintain the lowest terminal temperature.

With the terminal length, ℓ_u, and diameter, d_u, decided, the resistance of the two terminals, R_u, (one per end) can be calculated:

$$R_u = 2 \times \frac{4\ell_u \rho}{\pi d^2}$$

$$R_u = 2 \times \frac{4 \times 0.35 \times 1.39}{3.14 \times 16^2} = 0.0048\ \Omega$$

CALCULATION OF WIRE DIAMETER
The preliminary wire diameter in mm (or in) is calculated as:

$$d = \frac{1}{k_d} \sqrt[3]{I^2 \frac{\rho C_t}{p_s}}$$

where k_d is 2.91 for metric units (or 335 for imperial). The diameter that would give a surface load of 6.0 W/cm² (38.7 W/in²) at full power is:

$$d = \frac{1}{2.91} \sqrt[3]{175.4^2 \frac{1.39 \times 1.06}{6.0}} = 6.74\ \text{mm}\ (0.265\ \text{in})$$

The closest standard dimension is 7.0 mm (0.276 in).

CALCULATION OF WIRE LENGTH

The cold resistance of the element, R_{20}, can be calculated as:

$$R_{20} = \frac{R_T}{C_t} - R_u$$

where R_u is the cold resistance of the two terminals combined.

$$R_{20} = \frac{1.083}{1.06} - 0.0048 = 1.017\ \Omega$$

The wire length, ℓ, can then be calculated as:

$$\ell = \frac{\pi d^2 R_{20}}{4\rho}$$

$$\ell = \frac{3.14 \times 7.0^2 \times 1.017}{4 \times 1.39} = 28.1\ \text{m}\ (92.2\ \text{ft})$$

Based on this diameter and length, and that the density of Kanthal® AF is 7.15 kg/cm^3 (0.258 lb/in^3), the wire weight will be 7.7 kg (17 lb).

SURFACE LOAD

The surface load can be calculated using:

$$p_s = \frac{I^2 C_t}{\eta}$$

where η for the selected wire dimension can be found in the table. For Ø7.0 mm Kanthal® AF it is 6,090 cm2/Ω.

$$p_s = \frac{175.4^2 \times 1.06}{6{,}090} = 5.35\,\frac{\text{W}}{\text{cm}^2}\left(34.5\,\frac{\text{W}}{\text{in}^2}\right)$$

An alternative is to use the formula:

$$p_s = \frac{I^2 \rho C_t}{24.67 \times d^3}\ (\text{metric})$$

$$p_s = \frac{I^2 \rho C_t}{3.77 \times 10^7 \times d^3}\ (\text{imperial})$$

BENDING RADIUS

A bending radius, r, of 9 mm (0.35 in) will be used in this example.

Maximum corrugation height

Three elements are suspended on a wall having a height of 1,000 mm (1,000/3 ≈ 333 mm per element [13.1 in/element]). Take into account that about 25% of this height per element should be reserved for clearance, leaving 75% of that height for the element.

$$H_{max} = 333 \times 0.75 = 250\ \text{mm}\ (9.84\ \text{in})$$

This number can be used as a preliminary height when calculating the number of pitches.

CALCULATION OF NUMBER OF PITCHES

The number of pitches is calculated as:

$$N = \frac{0.5 \times [\ell - (\ell_1 + \ell_2 + \cdots + \ell_n)]}{H + 1.14r - 0.43d}$$

where ℓ_1, ℓ_2, ... ℓ_n, are straight sections of the element.

Element type "a" (Fig. 3), no straight sections:

$$N = \frac{0.5 \times 28{,}100}{250 + 1.14 \times 9.0 - 0.43 \times 7.0} = 54.6 \approx 55$$

Since the maximum height was used in this calculation, the result must be rounded up to 55. With 55 pitches, the average pitch, s, will be:

$$s = \frac{L_e}{N} = \frac{3{,}100}{55} = 56\ \text{mm}\ \ (2.2\ \text{in})$$

Check that $s \geqslant 4r + 2d$

$$4r + 2d = 4 \times 9.0 + 2 \times 7.0 = 50\ \text{mm}\ (2.0\ \text{in}) \rightarrow \text{ok}$$

Element "b" (Fig. 3), two 200 mm long straight sections:

$$N = \frac{0.5 \times [28{,}100 - (200 + 200)]}{250 + 1.14 \times 9.0 - 0.43 \times 7.0} = 53.8 \approx 54$$

Rounding up, this gives 54 pitches. These 54 pitches need to be distributed over a total span of 2,700 mm (106.3 in), consisting of two 675 mm (26.6 in) wide outer parts, and the 1,350 mm (53.1 in) wide center part between the supporting beams (see Fig. 3).The outer parts correspond to ¼ of the span each and should thus contain approximately ¼ of the 54 pitches, and in the same way since the center part corresponds to ½ of the span, it should also have roughly half of the pitches. The exact numbers would be 13.5 pitches in the outer parts, and 27 pitches in the center. For a design using full pitches, the distribution will be 14 pitches in the outer parts and 26 in the center. The average pitch in the outer parts, s1, will thus be:

$$s_1 = \frac{675}{14} = 48 \text{ mm } (1.9 \text{ in})$$

and in the center:

$$s_2 = \frac{1{,}350}{26} = 52 \text{ mm } (2.0 \text{ in})$$

Check that s ⩾ 4 r + 2 d

$$4r + 2d = 4 \times 9.0 + 2 \times 7.0 = 50 \text{ mm } (2.0 \text{ in}) \rightarrow \text{not ok}$$

Note that the pitch in the outer parts will be less than 50 mm. As an alternative solution the furnace design can be revised by moving the 200 mm (7.0 in) ceramic supports inwards by 25 mm (1.0 in) (see Fig. 4). The average pitch in the outer parts then become:

$$s_1 = \frac{700}{14} = 50 \text{ mm } (2.0 \text{ in})$$

and in the center:

$$s_2 = \frac{1{,}300}{26} = 50 \text{ mm } (2.0 \text{ in})$$

Check that s ⩾ 4 r + 2 d

$$4r + 2d = 4 \times 9.0 + 2 \times 7.0 = 50 \text{ mm } (2.0 \text{ in}) \rightarrow \text{ok}$$

CALCULATION OF CORRUGATION HEIGHT

The element height, or corrugation height, is calculated as:

$$H = \frac{0.5 \times [\ell - (\ell_1 + \ell_2 + \cdots + \ell_n)]}{N} - 1.14r + 0.43d$$

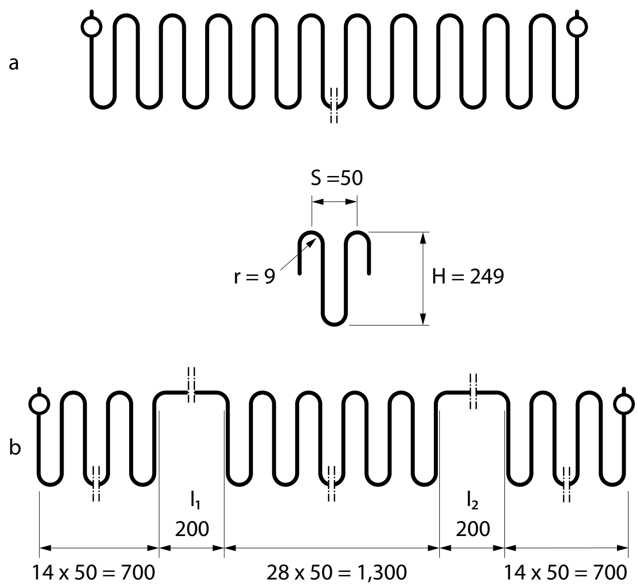
Element type "a" (Fig. 3), no straight sections:

$$H = \frac{0.5 \times (23{,}100)}{55} - 1.14 \times 9.0 + 0.43 \times 7.0 =$$
$$248 \text{ mm } (9.8 \text{ in})$$

Element "b" (Fig. 3), two 200 mm long straight sections:

$$H = \frac{0.5 \times [23{,}100 - (200 + 200)]}{54} - 1.14 \times 14.5 + 0.43 \times 2.5 =$$
$$249 \text{ mm } (9.8 \text{ in})$$

FIGURE 4

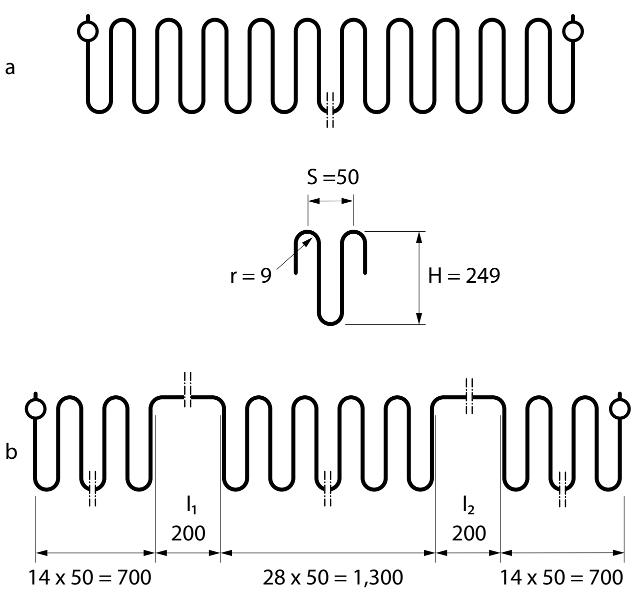


DEEP-CORRUGATED KANTHAL® AF STRIP ELEMENTS

The element design is shown in Fig. 5. The furnace is equipped with four elements of type "a" and two elements of type "b". As can be seen from the sketch, element "b" has two straight parts because of the supporting beams for the charge.

FURNACE DATA
Power (total): 200 kW
Furnace temperature, T_f: 1,100°C (2,010°F)
Assumed element temperature, T_e (for calculations): 1,200 °C (2,190 °F)
Number of 3-phase groups: 1
Power per phase: 66.67 kW
Voltage: 220 V
Current: 303 A
Resistance, hot: 0.726 Ω
Number of elements in series: 2
Element length, Le: 3.1 m (10.2 ft)

FIGURE 5



DATA PER ELEMENT
Power, P: 33.33 kW
Voltage, U: 110 V
Current, I: 303 A
Max surface load, p_s: 3.0 W/cm² (19.4 W/in²)
Resistance, hot, R_T: 0.363 Ω
Material: Kanthal® AF
Resistivity, ρ: 1.39 Ω mm²/m
Temperature factor, Ct (1,200°C): 1.06
Terminals: Round, length, ℓ_u: 350 mm (13.8 in)

CALCULATION OF TERMINALS
Determine the appropriate terminal diameter to handle the current and maintain the lowest terminal temperature.

With the terminal length, ℓ_u, and diameter, d_u, decided, the resistance of the two terminals, R_u, (one per end) can be calculated:

$$R_u = 2 \times \frac{4\ell_u \rho}{\pi d^2}$$

$$R_u = 2 \times \frac{4 \times 0.35 \times 1.39}{3.14 \times 20^2} = 0.0031\ \Omega$$

CALCULATION OF STRIP SIZE
The preliminary strip thickness is calculated as:

$$t = k_t \times \sqrt[3]{I^2 \frac{\rho \times C_t}{p_s}}, k_t = \sqrt[3]{\frac{1}{20n(1+n)}}$$

where n is the desired ratio of width/thickness. The version of kt above applies for the use of metric units. Aiming for a surface load of 3.0 W/cm² (19.4 W/in²), and n = 12 gives:

$$t = \sqrt[3]{\frac{1}{20 \times 12 \times (1+12)}} \times \sqrt[3]{303^2 \frac{1.39 \times 1.06}{3.0}} =$$

$$2.44\ \text{mm}\ (0.096\ \text{in})$$

The closest standard dimension is 2.5 mm thickness (0.10 in). Aiming for a 12 times wide strip means that

$$b = 12 \times 2.5 = 30\ \text{mm}\ (1.2\ \text{in})$$

CALCULATION OF STRIP LENGTH

The cold resistance of the element, R_{20}, can be calculated as:

$$R_{20} = \frac{R_T}{C_t} - R_u$$

where R_u is the cold resistance of the two terminals combined.

$$R_{20} = \frac{0.363}{1.06} - 0.0031 = 0.339\ \Omega$$

The strip length, ℓ, can then be calculated as:

$$\ell = \frac{R_{20}tb}{\rho}$$

$$\ell = \frac{0.339 \times 2.5 \times 30}{1.39} = 18.3\ \mathrm{m}\ (60\ \mathrm{ft})$$

Based on this width, thickness and length, and that the density of Kanthal® AF is 7.15 kg/cm³ (0.258 lb/in³), the strip weight will be 9.8 kg (21.6 lb).

SURFACE LOAD

The surface load can be calculated using:

$$p_s = \frac{I^2 C_t}{\eta}$$

where n for the selected strip dimension can be found in the table. For 2.5 × 30 mm Kanthal® AF it is 35,100 cm²/Ω.

$$p_s = \frac{303^2 \times 1.06}{35{,}100} = 2.77\frac{\mathrm{W}}{\mathrm{cm}^2}\left(17.9\frac{\mathrm{W}}{\mathrm{in}^2}\right)$$

An alternative is to use the formula:

$$p_s = \frac{1}{20n(1+n)} I^2 \frac{\rho C_t}{t^3}\ \text{(metric)}$$

$$p_s = \frac{\pi}{96 \times 10^6 \times n(1+n)} I^2 \frac{\rho C_t}{t^3}\ \text{(imperial)}$$

which gives the same result.

BENDING RADIUS

Ceramic supports to be used have a diameter of 28 mm (1.1 in) and permit a maximum strip width of 33 mm (1.3 in). This gives a minimum bending radius, r, of 14 mm (0.55 in). Add 0.5 mm (0.02 in) for clearance, giving:

$$r = \frac{28}{2} + 0.5 = 14.5\ \mathrm{mm}\ (0.57\ \mathrm{in})$$

MAXIMUM CORRUGATION HEIGHT

Three elements are suspended on a wall having a height of 1,000 mm (1,000/3 ≈ 333 mm per element [13.1 in/element]). Take into account that about 25% of this height per element should be reserved for clearance, leaving 75% of that height for the element.

$$H_{max} = 333 \times 0.75 = 250\ \mathrm{mm}\ (9.84\ \mathrm{in})$$

This number can be used as a preliminary height when calculating the number of pitches.

CALCULATION OF NUMBER OF PITCHES

The number of pitches is calculated as:

$$N = \frac{0.5 \times [\ell - (\ell_1 + \ell_2 + \cdots + \ell_n)]}{H + 1.14r - 0.43t}$$

where ℓ_1, ℓ_2, ... ℓ_n, are the lengths of straight sections of the element.

Element type "a" (Fig. 5), no straight sections:

$$N = \frac{0.5 \times 18{,}300}{250 + 1.14 \times 14.5 - 0.43 \times 2.5} = 34.45 \approx 35$$

Since the maximum height was used in this calculation, the result must be rounded up to 35. With 35 pitches, the average pitch, s, will be:

$$s = \frac{L_e}{N} = \frac{3{,}100}{35} = 89\ \mathrm{mm}\ (3.5\ \mathrm{in})$$

Check that $s \geqslant 4r + 2t$:

$$4r + 2t = 4 \times 14.5 + 2 \times 2.5 = 63\ \mathrm{mm}\ (2.5\ \mathrm{in}) \rightarrow \mathrm{ok}$$

Element "b" (Fig. 5), two 200 mm long straight sections:

$$N = \frac{0.5 \times [18{,}300 - (200 + 200)]}{250 + 1.14 \times 14.5 - 0.43 \times 2.5} = 33.72 \approx 34$$

These 34 pitches will be distributed as 9 pitches in the outer parts and 16 in the center in this example. The average pitch in the outer parts, s_1, will thus be:

$$s_1 = \frac{675}{9} = 75 \text{ mm (3.0 in)}$$

and the average pitch in the center, s_2, will be:

$$s_2 = \frac{1{,}350}{16} = 84 \text{ mm (3.3 in)}$$

Check that s ⩾ 4 r + 2 t:

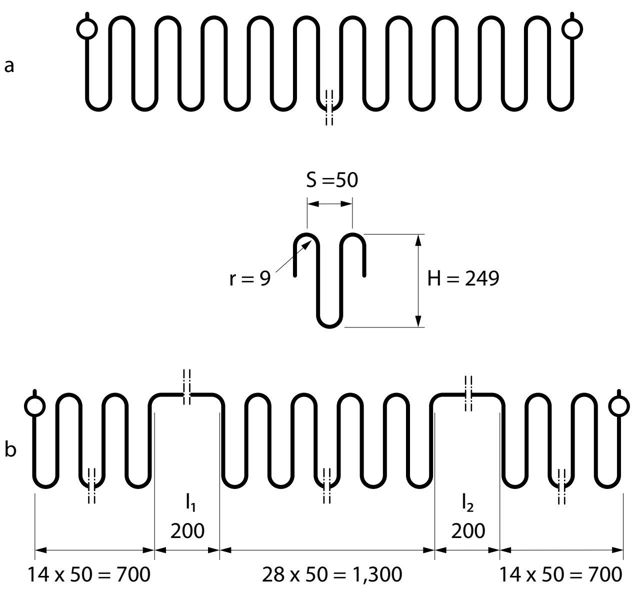
$$4r + 2t = 4 \times 14.5 + 2 \times 2.5 = 63 \text{ mm (2.5 in)} \rightarrow \text{ok}$$

CALCULATION OF CORRUGATION HEIGHT

The element height, or corrugation height, is calculated as:

$$H = \frac{0.5[\ell - (\ell_1 + \ell_2 + \cdots + \ell_n)]}{N} - 1.14r + 0.43t$$

FIGURE 6



Element type "a" (Fig. 6), no straight sections:

$$H = \frac{0.5 \times (18{,}300)}{35} - 1.14 \times 14.5 + 0.43 \times 2.5 =$$
$$246 \text{ mm (9.7 in)}$$

Element "b" (Fig. 6), two 200 mm long straight sections:

$$H = \frac{0.5 \times [18{,}300 - (200 + 200)]}{34} - 1.14 \times 14.5 + 0.43 \times 2.5 =$$
$$248 \text{ mm (9.8 in)}$$

Check maximum corrugation height according to the recommendation. In this case height was limited to a maximum of 250 mm to fit in the furnace with the desired clearance.

CALCULATION OF ELEMENT TEMPERATURE

Element temperature, T_e, in °C is calculated as:

$$T_e = -273 + \sqrt[4]{\frac{p_s}{\varepsilon\delta \times 5.67 \times 10^{-12}} + (T_f + 273)^4}$$

where ε is the emissivity of the strip, δ is a form factor, and T_f is the furnace temperature. The emissivity, ε, is 0.70 for Kanthal® alloys, and 0.88 for Nikrothal® alloys.

The form factor, δ, is calculated as:

$$\delta = \frac{b + t + \frac{s}{2} - \sqrt{\frac{s^2}{4} + b^2}}{b + t}$$

For this calculation, use the smallest pitch, s, in the design, which will likely be the hottest position. In this case, the smallest pitch is 75 mm, representing the outer parts of the bottom row (element type "b").

$$\delta = \frac{30 + 2.5 + \frac{75}{2} - \sqrt{\frac{75^2}{4} + 30^2}}{30 + 2.5} = 0.676$$

The calculated element temperatures will thus be:

$$T_e = -273 + \sqrt[4]{\frac{2.77}{0.70 \times 0.676 \times 5.67 \times 10^{-12}} + (1{,}100 + 273)^4} =$$
$$1{,}190\ °\text{C (2,170 °F)}$$

which is acceptable for Kanthal® AF.

COMPARISON BETWEEN NIKROTHAL® 80 AND KANTHAL® AF

The comparison has been made under the following assumed conditions: The same power, hot resistance, and cross sections for terminal and strip.

$$p_s = \frac{I^2 C_t}{\eta} = 303^2 \times \frac{1.07}{44{,}700} = 2.2\,\frac{W}{cm^2}\ \left(14.2\,\frac{W}{in^2}\right)$$

where η and C_t are looked up in the tables. Ct was looked up for 1,200 °C, i.e. 100 °C higher than the furnace temperature to take into account that the element is always hotter. The resistance per unit length, R_ℓ, used below for calculation of length, can also be found in the tables for the chosen strip dimension of Nikrothal® 80.

$$R_u = 2 \times \frac{4\ell_u \rho}{\pi d^2} = 2 \times \frac{4 \times 0.35 \times 1.09}{3.14 \times 20^2} = 0.0024\ \Omega$$

$$R_{20} = \frac{R_T}{C_t} - R_u = \frac{0.363}{1.07} - 0.0024 = 0.0337\ \Omega$$

$$\ell = \frac{R_{20}}{R_{20/m}} = \frac{0.337}{0.0145} = 23.2\ \text{m (76.1 ft)}$$

The density of Nikrothal® 80 is 8.30 g/cm³ (0.30 lb/in³), which gives a strip weight of 14.4 kg (31.8 lb).

For elements of type "a":

$$N = \frac{0.5 \times 23{,}200}{250 + 1.14 \times 14.5 - 0.43 \times 2.5} = 43.70 \approx 44$$

$$s = \frac{3{,}100}{44} = 70\ \text{mm (2.8 in)}$$

$$H = 0.5 \times \frac{23{,}200}{44} - 1.14 \times 14.5 + 0.43 \times 2.5 = 248\ \text{mm (9.8 in)}$$

For elements of type "b":

$$N = \frac{0.5 \times [23{,}200 - (200 + 200)]}{250 + 1.14 \times 14.5 - 0.43 \times 2.5} = 42.95 \approx 43$$

Distributed as 11 pitches per outer side, and 21 in the center region:

$$s_1 = \frac{675}{11} = 61.4\ \text{mm (2.4 in)};\ s_2 = \frac{1{,}350}{21} = 64\ \text{mm (2.5 in)}$$

$$H = 0.5 \times \frac{[23{,}200 - (200 + 200)]}{43} - 1.14 \times 14.5 + 0.43 \times 2.5 = 250\ \text{mm (9.8 in)}$$

Calculation of element temperature, s = 61.4 mm (2.4 in):

$$\delta = \frac{30 + 2.5 + \frac{61.4}{2} - \sqrt[2]{\frac{61.4^2}{4} + 30^2}}{30 + 2.5} = 0.624$$

The emissivity, ε, for Nikrothal® alloys is 0.88.

$$T_e = -273 + \sqrt[4]{\frac{2.2}{0.88 \times 0.624 \times 5.67 \times 10^{-12}} + (1{,}100 + 273)^4} = 1{,}164\ °C\ (2{,}130\ °F)$$

ELEMENT "A" - COMPARISON TABLE STRIP 30 X 2.5 MM (1.2 X 0.1 IN)

	KANTHAL® AF	NIKROTHAL®
Power, kW	33.33	33.33
Hot resistance, Ω	0.363	0.363
Element height, mm (in)	246 (9.7)	250 (9.8)
Strip length, m (ft)	18.3 (61.9)	23.2 (76.1)
Strip weight. kg (lbs)	9.8 (21.6)	14.4 (31.8)
Number of supports	34	43

The strip length is 21% shorter and the element weight is 32% less with Kanthal® AF compared with Nikrothal® 80. The number of supporting pins is reduced by 21% with Kanthal® AF.