Energy efficient ceramic infrared heater
Simulation and modelling

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Energy conservation is one of the key factors determining profitability and success of any unit operation. Infrared heating provides significant advantages over conventional heating, including reduced heating time, uniform heating, reduced quality losses, versatile, simple and compact equipment, and significant energy savings [1].

Many different forms of infrared heat sources have been developed throughout the years. The familiar forms seen today are metal sheathed tubular heaters, quartz tubes, quartz lamps; gas fired catalytic, flat faced panels and ceramic emitters. The ceramic infrared has the most radiant efficiency, emitting 96% of radiant energy [2]. Ceramic infrared heaters are applied in various domestic and industrial uses, majority of which includes heating, drying purposes and infrared saunas.

Features of ceramic infrared heaters

These heaters are employed due to the following features:

- The efficient heat transfer to the target reduces the processing time and energy costs.
- The air in the equipment is not heated and consequently the ambient temperature may be kept at normal levels.
- It is possible to design compact and automatic constructions with high controllability and safety.
- Heating is more uniform than in conventional ovens because surface irregularities on the target have smaller effect on the rate of heat transfer [3].

Advantages of infrared heaters

The advantages associated with infrared technology are listed but are not limited to the following:

- Instant heat: Produces heat on turn-on. No need to wait for heat build-up.
- Negligible maintenance: No moving parts to wear out, no air filters or lubrication required.
- Clean: There are no by-products of combustion as with fossil fuels burning units.
- Safe: No open flame, no leakage, no malfunctioning moving parts.
- Efficient: All electric heaters convert energy to heat at 100%.
- Reduce operating costs: Compared to unit heaters, IR accounts for up to 50% savings on energy/fuel.
- Zone control flexibility: Could be controlled to heat different zones at different temperatures.

  ** (Fostoria electric infrared heaters manual).*

In addition, infrared heating, when compared to conventional heating, offers an alternate source of energy, shorter response time, high degree of process control and uniform drying temperatures [3].

Energy savings potential

Tests conducted by Roth et al [4], compared unit heater and radiant infrared heater performance in a 20 ft (6 m) high test building. The tests found that, after adjusting for the outdoor temperatures over the test periods, the radiant infrared heaters consumed about half the energy to heat the same space as the unit heaters. A major factor in the increased energy consumption with unit heaters was that the unit heaters developed vertical temperature gradients more than twice as great as the radiant infrared heaters [4]. Arthur D Little Inc estimated conservative savings of around 20% when preliminary analysis conducted between the two types of equipment showed that higher insulation levels in roofs would reduce the difference between unit heater and radiant infrared heater energy consumption by about one-third, in which case the radiant infrared heater would consume approximately 33% less energy than unit heaters [5, 6].

Basic principles of IR heating

Infrared waves constitute part of the electromagnetic spectrum alongside other waves. Infrared energy is a form of electromagnetic energy. It is transmitted as a wave which penetrates the target and is then converted to heat. Infrared radiation is classified as the region of wavelengths between visible light (0,38 – 0,78 um) and microwaves (1 - 1 000 mm). The wavelength at which the maximum radiation from the heater occurs (peak wavelength) is determined by the temperature of the heater. This relationship is described by the basic laws for a blackbody radiation.

- The **Stefan-Boltzmann** law of radiation states that as the temperature of a heat source is increased, the radiant output increases to the fourth power of its temperature. [4]

  $E = kT^4$

- **Planck's Law** describes the spectral radiance of electromagnetic radiation at all wavelengths emitted in the normal direction from a blackbody at a temperature (T) as a function of frequency (v). This formula is given as:

  $E = hv / (e^{hv/kT} - 1)$

- **Wien's displacement law** states that the wavelength distribution of radiated heat energy from a blackbody at any temperature has essentially the same shape as the distribution at any other temperature, except that each wavelength is displaced, or moved over.

  $\lambda = \frac{b}{T}$

Basic heat transfer in infrared heaters

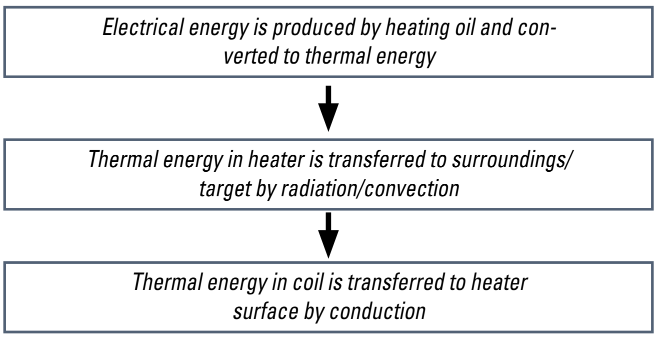

Figure 1. Heat transfer in infrared heater [7].

Heater design and modelling

Ceramic IR heater

Heaters differ in design by virtue of arrangement of current leads, shapes, presence or absence of reflectors, although all have filaments as a common feature. The filament determines the energy characteristics of heaters and accounts for the wide range of designs [8]. The most important parameters of any heater are the surface load, efficiency and durability.

Here we shall consider the design of a ceramic infrared heater which has a surface temperature higher than 400⁰C. The heater is made of ceramic body with resistance wire (filament) embedded in it. There is a fibre blanket placed just behind the filament to avoid heat loss from the back of the heater. This fibre blanket exhibits outstanding insulating properties at elevated temperatures and can withstand temperatures to the value of 1 300⁰C. They also have excellent thermal stability, low heat storage, free of binder or lubricant and immune to thermal shock [5].

Ceramic infrared heaters are designed to emit wavelengths in the far range at certain operational powers and temperatures. As voltage is applied to the leads, there is current and resistive losses in the filament that translates to heat build-up.

The higher the temperature, the higher the filament resistivity, hence the reduction in the amount of current and power consumed. The rise in temperature of the filament results in heat transfer by means of conduction to the ceramic body and then radiation to the surrounding.

Mathematical model

The passage of electric current through a filament when voltage is applied gives an expression [8].

$$i(t) = \frac{U}{R}\left(1 - e^{k1^{1}}\right) + c_2 e^{k_2^1} k_{1,2} = -\frac{1}{2RC}\left(\sqrt{1 - \frac{4R^2C}{L}}\right)$$

Where c_2 is a constant.
k_1 = R/L
k_2 = -1/RC + R/L

The mechanism involved in the heat transfer in ceramic heaters is conduction from the filament to the ceramic body. A Fourier equation can be used to calculate the rate of heating or cooling of the heater .

$$T = T_1 + (T_0 - T_1) e^{\frac{-2Na_2^1}{r_0}} \quad (a = c_p \gamma \lambda)$$

Where T, T_0, T_1 are the running temperature of the surface of the heater after the time t, the initial temperature of the heater, and the temperature of the medium respectively; a is diffusivity, equal to the product of the heat capacity of the heater, its density and the thermal conductivity of the insulating sheath; N is the heat transfer coefficient characterizing heat exchange with the medium; r_0 is the depth of penetration of the heat pulse.

The heating element reliability and stability are determined by the extent to which the heater remains constant over its service life. The relation in the following equation describes the rate of degradation [9]

$$\xi = \xi \exp\left(-\frac{Q}{RT}\right)$$

Where ξ 0 is a constant dependent on the composition and method of production of the material of the conducting phase, the electrical insulator, or the casing; Q is the energy of activation of the aging process, which depends on the ambient conditions and the thermo-mechanical stability of the material of the heater; T is the working temperature of the heater.

Surface energy balance

The rate at which energy is transferred from the heater surface to the surface of the target is equal and is given mathematically as:

$$E_{out} - E_{in} = 0$$

Considering a ceramic heater having a resistance wire of diameter D and length L initially at thermal equilibrium with the ambient air and its surroundings; this equilibrium condition is only disturbed when an electric current I is passed through the wire. An equation that could be used to compute the variation of the wire temperature with time during the passage of the current is developed using the first law of thermodynamics which is often used to determine unknown temperatures. Here, relevant terms include heat transfer by convection and radiation from the heater surface, internal energy generation due to electrical current passage through the wire, and a change in internal energy storage. Determining the rate of change if temperature and applying the first law of thermodynamics to a system of length L about the wire, it follows that:

$$E_g - E_{out} = E_{st}$$

Where the energy generation due to the electric resistant heating is given by:

$$E_g = I^2 R_e L$$

Energy outflow due to convection and net radiation leaving the surface is given by:

$$E_{out} = h(\pi DL)(T - T_\infty) + \varepsilon\sigma(\pi DL)\left(T^4 - T_{sur}^4\right)$$

The change of energy storage due to the temperature change is:

$$E_{st} = \frac{dU}{dt} = \rho c V \frac{dT}{dt}$$

Where ρ and c are the density and specific heat, respectively of the wire material and V is the volume of the wire V= $(\pi D^2/4)$ L.
Substituting the rate equations into energy balance, it follows that:

$$I^2 R_e L - h(\pi DL)(T - T_\infty) - \varepsilon\sigma(\pi DL)\left(T^4 - T_{sur}^4\right) = \rho c\left(\frac{\pi D^2}{4}\right)L\frac{dT}{dt}$$

Hence, the time rate of change of the wire temperature is:

$$\frac{dT}{dt} = \frac{I^2 R_e - \pi D h(T - T_\infty) - \pi D\varepsilon\sigma\left(T^4 - T_{sur}^4\right)}{\rho c\left(\pi D^2/4\right)}$$

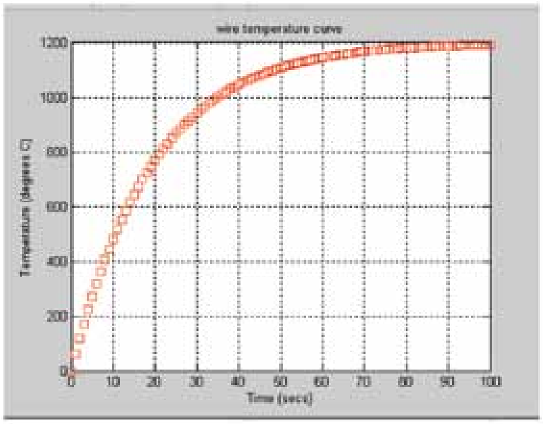

Figure 2: Rate of change of wire temperature.

Physical properties of ceramic IR heaters

The change in temperature of a ceramic heater depends solely on the temperature of the heating element embedded inside the ceramic. Ceramic IR heaters operate in the regions of medium to far wavelengths. Here we shall consider heating elements and ceramic absorption of infrared emissions.

Ceramic IR heaters have slower response time of 5 - 7 minutes [10] when compared to the quartz lamps that reach maximum temperatures in seconds.

Resistance wire (heating element)

We consider Nickel-chromium (80 Ni, 20 Cr) used as heating element in industrial furnaces as well as in electric household appliances. This element has special advantages in that it has very good mechanical properties in the hot state. Below are the physical and mechanical properties given for a 1 mm, 0,04 in diameter for a Nikrothal alloy [9].

Diameter(mm)	Length(m)	Area(mm²)	Resistivity ρ	Resistance@200C	Power(KW)
0,5	14	0,196	1,09	77,86	0,62
0,5	18	0,196	1,09	100,10	0,48
0,5	22	0,196	1,09	122,35	0,40
0,5	35	0,196	1,09	194,64	0,25
0,5	42	0,196	1,09	233,57	0,21
0,5	50	0,196	1,09	278,06	0,17
0,3	3	0,707	1,09	46,25	1,05
0,3	4	0,707	1,09	61,67	0,78
0,3	5	0,707	1,09	77,09	0,63
0,3	6	0,707	1,09	92,50	0,52
0,3	8	0,707	1,09	123,34	0,39
0,3	12	0,707	1,09	185,01	0,26
0,3	15	0,707	1,09	231,26	0,21
0,8	38	0,503	1,09	82,35	0,59
0,8	45	0,503	1,09	97,51	0,50
0,8	56	0,503	1,09	121,35	0,40
0,8	70	0,503	1,09	151,69	0,32
0,8	85	0,503	1,09	184,19	0,26
0,8	113	0,503	1,09	244,87	0,20

Table 1: Calculated resistance and lengths of wire.

To calculate resistance of wire and output power of heater, the formulas below is used:

$$R = \rho \left(\frac{\ell}{A} \right) (\Omega)$$

Where R = Resistance, ρ = Resistivity, l = Length (m), A = Area (m^2)

Power,

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

Where V = Voltage (@220 V single phase), R = Resistance ( )
Refer to Table 1 for calculated values of resistances and power at different lengths and diameter of wire.

Fibre blanket

Fibre blanket is used in the heater to prevent heat from escaping through the back of the heater. The blanket used in this case is supplied by Thermal Ceramics and specifications are as follows: This is a blanket made from high temperature insulation wool. It exhibits outstanding insulating properties at elevated temperatures. The blanket has an excellent thermal stability and retains its original soft fibrous structure up to maximum continuous use temperature. It contains neither binder nor lubricant and does not emit any fume or smell during the first firing. It is flexible, easy to cut and shape and easy to install. It can withstand temperatures of up to 13000C [5].

Benefits

- Excellent thermal insulating performances
- Free of binder or lubricant
- Thermal stability
- Low heat storage
- Flexible and resilient
- Immune to thermal shock
- No reaction with alumina based bricks in application in the range of the typical use temperature
- Exonerated from any carcinogenic classification under nota Q of directive 97/69 EC

Ceramic heaters come in various shapes and sizes. Examples of which are FTE (full trough emitter), FFE (full flat emitter), HTE (half trough emitter), HFE (half flat emitter), HSE (half square emitter) and LTE (large trough emitter). These shapes are determined by the moulds. Moulds could be carved from solid objects like wax or aluminum or whatever the manufacturer deems fit. Different shapes give different radiation patterns.

Result

Simulations conducted on infrared heaters to show warm up and cool down temperatures with respect to time was conducted. The type of infrared heater used in this study was the super high temperature ceramic radiator (SHTS) manufactured by Elstein and has a maximum operating temperature of 1 200°C. In addition it has the following specifications:

- Rated power 800 W at 230 V
- Radiation efficiency more than 75%
- Heat-up constant approximately 1,2 minutes
- Area power densities up to 8O kW/m2

The open loop step response of the IR heater under test resulted in the curves shown in the *Figures 3 and 4*. The curve in figure 7 was chosen as a reasonable compromise for the step response of the heater under test.

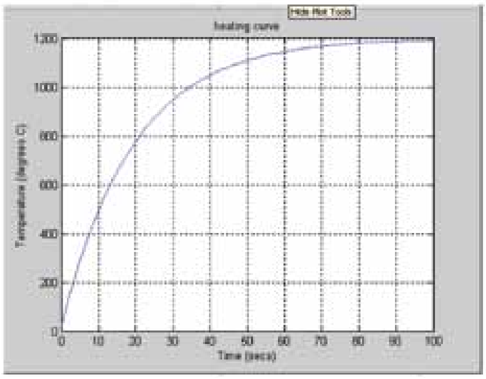

Figure 3: Infrared heater warm-up curve (above).

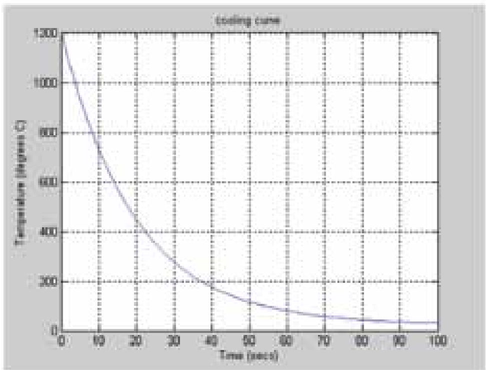

Figure 4: Infrared heater cool-down curve.

Conclusion

Modelling and simulation of an energy efficient ceramic heater has been employed. The filament temperature and wavelength emissions as well as the radiation patterns have also been explored. Mathematical modelling using energy surface balances and Fourier equations have also been employed in determining the heater radiation. Simulation results shows heat up and cool down temperatures at different time intervals.

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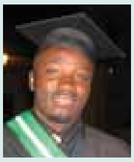

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