CONflux
intelligent heating

Technology Guide

1 Introduction to PTC heaters

1.1 PTC – Positive Temperature Coefficient

A thermistor is an electrical component with a temperature dependent resistance. When the characteristic is such that the electrical resistance increases nonlinearly with temperature, it is referred to as a PTC thermistor. Typically, the resistance versus temperature curve can be split in two distinct parts separated by a trip region, see Figure 1.1. Below the trip region the resistance is small and slowly increasing, above the trip region the resistance increases very rapidly.

Other resistance versus temperature characteristics also exist. For example, CTC (Constant Temperature Coefficient) and ZTC (Zero Temperature Coefficient) materials have linearly increasing and constant resistances respectively. Conductors typically have a CTC characteristic with a weak temperature coefficient.

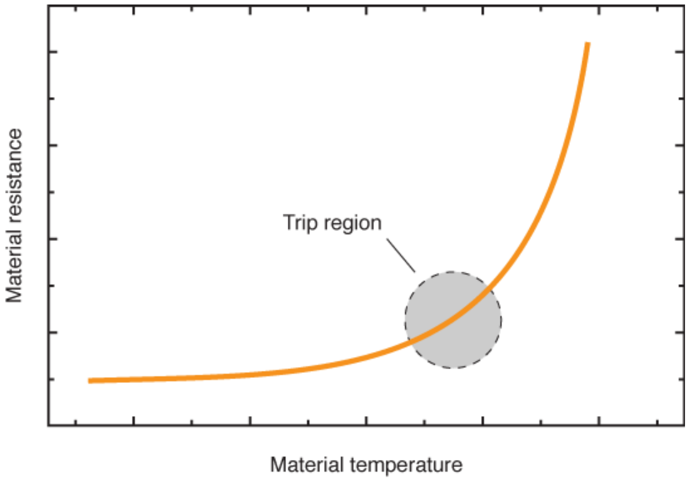


Figure 1.1 Typical resistance versus temperature curve for a PTC material.

1.2 PTC heaters

One typical application for PTC thermistors is as heating element. When connected into an electrical circuit such a component will generate heat due to the process of Joule heating. The heating power, P, of a material with resistance R and temperature T, is given by

$$P(T) = \frac{V^2}{R(T)}$$

where V is the applied voltage. When the power is switched on, the material starts to heat up. As the material becomes warmer it will dissipate more heat to its surroundings, due to thermal convection, conduction and radiation. Eventually the system reaches a thermal equilibrium with its surrounding (the heating rate is equal to the cooling rate), characterised by an equilibrium heating power P_{eq} and an equilibrium temperature T_{eq}. Neglecting thermal radiation and convection,

$$P_{\mathrm{eq}} = U \times \Delta T$$

Here, U is the total heat transfer coefficient which contains all cooling parameters and $\Delta T=T_{eq}-T_A$ is the equilibrium temperature increase, with T_A being the ambient temperature. Unless the voltage or the ambient conditions are changed, the temperature will stay constant in this state. If the voltage or the ambient temperature is increased, the material will reach a new state of equilibrium at a higher temperature. Correspondingly, more efficient cooling (i.e. higher U) will lead to a new state of equilibrium at a lower temperature.

To achieve efficient heating (i.e. large P), R must be small. For traditional CTC and ZTC heater materials, where R is largely independent of T, the equilibrium temperature is dangerously high, and one must resort to external overheating protection in the form of thermal fuses and electronics.

For PTC materials, *R* increases with temperature and hence *P* decreases with temperature. This means that even though *P* is large for low temperatures, ensuring efficient heating when it is really needed, the state of equilibrium is reached much faster than for traditional heaters and the equilibrium temperature is correspondingly lower. The same reasoning can be applied to systems at constant ambient temperature but with varying cooling – *P* increases with increased cooling efficiency. The term self-regulation is often used for a PTC material's ability to adapt its heating power to its surroundings.

The principal difference between a PTC and CTC heater is illustrated in Figure 1.2, which shows equilibrium heating power (or temperature increase) as a function of ambient temperature and cooling.

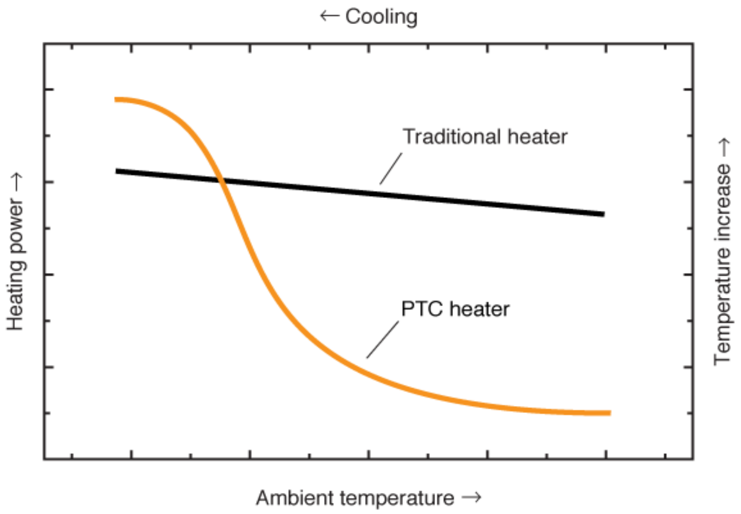


Figure 1.2 Equilibrium heating power and temperature increase versus ambient temperature and cooling. PTC heater compared to a traditional (CTC) heater.

2 Core technologies

2.1 The SIP compound

SIP – Superimposed Impedance Polymer – is an electrically conductive polymer compound with an intrinsic PTC characteristic. It consists of three primary ingredients; two carbon blacks with different resistivity characteristics and an isolating polymer matrix. The superimposed resistance versus temperature behaviour of the two carbon blacks in the presence of the isolating polymer gives a strong PTC effect. The trip region can be shifted by varying the amounts of the primary ingredients. Typically, the polymer matrix consist of silicone rubber (PDMS – Polydimethylsiloxane), but other polymers are possible.

The SIP compound is covered by a Swedish patent. Patent applications have been submitted in Canada, China, Europe ("EP-application"), Japan, South Korea and USA.

2.2 The ZPZ foil

The ZPZ foil is an electric heating foil based on the SIP compound. ZPZ - Zero Positive Zero - means that the SIP compound is sandwiched between two thin metal sheets. Typically, the metal sheets are made of copper (with a very small resistivity). With this three-layered structure, the entire metal sheets act as electrodes and the electric current through the SIP layer flow peripendicular to the surface. See Figure 2.1. By varying the thickness of the SIP layer and the constitution of the SIP compound, the electrical performance of the ZPZ foil can be adjusted to different technical specifications. See appendix A for a table of specifications.

Contacts are attached to each of the metal sheets by standard techniques, for instance soldering. To electrically isolate and mechanically protect the ZPZ foil, it can be encapsulated. Different materials with different characteristics can be chosen, for instance PET, PI or silicon.

The ZPZ foil is covered by a Swedish patent. Patent applications have been submitted in Canada, China, Europe ("EP-application"), Japan, South Korea and USA.

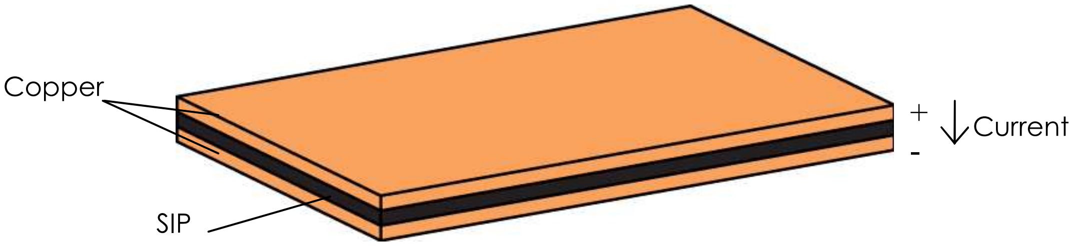


Figure 2.1 Sketch of a ZPZ foil.

2.3 The ZPI foil

The ZPI foil is an electric heating foil based on the SIP compound. ZPI – Zero Positive Infinity - means that the SIP compound is sandwiched between a metal sheet and an electrically isolating sheet. Typically, the metal sheet is made of copper (with a very small resistivity) and the isolating sheet is made of a polymer. An electrode pattern with two interlacing nodes is created by for instance chemical etching of the metal sheet. Thus the electric current runs through the SIP compound between the electrode nodes. See Figure 2.2. Note that if an inner node (going out from the main node) is damaged, the surrounding parts of the ZPI foil will be unaffected and remain fully functional. By varying the electrode pattern and the constitution of the SIP compound, the performance of the ZPI foil can be adjusted to different technical specifications. See appendix A for a table of specifications.

Contacts are attached to each of the electrode nodes by standard techniques, for instance soldering. To electrically isolate and mechanically protect the ZPI foil, it can be encapsulated. Different materials with different characteristics can be chosen, for instance PET, PI or silicon.

For the ZPI foil, a Swedish patent application has been submitted.

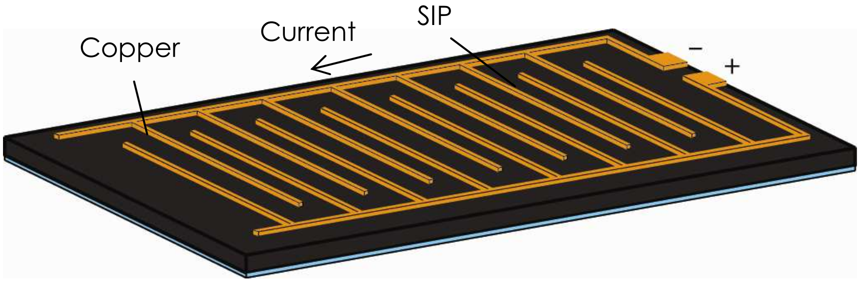


Figure 2.2 Sketch of a ZPI foil.

3 The ZPZ foil

3.1 Pointwise PTC characteristic

Because of the ZPZ design, all points on the ZPZ foil surface are independent. Each point can in fact be thought of as an individual PTC heater, wired in parallel with all other points, as illustrated in Figure 3.1. Note, however, that all points have the same PTC characteristic, since the SIP compound is the same in all points.

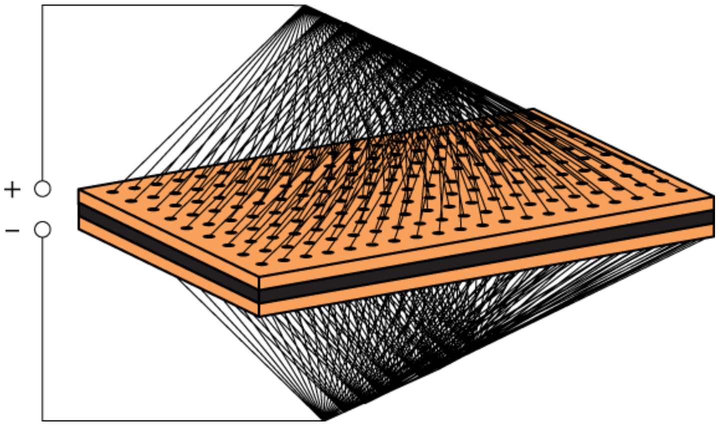


Figure 3.1 Each point on the ZPZ foil is an independent PTC heater, wired in parallel with all other points.

3.1.1 Pointwise self-regulation

In traditional etched foil heaters, one tries to compensate for different thermal loads across the heater surface by varying the width and density of the etched circuit, hence creating zones with different watt densities. But once the circuit is etched, there is no way to change it. To increase power in one zone, one has to increase power in all zones. This leaves no room for flexibility and requires a detailed analysis of the thermal properties of the system at hand.

In contrast, the ZPZ foil can automatically accommodate for varying thermal loads, to a large degree. Pointwise PTC characteristic means pointwise self-regulation – each point on the ZPZ foil surface will adapt to its surroundings and regulate its heating power accordingly. Lower ambient temperature and/or more efficient cooling gives more power, higher ambient temperatures and/or less cooling gives less power, as illustrated in Figures 3.1.1 and 3.1.2. The extent to which the ZPZ foil can compensate for different thermal loads depends on details of the design, such as SIP characteristic, voltage and encapsulation.

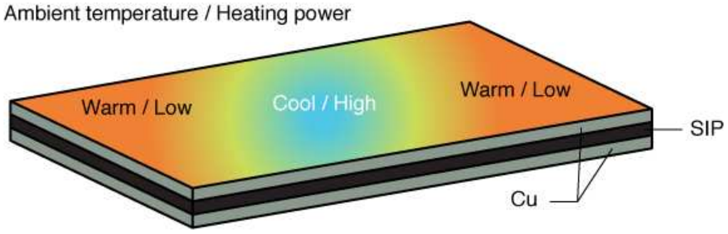


Figure 3.1.1 Pointwise self-regulation to varying ambient temperatures.

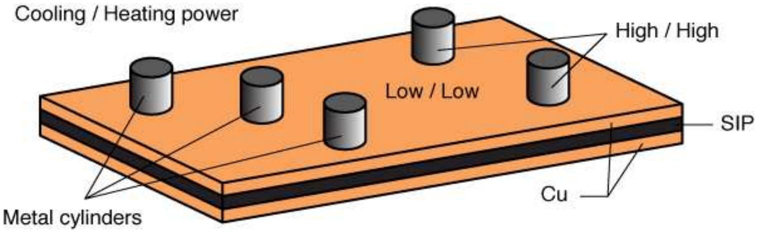


Figure 3.1.2 Pointwise self-regulation to varying cooling conditions. The heating power is higher beneath the metal cylinders.

3.1.2 Pointwise temperature limiting

Pointwise self-regulation implies pointwise temperature limiting. We define the limiting temperature T_{lim} as the equilibrium temperature of a ZPZ foil suspended horizontally in still air at room temperature, a setup representing minimal cooling conditions (i.e. minimal U). Hence the temperature of the ZPZ foil will not exceed T_{lim} as long as the ambient temperature stays close to room temperature. Should the ambient temperature increase, the temperature of the ZPZ foil will also increase but, due to the PTC behaviour, the increase will be less.

There are two categories of heating applications based on the ZPZ foil; with and without electronic temperature regulation. In the first case, the ZPZ foil is held at a constant operating temperature T_{op} by an electronic circuit which regulates the supplied power. In the second case, the ZPZ foil is allowed to reach a self-regulated equilibrium temperature T_{eq}. The relationship between T_{op}, T_{eq} and T_{lim} is illustrated in Figure 3.1.2.

Temperature limiting corresponds to a two-stage overheating protection system. Should the temperature regulating electronic circuitry fail, the ZPZ foil temperature will increase but it will stabilize at T_{eq} and not go into thermal runaway. Even if the cooling conditions changes dramatically, the ZPZ foil temperature will never exceed T_{lim}.

There is no equivalent to T_{lim} in a traditional etched foil heater, since the temperature increase is practically independent of ambient temperature. In order to avoid dangerously high temperatures one therefore has to resort to external safety devices such as thermal fuses or electronics. The built-in safety of the ZPZ foil, inherent to the material itself, is a more elegant and reliable solution. Moreover, whereas external overheating protection devices monitor a single point on the heater surface, the ZPZ foil's temperature limiting is *pointwise*. Every point on the ZPZ foil surface has a built-in temperature limiter.

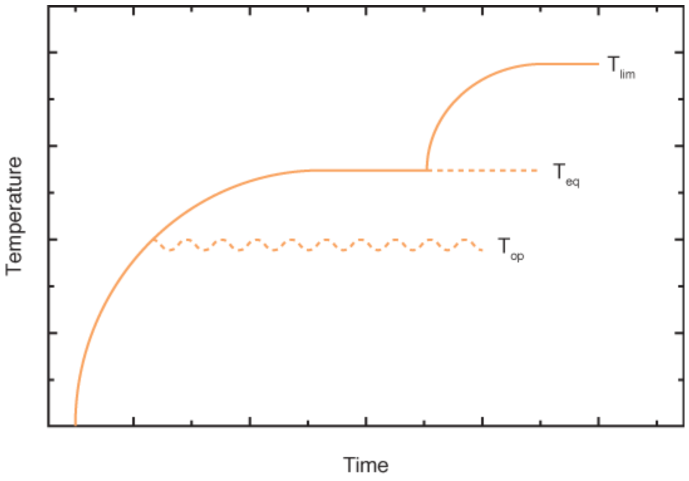


Figure 3.1.2 Pointwise temperature limiting. T_{op} is the foil temperature in an electronically regulated heating application, T_{eq} is the foil temperature in a self-regulated application, T_{lim} is the maximum foil temperature.

3.2 100% surface coverage

In a traditional etched foil heater, the actual surface covered by the circuit is approximately 50% of the heater surface. In order to achieve a certain average power density or temperature, the power density and temperature of the circuit has to be roughly twice as high. Therefore, there will always be a temperature variation across an etched foil heater surface – it is part of the construction itself.

The ZPZ foil on the other hand, has almost 100% surface coverage (depending on design, isolation, soldering points etc), which allows for a smoother temperature distribution and hence that the power density and temperature can be kept lower than in the etched foil case. It is usually preferable to work with as low power densities and temperatures as possible.

3.3 Rapid warm-up

The ZPZ foil's powerful PTC effect allows for a rapid warm-up, since the initial heating power is much higher than the equilibrium one. The benefits compared to an etched circuit foil are illustrated in Figures 3.3.1 and 3.3.2 for two different cases. In both cases, the heater is supplied with full power until the operating temperature is reached, after which an electronic regulation circuit sets in and cycles the power on and off in order to keep the desired temperature constant.

In the first case, Figure 3.3.1, the ZPZ foil is designed for the same operating power as the etched foil. Since the average initial power is higher, the operating temperature is reached faster.

In the second case, Figure 3.3.2, the ZPZ foil is designed to reach the operating temperature in the same time as the etched foil. Because of the PTC effect, the ZPZ foil's operating power will then be lower than the etched foil's. Maintaining a constant operating temperature with a lower power is in general less demanding for the regulatory circuitry, which may be more important than a rapid warm-up time in some applications.

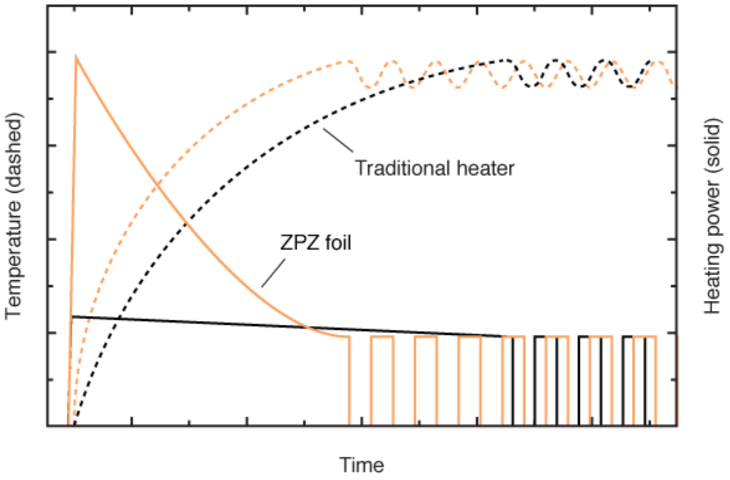


Figure 3.3.1 Rapid warm-up: Both heaters are supplied with full power until the operating temperature is reached, after which an electronic regulation circuit sets in and cycles the power on and off in order to keep the desired temperature constant. The ZPZ foil is designed for the same operating power as the traditional heater.

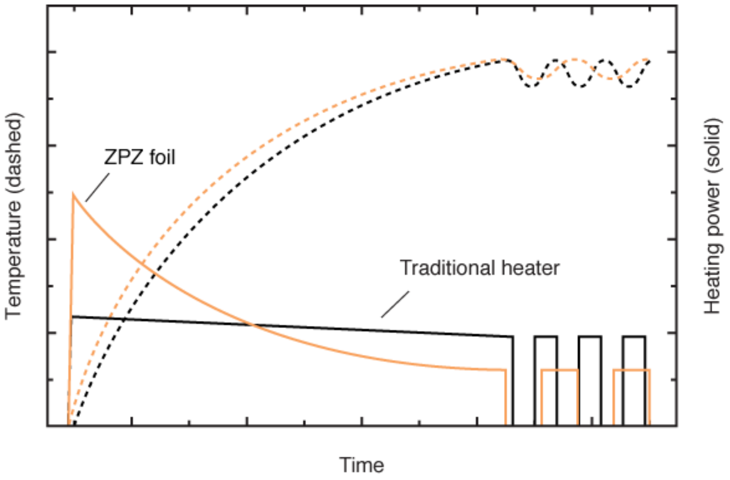


Figure 3.3.2 Low power regulation: Both heaters are supplied with full power until the operating temperature is reached, after which an electronic regulation circuit sets in and cycles the power on and off in order to keep the desired temperature constant. The ZPZ foil is designed to reach operating temperature in the same time as the traditional heater.

3.4 Functionality independent of form

Due to the geometry, the power density and the temperature of the ZPZ foil is independent of area. Once the SIP compound has been specified, the design process is reduced to cut out the desired form and size. Should the same voltage, power density and temperature specifications be required in another project, no changes need to be made to the ZPZ foil or the SIP compound.

4 The ZPI foil

4.1 Pointwise PTC and rapid warm-up

Due to the characteristics of the SIP compound and the construction of the ZPI foil, both the pointwise PTC characteristic (as described in sec 3.1) and the rapid warm-up (as described in sec 3.3) is present also for the ZPI foil. The surface coverage of a ZPI foil will depend on the electrode pattern, and can thus be both low, high and vary over the surface. Note here that the surface coverage will set the scale of the resolution of the pointwise PTC and the strength of the rapid warm-up.

4.2 High Voltage

The ZPI design makes high voltage applications possible. The rated voltage is determined by the distance between the two electrode nodes. To match the two node pattern to a technical specification is very easy using standard production techniques. The inherent pointwise safety ensures that the electrical and thermal control is at maximum.

4.3 Geometrical flexibility

The ZPI design implies a very flexible product. The structure of interlacing nodes together with the flexibility of the SIP compound ensures that the ZPI foil can meet complex geometrical requirements. Additionally, the two node pattern can be created to vary over the surface. The inherent pointwise safety ensures that the electrical and thermal control is at maximum. See Figure 4.1 for an example of a ZPI foil that has been bent.

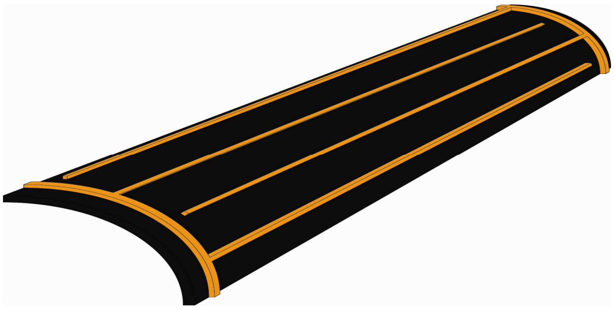


Figure 4.1 Example of a ZPI foil that has been bent according to a cylinder geometry.

5 Intelligent heating

5.1 Overview

The concept of intelligent heating encompasses technology, economy and ecology. The ZPZ foil’s inherent self-regulation and form independent functionality and the ZPI foil’s production efficiency and flexibility provide many opportunities to design cost-effective solutions with high efficiency. From a system based on intelligent heating you should expect a low total cost of ownership (TCO).

At Conflux we always strive towards optimal performance and minimal environmental stress. Energy efficiency is a key factor in reducing wastage and pollution. Pointwise self-regulation leads to an immediate optimization of energy consumption.

See table 5.1 for an overview of the three concepts of intelligent heating.

Intelligent heating technology		**Intelligent heating economy**		**Intelligent heating ecology**
Self-regulation		Optimized power consumption		Minimized energy wastage
Pointwise temperature limiting	>	Reduced regulatory and safety circuitry	>	Streamlined production – less materials and energy
Functionally independent of form		Cost effective product development		Reduced pre-production environmental impact

Table 5.1 The concept of intelligent heating illustrated.

The unique features of the ZPZ and the ZPI foil are evident from table 5.2, which gives a concise comparison of heating technologies on the market. (PTF is short for Polymer Thick Film.)

	PTC heater				**Constant heater**
	ZPZ	**ZPI**	**PTF**	**Ceramic**	**Etched foil**
Self-regulation	✓	✓	✓	✓	✗
Pointwise self-regulation	✓	✓	✗	✗	✗
Temperature limiting	✓	✓	✓	✓	✗
Pointwise temperature limiting	✓	✓	✗	✗	✗
100% surface coverage	✓	✗	✗	✗	✗
Rapid warm-up	✓	✓	✓	✓	✗
Functionality independent of form	✓	✓	✗	✗	✗
Geometrical flexibility	✗	✓	✓	✗	✓
Mains voltage	✗	✓	✓	✓	✓

Table 5.2 Comparing heating technologies. PTF: Polymer Thick Film.

5.2 Optimized power consumption

Once the design is set for a traditional etched foil heater, there is no way to increase heating power in one part of the heater without increasing power across the entire surface. Because of the pointwise self-regulation, the ZPI/ZPZ foil automatically distributes more power to cold regions and less power to hot regions. This optimized power distribution can give substantial power savings in some applications.

Example

A water pipe to a cabin equipped with ZPI/ZPZ foil, is buried and led through different sorts of ground materials, such as water, stone, earth etc. Cooling will affect these ground materials differently and the materials will in turn affect the water pipe to a different extent. Due to pointwise self-regulation, the heating effect will be optimized to the area in which there is a need for heating. This is achieved without necessarily having to heat up the rest of the pipe. This results in energy efficiency and reduced TCO. See appendix B for another, more detailed example.

5.3 Reduced regulatory and safety circuitry

Due to the very high equilibrium temperatures and lack of built-in temperature limiting of traditional heating materials, a typical heater application will often consist of both a heating element and additional regulatory and safety circuitry (for instance a thermal fuse). The intrinsic self-regulation and temperature limiting of the ZPI/ZPZ foil may allow, depending on for instance regulatory issues, for a reduced amount of such circuitry and components. This results in both reduced use of raw materials and in production energy consumption. In all, one can expect a reduced TCO.

Example
A telecom company intends to replace a ZTC/CTC heating technology in their base stations with a more efficient solution. With the ZPI/ZPZ foil as a replacement, the need of regulatory and safety-circuitry will be decreased. Since the need of these components decreases, the Conflux solution becomes easier/faster to install, safer and also more environmentally friendly.

5.4 Cost effective product development

Functionality independent of form enables a fast and cost effective product development process. Once the SIP compound has been specified, changes in area, shape or other design elements which do not require a different power density or surface temperature are easily accommodated for without changing the ZPZ foil. This also means that the same ZPZ foil can be used across an entire line of products with similar thermoelectrical specifications. Typically, product development is more energy inefficient than real production and a reduction in this area has large economical and environmental benefits.

For the ZPI foil only one side, the metal side, needs to be treated in production. Hence both changes in geometrical design and full scale production can be made very efficient using standardized techniques.

Example
A customer requests a heating product in variable sizes, but with identical temperatures/power densities. The adjustment of the ZPZ foil in this case only implies cutting in the requested sizes. This makes production very cost effective and provides environmental benefits due to the reduction of steps in the chain of production.

5.5 Total cost of ownership

Due to the unique self-regulatory capacity of the ZPI/ZPZ foil, it is possible to reduce the need of regulatory and safety circuitry. This can have a major impact on the total cost of ownership, TCO. In table 5.3 below we show a template of how to perform an estimate of the possible reduction in TCO.

TCO

Amount	Specification	Cost
lengths	Cable, of typ A and B	
quantity	Relay	
quantities	Thermostat/thermofuse	
hours	Handling charges	
hours	Operating cost	
years	Expected lifespan	
	…..	
	Total cost	XX

Table 5.3 TCO (total cost of ownership)

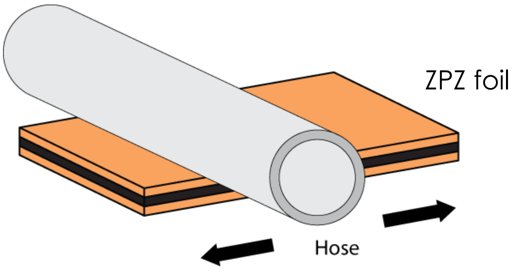
A Technical specification of the ZPI and the ZPZ foil

	ZPZ foil	ZPI foil
AC/DC voltage	Yes/Yes	Yes/Yes
Maximal voltage (V)	50	400
Maximal power density (W/cm^2)	4.0	3.0
Maximal limiting temperature (C)	60	70
Power tolerance	±10%	±10%
Bulk thickness (mm)	0.15 – 0.20	0.15 – 0.25
RoHS compliant	Yes	Yes

B An example of reduced power consumption

Assume a setup according to the figure below, with a planar electrical heater and a plastic hose, filled with flowing water, covering 50% of the total area of $A=1\ dm^2$. The hose can move, hence its position on the heater surface will vary. The ambient temperature is $T_A = 20C$, although the temperature of the water flowing through the hose is lower. Assume that the heat transfer coefficient with the surrounding air is $u_{air} = 12\ W/m^2K$.

One estimates that $p = 5.0\ W/dm^2$ is required below the hose, to ensure the water is heated enough.



For a traditional heater the power consumption is designed to be constant over the surface, since the position of the hose varies. Hence the total power consumption will be:
$P_{trad} = p*A\ \ = 5.0$ W.
Assume that the conducting wire itself covers 50% of the total area. The maximal surface temperature, obtained outside the hose and above the conducting wire, is: $T_{trad} = T_A + 2p/2u_{air} = 20 + 500/12 = 62C$ (assuming that heat is conducted equally up and down from the surface).

The ZPZ foil, with pointwise self-regulation, will adapt to the difference in thermal environment. For a typical ZPZ foil, the power density at the surface not covered by the hose will be reduced by a factor of around two. Hence the total power consumption becomes (where we add the contributions from the surface covered and not covered by the hose):
$P_{ZPZ} = p*0.5A + p/2*0.5A = p*3A/4 = 5.0*1.0*3/4 = 3.75$ W.

Since the ZPZ foil has 100% surface coverage, the maximal surface temperature outside the hose is: $T_{ZPZ} = T_A+p/2/2u_{air} = 20 + 500/4/12 = 30C$.

To summarize, we have assumed a setup with dynamic thermal conditions. The power density of the ZPZ foil will adapt to the thermal environment, whereas a traditional heater will have a constant power density. Due to this, the power consumption of the ZPZ foil will be lower than that of the traditional heater. Additionally, due to the difference in surface coverage (and the varying power density), the maximal surface temperature of the ZPZ foil will be lower than that of the traditional heater.

In this example and with these assumptions the Conflux ZPZ foil consumes 25% less power.