Development of Computer Aided Heat Treatment Planning System (CAHTPS)

By

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ABSTRACT

The thesis includes fundamental work in the following,

- Development of materials database which includes the main parameters of the various heat transfer models
- Validation and testing of the system capability and accuracy by means of various case studies

A computer aided heat treatment planning system (CAHTPS) is developed to assist the heat treatment process. The temperature distribution inside the furnace and the temperature of the various parts in the load can be determined. The various models for the heat treatment are analyzed and the various parameters in the equations are classified. The majority of the equations parameters were properties of various metals and non metals. Hence an extensive database is developed so as to assist the models.

The remaining physical conditions dependent parameters of the models were analyzed and the effects due to change in the conditions and these parameters are tested and studied by various case studies. The change in the loading pattern effects and change in the load quantity effects for the various cases are presented.

The thesis work establishes the system's application scope and the accuracy to be used in the current heat treatment industries.

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Chapter 1 Introduction and Systems Review

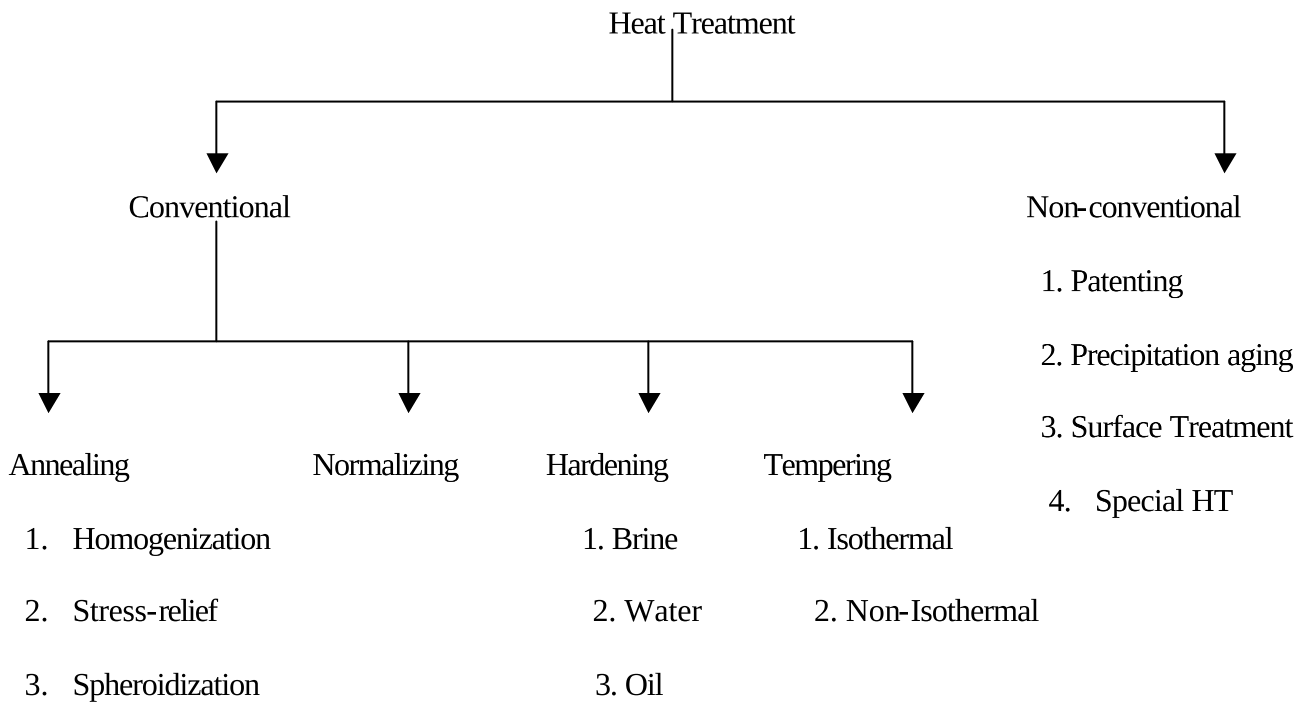
1.1 Heat treatment processes

Heat treatment is an important $15 billion industry manufacturing process used to improve and control the quality of the mechanical properties of metal parts. A heated workpiece in a heat-treating furnace will undergo a given thermal schedule, typically, a heating — soaking — cooling cycle. In this research the heating process is studied. In order to perform a quality heat-treatment, the heat source in a furnace is heated first by the electric or fired gas (indirect or direct). The heat flux arrived at the surfaces of workpieces through radiation and convection heat transfer and arises the surfaces temperature of the workpieces. Then the temperature in the interior of a workpiece is raised in the form of conduction heat transfer. Thus, the heat treatment of workpieces is such a process that the workpieces are heated up with the radiation/convection hybrid boundary condition on the surfaces and with the conduction heat transfer interiorly. The uniformity of temperature distribution and the delay time of inside temperature will contribute to the material property control and the heat treatment quality. To optimize the temperature control and load design, it is necessary to study the detail information about the temperature distribution in furnace and workpieces as a function of time.

The main types of heat treatment applied in practice are

1) Annealing
2) Normalization
3) Hardening and
4) Tempering

The heat treating processes are further classified as follows



1.2 Problem formulation

The quality of heat treatment for the metal parts depends on many factors, including part loading and furnace temperature control. It is desired to predict the heating history and temperature distributions in furnace and in workpiece so that the part loading design and temperature control can be improved. Unfortunately, there is currently no comprehensive technique which can be used to simulate heat-treating process and predict the temperature distribution of workpieces with arbitrary geometry in a loaded furnace. In current practice in heat treating industry, to ensure the quality, experimental methods have to be employed to measure the temperature in the furnace space or on the part surfaces. The following problems exist in current heat treating operations.

(1) There is no direct measuring method for the inside-workpiece temperature measurement in the heat treating process. The temperature of workpieces may vary with time and location, from surface to interior. Although the workpieces temperature may be measured by thermocouples set on the workpieces surface at selected points, the interior temperature of workpieces is still unknown. In order to obtain a uniform temperature between the surface and the interior, a delay of time is necessary for heat conduction after the surface temperature reached the specified temperature. Nowadays this time delay is determined by experience because there is no analytical model available yet. The problem is, if the holding time relatively short, the uniform temperature between the surface and the interior cannot be obtained; but if it is too long, the mechanical property of the surface material may be changed undesirably. Also, the production efficiency becomes lower.

(2) There is no direct control of workpieces temperature according to part heating condition. The quality of heat treatment is ensured by the furnace performance and thermal schedule so that the heating process of workpiece cannot be precisely controlled. The thermal schedule is determined based on experience.

(3) Part loading design is also experience based. Since there is no analytical model available to predict the temperature distribution in workpieces, it is difficult to carry out an optimization of the part loading. The unreasonable part loading may result in a non-uniformity of temperature distributions in workpiece.

To obtain the temperature distribution and heating history of workpiece, a comprehensive mathematical model needs to be developed for the heat transfer process in heat treatment. The heat conduction in workpiece can be modeled based on the well-known heat conduction principle. The difficult is that the boundary condition is varying in time and locations of the workpiece surfaces. The boundary condition is dominated by the convection and radiation in furnace. How to integrate the related three heat transfer models into a comprehensive model for heat treatment processes is the emphasis of the research. An effective numerical method is also necessary for applying the model for solutions.

1.5 Research objectives

After studying the heat treatment processes and the current industrial practices. The available systems for the processes was reviewed and found insufficient for the requirements for the heat treating processes industry. Hence the research objectives set were as follows:

- To develop physics-mathematical models based on the heat transfer theory for the various modes of heat transfer taking place between the furnace and the workpieces and among the workpieces itself.
- To study and analyze the various model parameters and their effects and develop a database containing the above model parameters that are properties of materials.
- To develop a user interface so as to obtain all the necessary data inputs or parameters for the models.
- To validate and implement the system in the current industries.

Chapter 2 Heat Transfer Principle, Models and Furnace Models

2.1 Heat transfer principle

Transportation of heat energy due to temperature difference is defined as heat transfer. Heat is a form of energy and is transported from one body to another due to the temperature differences in the bodies.

The heat can transfer by one, or by a combination of three separate modes known as conduction, convection and radiation. Conduction occurs in a stationary medium; convection requires a moving medium,; radiation occurs in absence of any medium, distinguishing it as part of electromagnetic spectrum. Although they are distinct processes, they can occur together.

The heat generated in a diesel engine, for example, is transferred from the combusted gas to the steel cylinder walls by the combined action of radiation and convection. Heat flows through the cylinder walls by conduction. In turn, the outer surface of the wall is cooled by convection, and so some extend radiation, owing to water circulating in the cooling passages. The physical processes that govern conduction, convection and radiation are quite different, leading to have a different approach for each process analysis.

2.1.1 Conduction heat transfer

Conduction occurs in a stationary medium. It is most likely to be of concern in solids, although conduction will be present to some extent in gases and liquids. In ?solids the mechanism of conduction is due to the vibration of the atomic lattice and the motion of the free electrons, the latter generally being a more powerful effect. The metallic solids are good conductors because of the contribution made by available free electrons.

Conduction is governed by Fourier's law, which states

"The rate of flow of heat through a simple homogenous solid is directly proportional to the area of the section at right angles to the direction of heat flow, and to change of temperature with respect to the length of the path of the heat flow"

It is represented mathematically by the equation:

$$Q \; a \; A \frac{dt}{dx} \qquad (1)$$

where Q = heat flow through a body per unit time (watts)

A = surface area of heat flow (perpendicular to direction of flow)m^2

dt = temperature difference of the faces of block (homogenous solid) of thickness 'dx' through which heat flows, °C or K

dx = thickness of body in the direction of flow, m

thus,

$$Q = -l \, . \, A \frac{dt}{dx} \qquad (2)$$

where ? = constant of proportionality and known as *thermal conductivity*

The negative sign is to take care of the decreasing temperature along with the direction of increasing thickness or the direction of the flow. The temperature gradient dt/dx is always negative along positive x direction and, therefore the value of Q become positive.

2.1.2 Convection heat transfer

Heat transfer due to medium in form of liquid or gas occurs in convection heat transfer. The convection heat transfer equation between a surface and an adjacent medium is prescribed by *Newton's law of cooling*

$$Q = h\ A(t_s - t_f) \tag{3}$$

where, Q = rate of convective heat transfer (watts)

A = surface area exposed to heat transfer (m^2)

t_s = surface temperature,

t_f = fluid temperature

h = coefficient of convection heat transfer

The coefficient of convection heat transfer *'h'* is defined as "the amount of heat transmitted for a unit temperature difference between the fluid and unit area of surface in unit time". The value of '*h*' depends on thermodynamic properties (viscosity, density, specific heat etc), nature of fluid flow, and geometry of the surface and prevailing thermal conditions.

2.1.3 Radiation heat transfer

Radiation heat transfer is concerned with the exchange of thermal radiation energy between two or more bodies. Thermal radiation is defined as electromagnetic radiation in the wavelength range of 0.1 to 100 microns (which encompasses the visible light regime), and arises as a result of a temperature difference between 2 bodies.

No medium need exist between the two bodies for heat transfer to take place (as is needed by conduction and convection). Rather, the intermediaries are photons which travel at the speed of light.

The heat transferred into or out of an object by thermal radiation is a function of several components. These include its surface reflectivity, emissivity, surface area, temperature, and geometric orientation with respect to other thermally participating objects. In turn, an object's surface reflectivity and emissivity is a function of its surface conditions (roughness, finish, etc.) and composition.

The equation for radiative heat transfer between a surface and its surroundings is:

$$q_{rad} = E \times s \times A \times (T_s^4 - T_{sur}^4) \quad (4)$$

where:

q_{rad} = heat flux in watts (W).

E = emissivity. E is a ratio that describes how well a surface emits radiation compared to a perfect emitter.

s = 5.67 x 10^{-8} W / (m^2 x K^4). s is the Stefan-Bolztmann constant and characterizes radiation from a perfect emitter.

A = surface area in meters squared (m^2).

T_s = Surface temperature in Kelvin (K).

T_{sur} = Surrounding temperature in Kelvin (K).

2.2 Conduction heat transfer model

The workpiece can be classified into two categories, lumped capacitance and massive one. For the lumped capacitance the temperature can be assumed to be uniform during heating, while there is significant temperature gradient for the massive workpiece. Therefore the massive workpiece has to be discritized to calculate the temperature distribution. Bio number is used as criteria to classify the workpiece.

2.2.1 Classification of workpieces

The Bio number means the ratio of outside heat transfer coefficient to the conductive heat transfer coefficient inside the workpiece. It is always used to assess the temperature uniformity of the workpiece. The criteria is defined as

$$Bio = \frac{ht_{eff}}{l} \quad \begin{cases} < 0.1 & lumped \\ Otherwise & massive \end{cases} \tag{5}$$

where h is the heat transfer coefficient of the workpiece surface and environment,

$$h = h_{convection} + h_{radiation}$$

λ is the thermal conductivity, t_{eff} is the equivalent thickness of the workpiece.

For different shapes the equivalent thickness calculation is different, as follows:

$$t_{eff} = \frac{V}{A} \quad \text{Plate} \tag{6}$$

$$t_{eff} = \frac{2V}{A} \quad \text{Cylinder/ bar with rectangular section} \tag{7}$$

$$t_{eff} = \frac{3V}{A} \quad \text{Sphere/cubic} \tag{8}$$

where V is the workpiece volume.

Generally for natural convection, $h_{convection}$ can be obtained by convection model explained in the next section. The radiative coefficient $h_{radiation}$ can be defined as follows:

$$h_{radiation} = \frac{s \cdot e \cdot Fv \cdot (T_{fce}^4 - T_{ld}^4)}{(T_{fce} - T_{ld})} = s \cdot e \cdot Fv \cdot (T_{fce}^2 + T_{ld}^2)(T_{fce} + T_{ld}) \tag{9}$$

Here the maximum value of $h_{convection}$ and $h_{radiation}$ should be used. $h_{radiation\_\max}$ is

$$h_{radiation\_\max} = s \cdot e \cdot Fv \cdot (T_{fce\_\max}^2 + T_{ld\_\max}^2)(T_{fce\_\max} + T_{ld\_\max}) \tag{10}$$

2.2.2 Conduction model

Because of no 3-D geometrical modeling being used only conduction models for sphere, cylinder and plate are given. Therefore the workpiece have to be classified into these three shapes. For example the cubic can be classified as sphere, bar with rectangle section can be thought as cylinder. For sphere there is conduction in the radial direction only, for cylinder, conduction in radial direction only (no conduction in the axis direction), for plate conduction along the thickness. The differential equations, discretion equations and boundary conditions are shown below.

For sphere, the differential equation is

$$\frac{\partial T}{\partial t} = \frac{l}{r \cdot c}\left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r}\right) \tag{11}$$

where r is density, c is specific heat, r is the radius.

Numerical simulation equation is

$$T_i^{m+1} = T_i^m + \frac{l \cdot \Delta t}{r \cdot c}\left(\frac{T_{i+1}^m - 2T_i^m + T_{i-1}^m}{\Delta r^2} + \frac{2}{r}\frac{T_{i+1}^m - T_i^m}{\Delta r}\right) \tag{12}$$

Boundary conditions are

- At the surface:

$$l\frac{\partial T}{\partial n} = q_{rad} + q_{conv} \tag{13}$$

where q_{rad} and q_{conv} are the heat rate of radiation and convection, respectively.

- At center

$$l\frac{\partial T}{\partial n}=0 \tag{14}$$

For cylinder, the differential equation is

$$\frac{\partial T}{\partial t}=\frac{l}{r\cdot c}\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right) \tag{15}$$

Numerical simulation equation is

$$T_i^{m+1}=T_i^m+\frac{l\cdot\Delta t}{r\cdot c}\left(\frac{T_{i+1}^m-2T_i^m+T_{i-1}^m}{\Delta r^2}+\frac{1}{r}\frac{T_{i+1}^m-T_i^m}{\Delta r}\right) \tag{16}$$

For plate, the differential equation is

$$\frac{\partial T}{\partial t}=\frac{l}{r\cdot c}\frac{\partial^2 T}{\partial x^2} \tag{17}$$

Numerical simulation equation is

$$T_i^{m+1}=T_i^m+\frac{l\cdot\Delta t}{r\cdot c}\frac{T_{i+1}^m-2T_i^m+T_{i-1}^m}{\Delta x^2} \tag{18}$$

The boundary conditions for cylinder and bar are the same as those of sphere.

The above model contains main parameters which are properties of materials that are function of temperature. These all parameters are identified and included in the database.

2.3 Convection model

In the thermal analysis of workpieces in loaded heat-treating furnace, convection heat transfer is considered as one of the most important boundary condition. The heat energy that enter a workpiece by means of convection heat transfer can be calculated using

$$Q = h\cdot A_S\cdot(T_{flow} - T_S) \tag{19}$$

where h is the heat transfer coefficient; A_S is the surface area of workpiece; T_{flow} and T_S are the temperature of fluid and workpiece surface, respectively. Assuming that the T_{flow} is approximately equal to the furnace temperature, the

calculation objective of h will be discussed in this appendix. The average convection heat transfer coefficient, h, is generally calculated by[1]

$$h = \frac{k}{L^*} \cdot Nu_{L^*} \qquad (20)$$

where k is the thermal conductivity of gas (in $W/m{\cdot}K$); L^* is the equivalent length of part related to the part geometry and size; and Nu_{L^*} is the Nusselt number,

$$Nu_{L^*} = f\,(Ra,\ Pr,\ Geometric\ shape,\ boundary\ conditions).$$

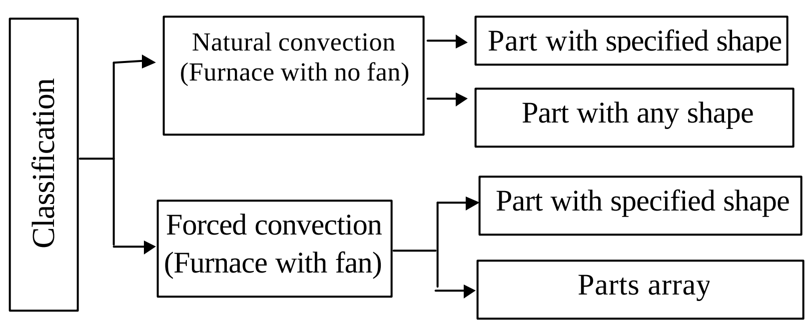


Figure 2.1. Classifications of calculation method in different furnace

In the calculation h, the key point is how to calculate the Nusselt number Nu_{L^*}. The problem can be classified into two types, natural convection and forced convection, according to the furnace conditions, as shown in figure 2.1. Each type of convection can be divided two cases, according to the parts arrangements.

The calculations of L^* and Nu_{L*} are to be presented in the following sections.

2.3.1 Natural Convection

If there is no recirculating fan in the furnace, the problem can be taken as natural convection. There is no specific effect of part arrangement on the natural convection heat transfer calculation. In this passages the calculation of the equivalent length of part and the Nusselt number are presented first, and then some effect factors of convection coefficient is discussed.

The calculations of L^* and Nu_{L*} with specified Part shapes

Figure 2.2 shows some specified part shapes with their arrangements. The equivalent length can be calculated by[9]:

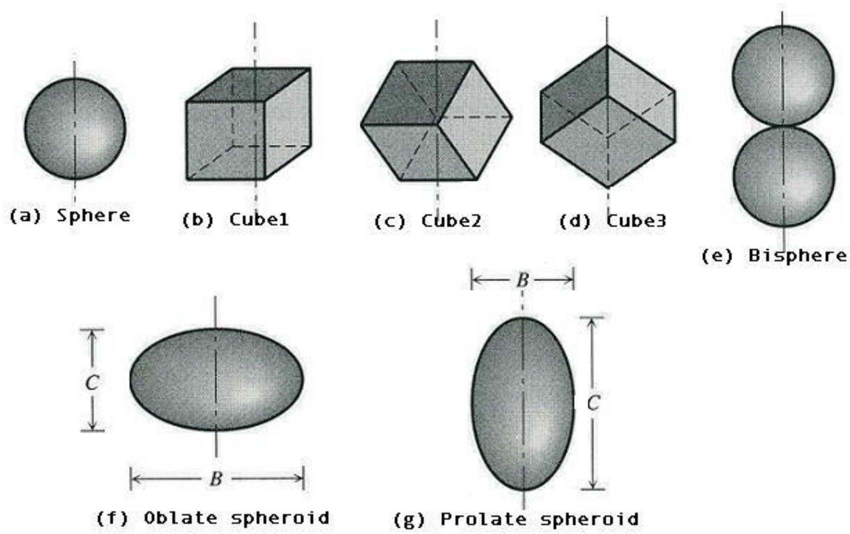


Figure 2.2 Natural convection for various shapes of parts

$$L^* = A^{1/2} \tag{21}$$

where A is the surface area of part (in m^2);

The Nusselt number is calculated by [9],

$$Nu_{L*} = Nu_{L*}^0 + \frac{0.67 \cdot G_{L*} \cdot Ra_{L*}^{1/4}}{\left[1+\left(0.492/\Pr\right)^{9/16}\right]^{4/9}}, \qquad \text{(for } 0 < Ra_{L*} < 10^8\text{)} \tag{22}$$

where

- Nu^0_{L*} and; G_{L*} are the conduction limit Nusselt number and the geometric parameter, respectively. Table 1 lists the values of these two constants for the parts with different shape and orientations shown in figure 2.2.

- Pr is Prandtl number,

$$Pr = n/a \tag{23}$$

where n is kinematic viscosity of furnace gas (in m^2/s);

a is thermal diffusivity of furnace gas (in m^2/s), $a = k/(r \cdot c_p)$;

k is conductivity (in $W/m \cdot K$), r is density (in kg/m^3), and c_p is specific heat of gas (in $J/kg \cdot K$)

Table 2.1. Typical values of Nu^0_{L*} and G_{L*} [9]

Body Shape	Nu^0_{L*}	G_{L*}
Sphere	3.545	1.023
Bi-sphere	3.475	0.928
Cube 1	3.388	0.951
Cube 2	3.388	0.990
Cube 3	3.888	1.014
Vertical cylinder	3.444	0.967
Horizontal cylinder	3.444	1.019
Cylinder at 45 ^oC (H = D)	3.444	1.004
Prolate spheroid (C/B = 1.93)	3.566	1.012
Oblate spheroid (C/B = 0.5)	3.529	0.973
Oblate spheroid (C/B = 0.1)	3.342	0.768

- Ra_{L*} is the Rayleigh number,

$$Ra_{L*} = \frac{g \cdot b \cdot (T_w - T_\infty) \cdot L^{*3}}{a \cdot n}, \quad (\text{for } 0 < Ra_{L*} < 10^8) \tag{24}$$

where g is gravitational acceleration (in m/s^2); b is the coefficient of volumetric thermal expansion for ideal gas (in K^{-1}), $b = 1/273$ (Charles' law of volume); T_w is sphere surface temperature (in K); $T_{¥}$ is free-stream temperature (in K); L^* is the equivalent length (in m).

<u>General equation for any shape of parts</u>

Because the values in table 2.1 do not vary appreciably, a general expression based on the average values of $Nu_{L^*}^0$ and G_{L^*}, and valid for $Pr \geq 0.7$ is [9]

$$Nu_{L^*} = 3.47 + 0.51 \cdot Ra_{L^*}^{1/4} \tag{25}$$

where Ra_{L^*} can be calculated using Eq. (24)

<u>The effects of natural convection</u>

According to the equations mentioned above, if the geometry and material of workpiece are specified, there are two factors that affect the convection heat transfer coefficient: the physical properties of gas medium, and the temperature difference between gas medium and workpiece. To test their effects, take a blade as the heat-treated part, as shown in figure 2.3. Assume that the furnace gas medium is air, some typical properties of air at atmospheric pressure are shown in table 2.2.

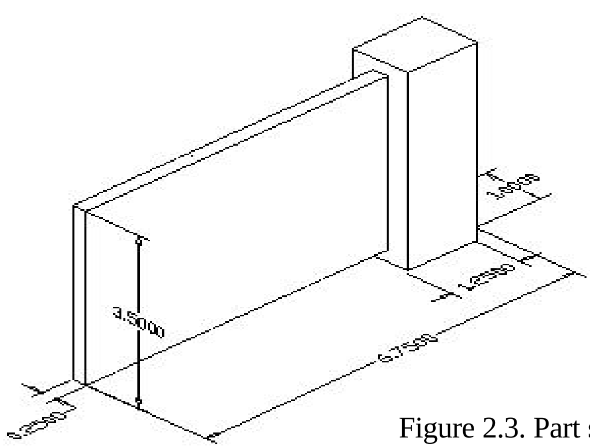


Figure 2.3. Part shape and size

Table 2.2 Properties of air[1]

T (^oC)	r (kg/m^3)	c_p ($KJ/kg \cdot K$)	m ($kg/s \cdot m$)	n (cm^2/s)	k ($W/m \cdot K$)	a (cm^2/s)	Pr
0	1.293	1.006	1.71×10^{-5}	0.132	0.024	0.184	0.72
10	1.247	1.006	1.76×10^{-5}	0.141	0.025	0.196	0.72
20	1.205	1.006	1.81×10^{-5}	0.150	0.025	0.208	0.72
30	1.165	1.006	1.86×10^{-5}	0.160	0.026	0.223	0.72
60	1.060	1.008	2.00×10^{-5}	0.188	0.028	0.274	0.70
100	0.946	1.011	2.18×10^{-5}	0.230	0.032	0.328	0.70
200	0.746	1.025	2.58×10^{-5}	0.346	0.039	0.519	0.68
300	0.616	1.045	2.95×10^{-5}	0.481	0.045	0.717	0.68
500	0.456	1.093	3.58×10^{-5}	0.785	0.056	1.140	0.70
1000	0.277	1.185	4.82×10^{-5}	1.745	0.076	2.424	0.72

• The effects of temperature difference

To test the effect of temperature difference on convection coefficient, we need to fix the air temperature to a constant so as to make the physical properties of air keep constant. In this case the air temperature is fixed to 500 ^oF and 1000 ^oF, respectively. Assume the initial temperature of part is 70 ^oF. According to table 2.2, the air properties at 500 ^oF are: T = 500 ^oC ; r = 0.456 kg/m^3 ; c_p = 1.093 $KJ/kg \cdot K$; $m = 3.58\times10^{-5}$ $kg/s \cdot m$; n = 0.785 cm^2/s; k = 0.056 $W/m \cdot K$; a = 1.140 cm^2/s; and Pr = 0.70.

Figure 2.4 shows the curves. In the figure T_{-ld} is the workpiece heating-up curve; *delta_T* is the temperature difference between air medium and workpiece during heating-up; and h is the convection coefficient corresponding with temperature difference.

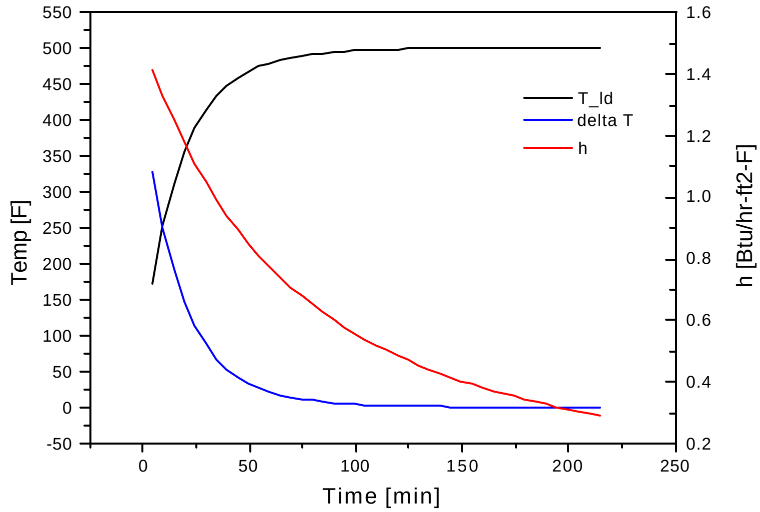


Figure 2.4. Temperature, temperature difference and convection coefficient (At air temperature $T_{\_air}$ = 500 ^oF)

If the air temperature is 1000 ^oF, the air properties are as follows:

T = 1000 ^oC ; r = 0.277kg/m^3 ; c_p = 1.185 KJ/kg·K; m = 4.82×10^{-5}kg/s·m; n = 1.745cm^2/s; k = 0.076W/m·K; a = 2.424cm^2/s; and Pr = 0.72.

Figure 2.5 shows the relationship between temperature difference and corresponding convection coefficient. It is shown that the effect of temperature difference on the convection coefficient is significant. While the temperature difference arises, the value of convection coefficient is increased.

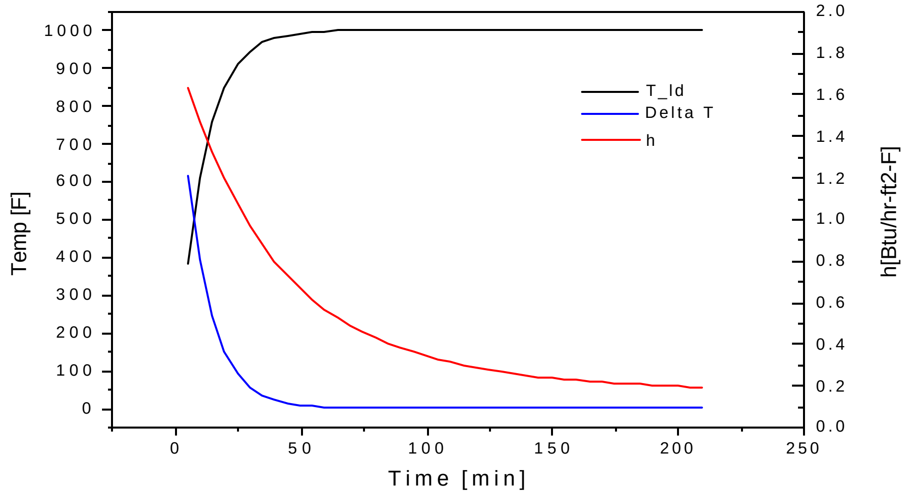


Figure 2.5. Temperature, temperature difference and convection coefficient

- The effects of air medium physical properties

To test the effect of physical properties on convection coefficient, we need to fix the temperature difference between air medium and workpiece. Because the air properties vary with the temperature (as shown in Table 2.2), the convection coefficient will vary with the air properties. In this test, six grades of temperature differences, 20 ^oF, 50 ^oF, 100 ^oF, 200 ^oF, 300 ^oF, and 400 ^oF, are taken respectively to calculate the corresponding convection coefficients. Figure 2.6 shows the convection coefficients profiles vs. the air temperature. It is obvious that the effect of convection coefficients with air properties is not so much (the change region is within 0.2 *Btu/hr-ft2-F*) than that of the temperature differences. For every fixed temperature differences, convection coefficients will change within the range of 0.2 *Btu/hr-ft2-F*. But the change with temperature difference is more than 1 *Btu/hr-ft2-F* if the temperature differences change from 20 ^oF to 400 ^oF.

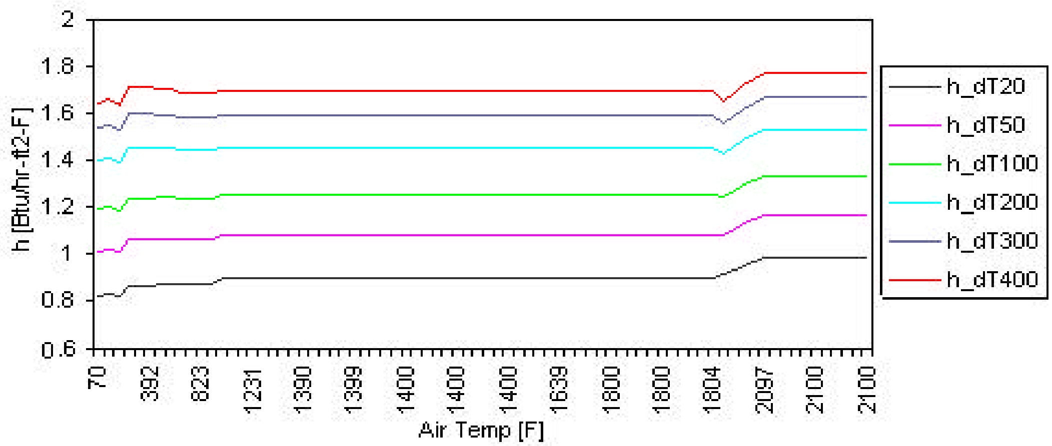


Figure 2.6. Natural convection coefficient vs. air temperature with specified temperature difference

2.3.2 Forced Convection

There are two kinds of situations in forced convection heat transfer, for single part with specified shapes and for array of parts. In both cases, the calculation of equivalent length, L^*, can use equation (21). But there are different methods for the calculation of the Nusselt number. It depends on not only the medium properties, but also the parts arrangement, i.e., part load pattern.

The calculations of Nu_{L*} with specified part shapes

For single part with specified shapes in Figure 2.2, following experimental equation can be used to calculation the Nusselt number, Nu_{L*} [1]

$$Nu_{L*} = Nu_{L*}^{0} + \left[0.15 \left(\frac{p}{L^*} \right)^{1/2} \cdot \mathrm{Re}_{L*}^{1/2} + 0.35\,\mathrm{Re}_{L*}^{0.566} \right] \cdot \mathrm{Pr}^{1/3} \qquad (26)$$

where

- p is the maximum perimeter of the part, perpendicular to the flow direction U_{∞} (U_{∞} is the velocity of flow, in *m/s*) ;

- Nu^0_{L*} is the overall Nusselt number in the no-flow (pure conduction) limit,

representative value of this constant are listed in Table 1.

- Re_{L*} is Reynolds number, it equals to [10]

$$\mathrm{Re}_{L*} = \frac{U_\infty \cdot L^*}{n} \tag{27}$$

- Pr is Prandtl number, use equation (23) to calculate.

Note that this equation is recommended for

$$0 < Re_{L*} < 2\times10^5\ ,\quad Pr > 0.7,\ 0 < C/B < 5 \tag{28}$$

<u>Arrays of parts</u>

For the multiple parts situation, there are three kinds of arrangements, aligned part loads, staggered part loads, and packed part loads. In this paper we will only discuss the first two load patterns. Figure 2.7 shows their arrangements.

Assuming that the air fluid velocity is U_∞, and the temperature of flow is T_∞, the transverse and longitudinal pitches are S_T and S_L, respectively, the number of rows of parts transverse to the flow is N. For convenience, the equivalent length is called equivalent diameter, D^*. The calculation of D^* is same as L^*.

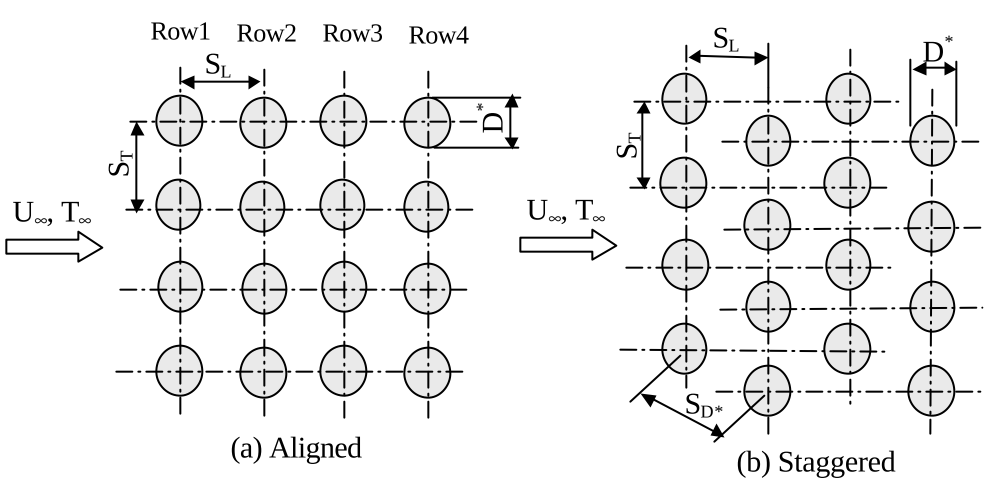


Figure 2.7. Configurations of arrays of parts

For the calculation of Nu_{D*}, there are two different equations according to the rows number of parts [10]:

$$\left.\begin{aligned} Nu_{D*}^{N} &= \frac{1+(N-1)\cdot\Phi}{N}\cdot Nu_{D*}^{1}, \quad && \text{if } N < 10 \\ Nu_{D*}^{N} &= \Phi\cdot Nu_{D*}^{1}, && \text{if } N \geq 10 \end{aligned}\right\} \tag{29}$$

where N is the number of rows of parts transverse to the flow; Φ is an arrangement factor, it equals to

$$\left.\begin{aligned} &\text{- For aligned parts: } \Phi_{aligned} = 1+\frac{0.7}{y^{1.5}}\cdot\frac{S_L/S_T-0.3}{(S_L/S_T+0.7)^2} \\ &\text{- For staggered parts: } \Phi_{staggered} = 1+\frac{2}{3P_L} \end{aligned}\right\} \tag{30}$$

where S_L and S_T are shown in figure 3; ψ is a factor and it is defined as [11]:

$$\left.\begin{aligned} \Psi &= 1-\frac{p}{4P_T}, \quad && \text{if } P_L \geq 1 \\ \Psi &= 1-\frac{p}{4P_T\cdot P_L}, && \text{if } P_L < 1 \end{aligned}\right\} \tag{31}$$

where P_T is the transverse pitch, $P_T = S_T/D^*$

P_L is the longitudinal pitch, $P_L = S_L/D^*$

- Nu_{D*}^{1} is the Nusselt number for the first row. Use equation (26) to calculate Nu_{D*}^{1}. In calculating Re_{D*}, the maximum velocity of fluid in the space between parts is used [9]:

$$\mathrm{Re}_{L*} = \frac{U_{Max}\cdot D^*}{n} \tag{32}$$

where $D^* = A^{1/2}$ is the equivalent diameter.

The maximum fluid velocity, U_{Max}, is calculated as follows [11]:

$$\left.\begin{aligned}
&\text{Aligned:} \quad U_{Max} = \frac{U_\infty \cdot S_T}{S_T - D^*} \\
&\text{Staggered:} \; U_{Max} = \frac{U_\infty \cdot S_T}{S_T - D^*} \qquad \text{for } S_{D^*} > \frac{1}{2}\left(S_T + D^*\right) \\
&\qquad\qquad U_{Max} = \frac{U_\infty \cdot S_T}{2(S_D - D^*)} \qquad \text{for } S_{D^*} < \frac{1}{2}\left(S_T + D^*\right) \\
&\text{where } S_{D^*} = \left[S_L^2 + \left(\frac{S_T}{2}\right)^2\right]^{1/2}
\end{aligned}\right\} \qquad (33)$$

$U_¥$ is the average fluid velocity in the furnace working space;

S_L, S_T, and D^* are shown in figure 2.6.

The effects of Forced convection

According to the calculation equations mentioned above, if the geometry and the material of workpiece is specified, there are three factors that affect the forced convection coefficient: the physical properties of gas medium, the fluid velocity, and the arrangement of parts (i.e. part loading pattern, including rows number of parts and the distance between parts). Take the blades as an example here, figure 2.8 shows the aligned arrangement.

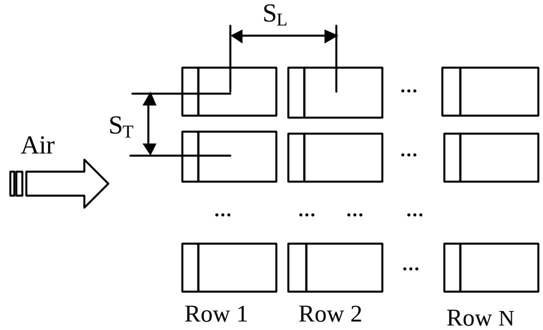


Figure 2.8. The arrangement of parts

The effects of gas flow physical properties

Take the air flow speed to four grades, say, 4.89 m/s, 7.33 m/s, 9.78 m/s, and 12.22 m/s, respectively; Fix the parts arrangement: S_T = 5 in, S_L = 8 in, N = 4. Figure 2.9 is the temperature profile of air with time. Input all the data to system, four convection coefficient curves can be obtained as shown in figure 2.10. It is shown that, if the air temperature changes from 70 ^{o}F to 2100 ^{o}F, then the values of convection coefficient will changes within 2 *Btu/hr-ft2-F*.

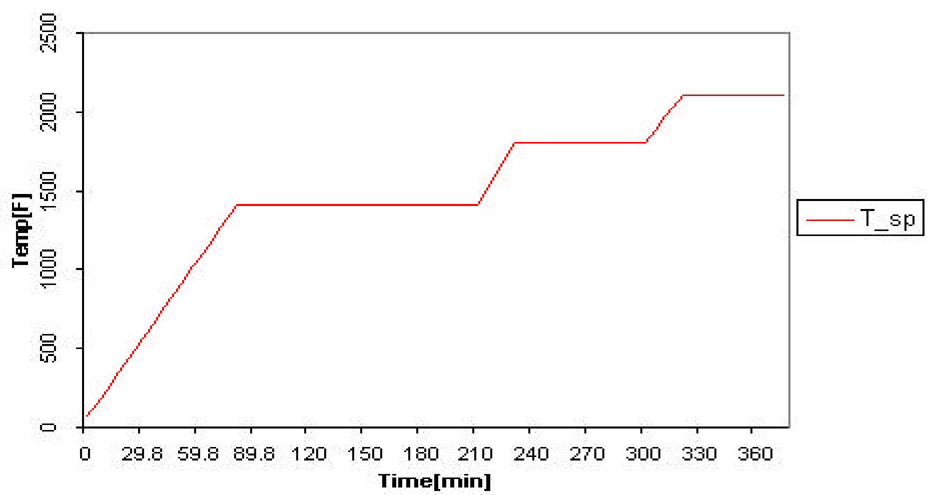


Figure 2.9. Air temperature vs. time profile in forced convection

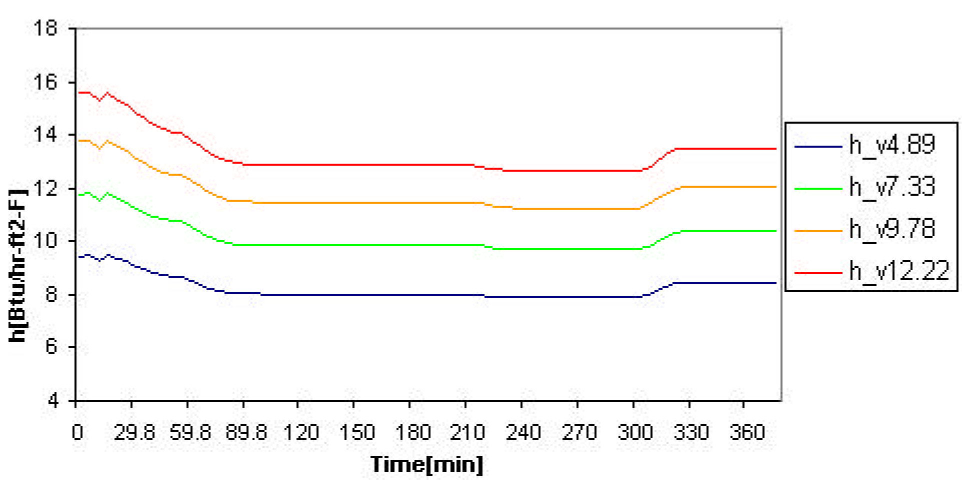


Figure 2.10. Convection coefficient vs. time profile in forced convection

The effects of gas medium velocity

There are two ways to change the gas flow velocity: change the fan speed, and change the arrangement. Fix S_T = 5 in, S_L = 8 in, N = 4, and fix the air temperature to 500 °F, 1000 °F, 1500 °F and 2000 °F, respectively. Let air speed equals to 4.89 m/s, 7.33 m/s, 9.78 m/s, and 12.22 m/s, then the convection coefficient curves can be shown in figure 2.11. According to the curves, if the speed changes from 4.89 m/s to 12.22 m/s, the maximum change range of convection coefficient will be about 5 *Btu/hr-ft2-F*.

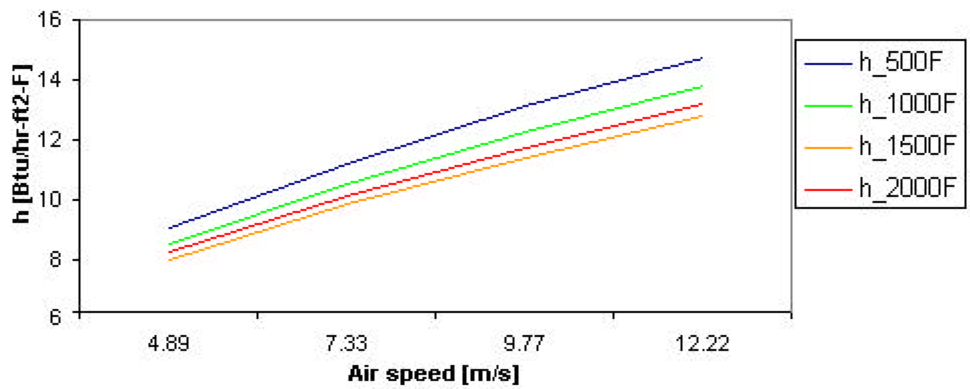


Figure 2.11. Convection coefficient vs. air speed in forced convection

The effects of rows number of parts

Fix the airflow speed to 4.89 m/s, take the rows number as 4, 6, 8, and 10, respectively. the convection coefficients vs. time profiles are shown in following figure. According to the curves, if the row number is changed from 4 to 10, the maximum change range of convection coefficient will be about 2 *Btu/hr-ft2-F*. It is note that if the row number is more than ten, the convection coefficient will keep constant and same as the value for ten.

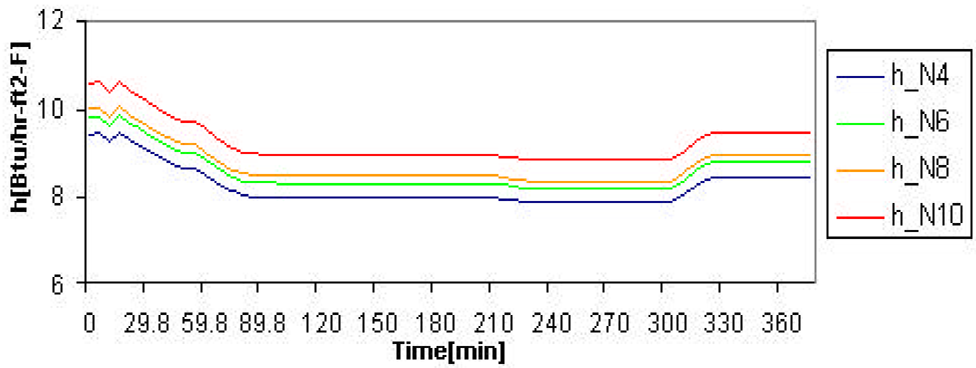


Figure 2.12. Convection coefficient vs. time profile in forced convection

<u>The effects of arrangement of parts</u>

Assume N = 4, air fluid speed to 4.89 m/s, let

S_T = 5 in, S_L = 8 in;

S_T = 8 in, S_L = 11 in;

S_T = 11 in, S_L = 14 in; and

S_T = 14 in, S_L = 17 in; respectively,

then the convection coefficient curves are shown in Figure 2.13. It is shown that the distance between parts affects the convection coefficient significantly.

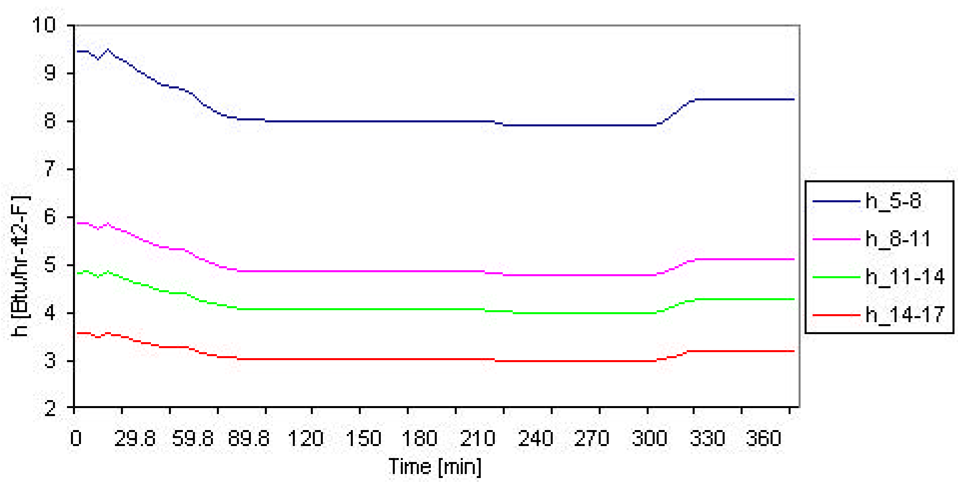


Figure 2.13. Convection coefficient vs. Time profile in forced

2.4 Radiation model

In the heating of parts there are two kinds of radiation heat transfer: from furnace to workpiece and from workpiece to workpiece.

Radiation between furnace and workpiece:

$$Q_{rad\_fce\_wp} = s \cdot e \cdot Fv_{wp\_fce} \cdot A \cdot (T_{fce}^{\ 4} - T_{wp}^{\ 4}) \quad (34)$$

where s is Stenfan-Boltzmann constant, T_{fce} is furnace temperature, T_{wp} is furnace temperature, Fv_{wp_fce} is view factor from workpiece to furnace, A is the surface area of workpiece, e is emissivity of the workpiece.

Radiation between workpiece and workpiece:

$$Q_{rad\_wp\_wp} = s \cdot e \cdot Fv_{wp1\_wp2} \cdot A \cdot (T_{wp1}^{\ 4} - T_{wp2}^{\ 4}) \quad (35)$$

where Fv_{wp1_wp2} is view factor from workpiece to workpiece.

<u>View factor calculation</u>

The view factor is defined as the fraction of total radiant energy leaving one surface and is intercepted by another surface, as shown in Figure 2.14. Mathematically, The view factor can be expressed by the following equation:

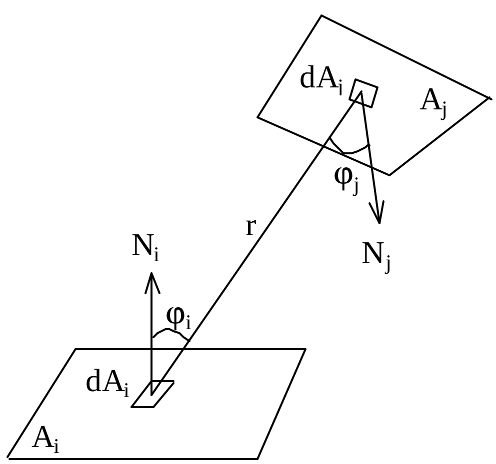


Figure 2.14. View factor calculation terms

$$F_{ij} = \frac{1}{A_i} \int_{Ai} \int_{Aj} \frac{\cos \varphi_i \cos \varphi_j}{\pi r^2} (d A_i)(d A_j) \qquad (36)$$

The calculation of view factor is one of important subjects in the radiation heat transfer analysis. In the calculation of view factor for regular geometries, some analytical methods and contour integral techniques are quite efficient. For example, the calculation of view factor for typical geometries is well documented in the standard texts[9-10]. For the extremely irregular geometries, however, the calculation is quite complex.

In the above radiation equation, the calculation of view factor is the point. There are many kinds of methods for the calculation of view factor, integration, Monte Carlo method ant etc. However all accurate methods for view factor calculation of workpiece of arbitary shape are based on geometrical models. Here a simple method is given without geometrical models as the result of a compromise of accuracy and application.

Assume radiation just exists between a workpiece and its six neighbor workpieces, i.e., left, right, front, back, top and bottom ones. The view factors of a workpiece to each of the six neighbors are proportional to the relative surface area exposed to each other. So the view factor can be denoted by the ratio of exposed area over the total surface area. For the boundary workpiece, its view factor to the furnace is the surface area exposed to furnace over the total workpiece surface area. The total view factor of a workpiece is 1.0. So,

$$Fv_{wp\_fce} = \frac{\text{exposed surface area of workpiece to furnace}}{\text{total surface area of workpiece}} \qquad (37)$$

$$Fv_{wp\_wp} = \frac{\text{exposed surface area to each other}}{\text{total surface area of workpiece}} \qquad (38)$$

And assume that the surface area exposed to each other are proportional to the respective surface area of the cubic with the lengths same as the workpiece distance in row, column and layer direction, as shown in Fig. 2.15 and 2.16 .Fig. 2.15 is a 2-D illustrative diagram with two kinds of workpiece shape given. The rectangle surrounding the workpiece is used to replace the workpiece for the view factor calculation. Therefore the view factor of workpiece to the eastern workpiece is as follows:

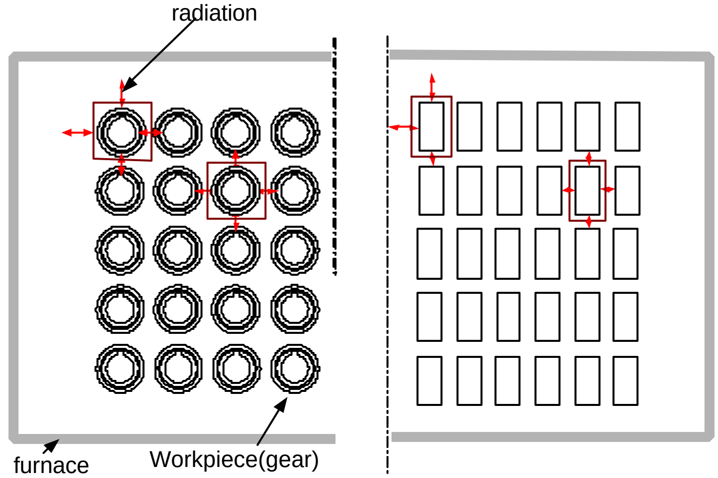


Fig. 2.15 Radiation between furnace and workpiece, among workpieces

$$Fv_{i-e} = \frac{A_{i-e}}{(A_{i-e} + A_{i-w} + A_{i-n} + A_{i-s} + A_{i-f} + A_{i-b})} \tag{39}$$

where A_{i-e}, A_{i-w}, A_{i-n}, A_{i-s}, A_{i-f}, A_{i-b} are the surface areas of the cubic. They are calculated by the workpiece distances.

$$A_{i-e} = A_{i-w} = D_{row} \times D_{lay} \tag{40}$$

$$A_{i-n} = A_{i-s} = D_{row} \times D_{col} \tag{41}$$

$$A_{i-f} = A_{i-b} = D_{col} \times D_{lay} \tag{42}$$

where D_{row}, D_{col}, D_{lay} are the workpiece distances in row, column and layer as shown in Fig. 2.16.

Other view factors between a workpiece to its neighbors are calculated by the same way.

View factor calculations from workpiece to furnace are classified into three categories, corner, edge and face of the load.

Workpieces located at the corner of load have three faces exposed to the furnace, while those located at the edge and face of load just have two faces and one face exposed to the furnace, respectively. So their view factor toward the furnace is differently calculated.

View factor of corner workpieces and furnace:

$$Fv_{fce\_wp} = \frac{A_{i-e} + A_{i-n} + A_{i-f}}{(A_{i-e} + A_{i-w} + A_{i-n} + A_{i-s} + A_{i-f} + A_{i-b})} \tag{43}$$

View factor of edge workpieces (except the corner ones) to furnace:

$$Fv_{fce\_wp} = \frac{A_{i-e} + A_{i-n}}{(A_{i-e} + A_{i-w} + A_{i-n} + A_{i-s} + A_{i-f} + A_{i-b})} \tag{44}$$

or

$$Fv_{fce\_wp} = \frac{A_{i-n} + A_{i-f}}{(A_{i-e} + A_{i-w} + A_{i-n} + A_{i-s} + A_{i-f} + A_{i-b})} \tag{45}$$

or

$$Fv_{fce\_wp} = \frac{A_{i-f} + A_{i-e}}{(A_{i-e} + A_{i-w} + A_{i-n} + A_{i-s} + A_{i-f} + A_{i-b})} \tag{46}$$

View factor of side workpieces (except the corner and edge ones) to furnace:

$$Fv_{fce\_wp} = \frac{A_{i-e}}{(A_{i-e} + A_{i-w} + A_{i-n} + A_{i-s} + A_{i-f} + A_{i-b})} \tag{47}$$

or

$$Fv_{fce\_wp} = \frac{A_{i-n}}{(A_{i-e} + A_{i-w} + A_{i-n} + A_{i-s} + A_{i-f} + A_{i-b})} \tag{48}$$

or

$$Fv_{fce\_wp} = \frac{A_{i-f}}{(A_{i-e} + A_{i-w} + A_{i-n} + A_{i-s} + A_{i-f} + A_{i-b})} \tag{49}$$

For the cubic or spherical workpieces the view factor of workpiece to each adjacent workpiece is 1/6.

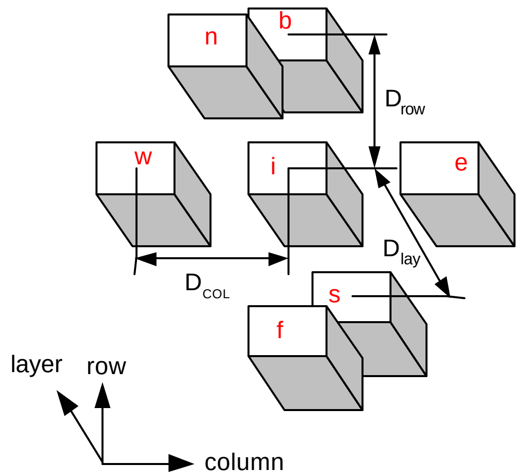


Fig. 2.16 load pattern and distances between workpiece and workpiece

The emissivity of the materials play very important role in the calculation of radiative heat transfer. The emissivity of various materials is very difficult to obtain by experimental procedures. A database is established for the various materials emissivity as a function of temperature and surface finish of the workpiece.

2.5 Furnace temperature calculation

The Furnace temperature calculation is extended to all types of batch furnaces, including indirect-fired furnaces, direct-fired furnace, and electric furnaces. For all type of the furnaces, the average furnace temperature T_{-fce} at time k can be calculated by [2]:

$$T^{k+1}_{\_fce} = T^{k}_{\_fce} + \frac{Q^{k}_{\_storage} \cdot dt}{HC_{\_fce}} \tag{50}$$

where $Q_{\_storage}$ is the heat storage in heat-treating furnace;

$HC_{\_fce}$ is the heat capacity of furnace components;

k is the time step; and dt is the time interval.

But the calculation methods of heat storage $Q_{\_storage}$ and heat capacity $HC_{\_fce}$ are different. There are two types of furnaces will be discussed in the following passages: Gas-fired batch furnace and electric furnace. The calculation of $Q_{\_storage}$ and $HC_{\_fce}$ will be described in following passages. Table 1 lists the main energy terms in the furnace heat storage calculation.

Table 2.3. Energy terms and their definitions

Energy Items	Definitions
Gross Input	The total amount of heat used by the furnace.
Available Heat	Heat that is available to the furnace and its workload, including workpiece, furnace structural components, accessories, and heat losses due to furnace itself.
Heat to Load	Heat that ultimately reaches the product in the furnace.
Wall Losses	Heat conducted out through the furnace walls, roof and floor due to the temperature difference between inside and outside.
Radiation Losses	Heat lost from the furnace as radiant energy escaping through openings in walls, doors, etc.
Heat Storage	Heat absorbed by the insulation and structural components of the furnace to raise them to operating temperature.

Heat storage is calculated according to the energy balance,

(*Heat storage*) ~ *Function of* [(*Available heat*), (*Heat to load*), (*Wall losses*), (*Radiation losses*)]

(*Available Heat*) ~ *Function of* (*Gross input*)

Heat capacity is defined as:

$$HC_{\_fce} = \Sigma \; Mass\ of\ furnace\ components \text{ ´ } Specific\ heat\ of\ material$$

Table 2.4 lists the furnace components in the heat capacity calculations.

Table 2.4 Furnace components

Furnace components	Definitions
Furnace structural components	Roller rails, grate, fan, supports, conveyor, etc.
Insulations	Furnace walls including firebrick and insulating F.B.
Heating elements	Radiant tube, electric resistance element
Accessories	Basket/tray/fixture, firing-ring

2.5.1 Gas-fired Batch Furnaces

Figure 2.17 shows the energy term for direct-fired batch furnace, and Figure 2.18 shows the energy term for indirect gas-fired batch furnace with tube heating elements.

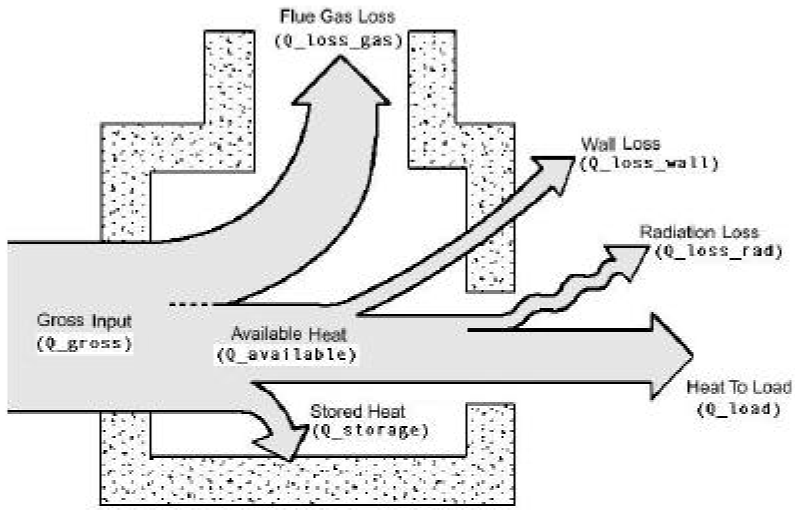


Figure 2.17. Heat balance in a fuel-fired heat treating

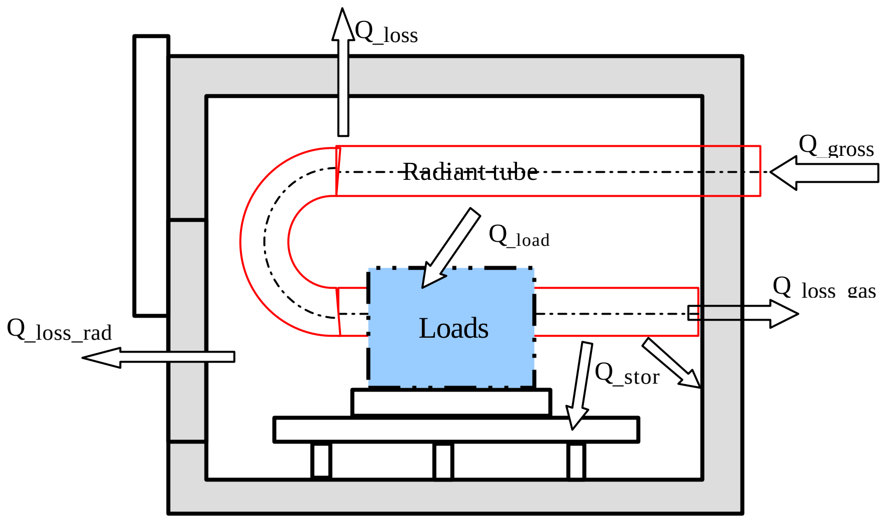


Figure 2.18 Heat balance in an Indirect gas-fired furnace with tube heating

<u>Heat storage calculation</u>

According to the energy balance equation,

$$Q_{\_storage} = Q_{\_available} - (Q_{\_load} + Q_{\_loss\_wall} + Q_{\_loss\_rad} + Q_{\_air} + Q_{\_fan}) \qquad (51)$$

<u>Energy terms calculation</u>

The terms used in heat balance calculations in furnace are:

- Available heat input:

For the natural gas, available heat input is adjusted by both fuel corrected coefficient and *PID* control system:

$$Q_{\_available} = K_{PID} \cdot K_{fuel} \cdot Q_{\_gross} \tag{52}$$

where

— K_{fuel} is the fuel correct coefficient and reference [2] gives its calculation.

— K_{PID} is the PID output and reference [2] gives its calculation.

— $Q_{\_gross}$ is the given value from furnace capacity and it equals to the amount of fuel burned multiplied by its heating value. Table 4 gives the heating value of some fuel gases.

- Furnace wall Losses [12]:

$$Q_{\_loss\_wall} = A_{\_fce} \times f\,(T_{\_fce}) \tag{53}$$

where $A_{\_fce}$ is furnace wall area (inside); $f\,(T_{\_fce})$ is a function for heat loss, in Btu/ft^2-hr. Typical heat loss data are tabulated in Table 2.5.

- Radiation Losses [4]:

$$Q_{\_loss\_rad} = A_{\_open} \cdot s \cdot \left(T_{gas}^4 - T_{amb}^4\right) \tag{54}$$

where $Q_{\_loss\_rad}$ is the radiation losses, $A_{\_open}$ is the opening area, T_{gas} is the temperature of furnace gas, T_{amb} is the temperature of ambient outside furnace, σ is Stefan-Boltzmann constant.

Table 2.5 Heat loss for different furnace walls construction (Btu/hr-ft^2)

Wall Construction	Hot Face Temperature, °F							
	1000	**1200**	**1400**	**1600**	**1800**	**2000**	**2200**	**2400**
9" Hard Firebrick	550	705	862	1030	1200	1375	1570	1768
9" Hard Firebrick + 4.5" 2300° Insulating F.B.	130	168	228	251	296	341	390	447
9" Hard Firebrick + 4.5" 2000° Insulating F.B. +2" Block Insulation	111	128	155	185	209	244	282	325
4.5" 2000° Insulating F.B.	185	237	300	365	440	521	-	-
9" 2000° Insulating F.B.	95	124	159	189	225	266		
9" 2800° Insulating F.B.	142	178	218	264	312	362	416	474
9" 2800° Insulating F.B. + 4.5" 2000° Insulating F.B.	115	140	167	197	232	272	307	347
9" 2800° Insulating F.B. + 4.5" 2000° Insulating F.B. + 2" Block Insulation	71	91	112	134	154	184	204	230
9" 2800° Insulating F.B. + 3" Block Insulation	114	142	172	201	232	264	298	333
8" Ceramic Fiber – Stacked Strips, 8 #/cu ft Density	27	45	64	86	114	146	178	216
10" Ceramic Fiber – Stacked Strips, 8 #/cu ft Density	16	35	54	76	94	120	142	172
12" Ceramic Fiber – Stacked Strips, 8 #/cu ft Density	13	27	43	60	79	98	118	143
9" Hard Firebrick + 3" Ceramic Fiber Veneer, 8 #/cu ft Density	177	240	309	383	463	642	721	800
9" 2800° Insulating F.B. + 3" Ceramic Fiber Veneer, 8 #/cu ft Density	102	125	151	183	227	274	325	408

- Heat abso rbed by air [12]

$Q_{\_air}$ =

where (

where hv is the gross heating value of commercial fuel gases, as listed in Table 4[3]; R is the stoichiometric air/gas ratio, listed in Table 2.6; $Q_{\text{-}gross}$ is the gross heat input; $xs_{\text{-}air}$ is the combustion access air; r is air density; cp is the air specific heat; $T_{\_fce}$ is the furnace temperature; and $T_{\_air}$ is the air temperature before mixed enter furnace.

Table 2.6. Combustion properties of typical commercial fuel gases

Gas type	Heating value (Btu/ft3)	Heating value (Btu/lb)	Air/Gas Ratio (ft^3 air/ft^3 gas)	Air/Gas Ratio (lb air/lb gas)
Acetylene	1498	21,569	11.91	13.26
Hydrogen	325	61,084	2.38	33.79
Butane (natural gas)	3225	21,640	30.47	15.63
Butylene (Butene)	3077	20,780	28.59	14.77
Carbon Monoxide	323	4368	3.38	2.46

Carburetted Water Gas	550	11,440	4.60	7.36
Ethane	1783	22,198	16.68	15.98
Methane	1011	23,811	9.53	17.23
Natural (Birmingham, AL)	1002	21,844	9.41	15.68
Natural (Pittsburgh, PA)	1129	24,161	10.58	17.31
Natural (Los Angeles, CA)	1073	20,065	10.05	14.26
Natural (Kansas City, MO)	974	20,259	9.31	14.59
Natural (Groningen, Netherlands)	941	19,599	8.41	13.45
Propane (natural gas)	2572	21,500	23.82	15.37
Propylene (Propene)	2322	20,990	21.44	14.77

- Fan heat input:

It is calculated based on an empirical equation [12]:

$$Q_{\_fan} = HP_{\_fan} \cdot \left(\frac{520}{460 + T_{\_fce}} \right) \tag{57}$$

where $HP_{\_fan}$ is the horsepower of re-circulating fan.

<u>Effective heat capacity calculation of furnace components</u>

$$HC_{\_fce} = HC_{\_alloy} + HC_{\_heater} + HC_{\_insulation} \tag{58}$$

where $HC_{\_alloy}$ is the furnace alloy heat capacity, it equals to

$$HC_{\_alloy} = M_{\_alloy} \times c_{p\text{-}alloy} \tag{59}$$

where $M_{\_alloy}$ is the total mass of furnace alloys including grate, fan, basket/tray/fixture, conveyor, and supports; c_{p_alloy} is their specific heat.

$HC_{\_heater}$ is heater heat capacity, it equals to

$$HC_{\_heater} = M_{\_heater} \times c_{p\text{-}\,heater} \tag{60}$$

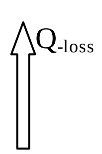
where $M_{\_heater}$ is the mass of heater, $c_{p\text{-}\,heater}$ is its specific heat.

$HC_{\_insu}$ is furnace insulation heat capacity, it equals to

$$HC_{\_insu} = M_{\_insu} \times c_{p\_insu} \tag{61}$$

where $M_{\_insu}$ is the mass of insulation, c_{p_insu} is specific heat.

<u>2.5.2 Electric Batch Furnaces</u>



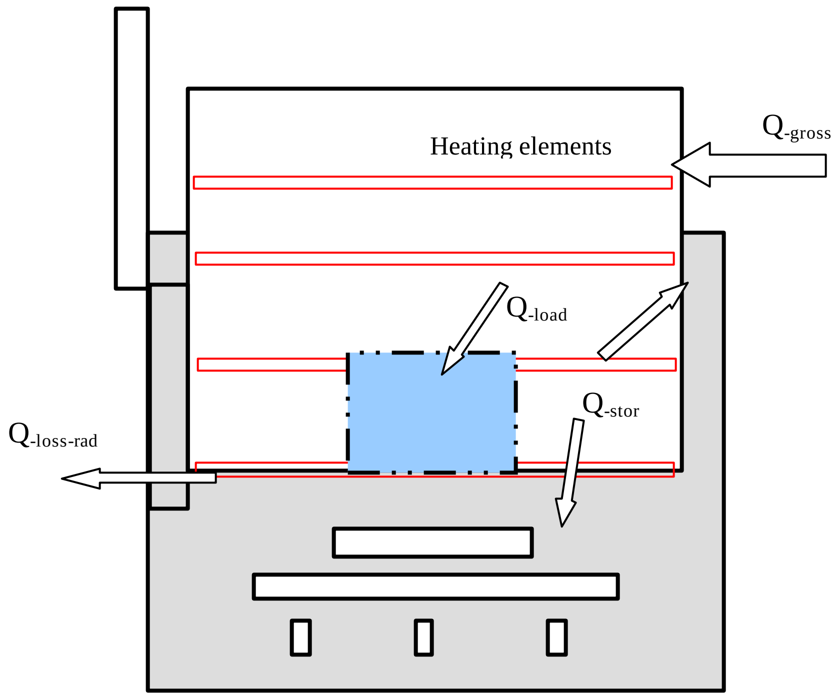


Figure 2.19. Heat balance in an electric heat treating furnace

Heat storage calculation

From Figure 2.5, the storage heat $Q_{\_storage}$ can be got:

$$Q_{\_storage} = Q_{\_available} - (Q_{\_load} + Q_{\_loss\_wall} + Q_{\_loss\_rad}) \tag{62}$$

Energy terms calculation

- Available heat input:

For electric furnace, available heat input is equal to the furnace gross heat input:

$$Q_{\_available} = K_{PID} \cdot Q_{\_gross} \tag{63}$$

- Furnace wall Losses [13]:

$$Q_{\_loss} = 3.6 \cdot A_{\_ext} \cdot \frac{T_g - T_a}{t_1/k_1 + t_2/k_2 + 1/a} \tag{64}$$

where T_g and T_a are the temperature of furnace gas in furnace and out of furnace;

t_1 and t_2 are the thickness of first and second insulations;

k_1 and k_2 are the heat conductivity of two insulations;

a is the thermal diffusivity from furnace outside to atmosphere, Table 2.7 gives some typical a values;

A_{-ext} is the furnace outside area;

3.6 is a time constant when use C-hr-kg-m unit system; the value will be 1.142 when use F-hr-lb-ft unit system.

Table 2.7 Thermal diffusivity (α) from furnace outside to atmosphere

(atmosphere temp: 20 ^oC, α unit: W/m^2-^oC)

Furnace outside wall Temp (^oC)	Side walls (steel plate)	Top wall (steel plate)	Bottom wall (steel plate)
30	9.48	10.72	7.82
35	10.09	11.47	8.26
40	10.59	12.07	8.63
45	11.04	12.60	8.96
50	11.44	13.08	9.26
55	11.81	13.52	9.55
60	12.17	13.93	9.83
65	12.50	14.32	10.09
70	12.83	14.69	10.35
75	13.14	15.05	10.61
80	13.45	15.40	10.86
85	13.75	15.74	11.11
90	14.04	16.07	11.35
95	14.34	16.40	11.60
100	14.62	16.72	11.84
105	14.91	17.04	12.09
110	15.20	17.35	12.33
115	15.48	17.66	12.58
120	15.76	17.97	12.82
125	16.04	18.28	13.07
130	16.33	18.59	13.31

- Radiation Losses [14]:

$$Q_{-rad} = 3.6 \cdot s \cdot A \cdot d\,t \cdot \left(T_g^4 - T_a^4\right) \tag{65}$$

where A is the opening area of furnace;

δt is the opening rate, i.e., the times of furnace that is opened per hour.

Effective heat capacity calculation of furnace components

$$HC_{\_fce} = HC_{\_alloy} + HC_{\_heater} + HC_{\_insulation} \quad (66)$$

where $HC_{\_alloy}$ is the furnace alloy heat capacity,

$$HC_{\_alloy} = M_{\_alloy} \times c_{p\text{-}alloy} \quad (67)$$

where $M_{\_alloy}$ is the total mass of furnace alloys including grate, fan, basket/tray/fixture, conveyor, and supports; c_{p_alloy} is their specific heat.

$HC_{\_heater}$ is heat capacity of electric heating element,

$$HC_{\_heater} = M_{\_heater} \times c_{p\text{-}\ heater} \quad (68)$$

where $M_{\_heater}$ is the mass of heating element, $c_{p\text{-}\ heater}$ is its specific heat.

$HC_{\_insu}$ is furnace insulation heat capacity, it equals to

$$HC_{\_insu} = M_{\_insu} \times c_{p\_insu} \quad (69)$$

where $M_{\_insu}$ is the mass of insulation, c_{p_insu} is specific heat.

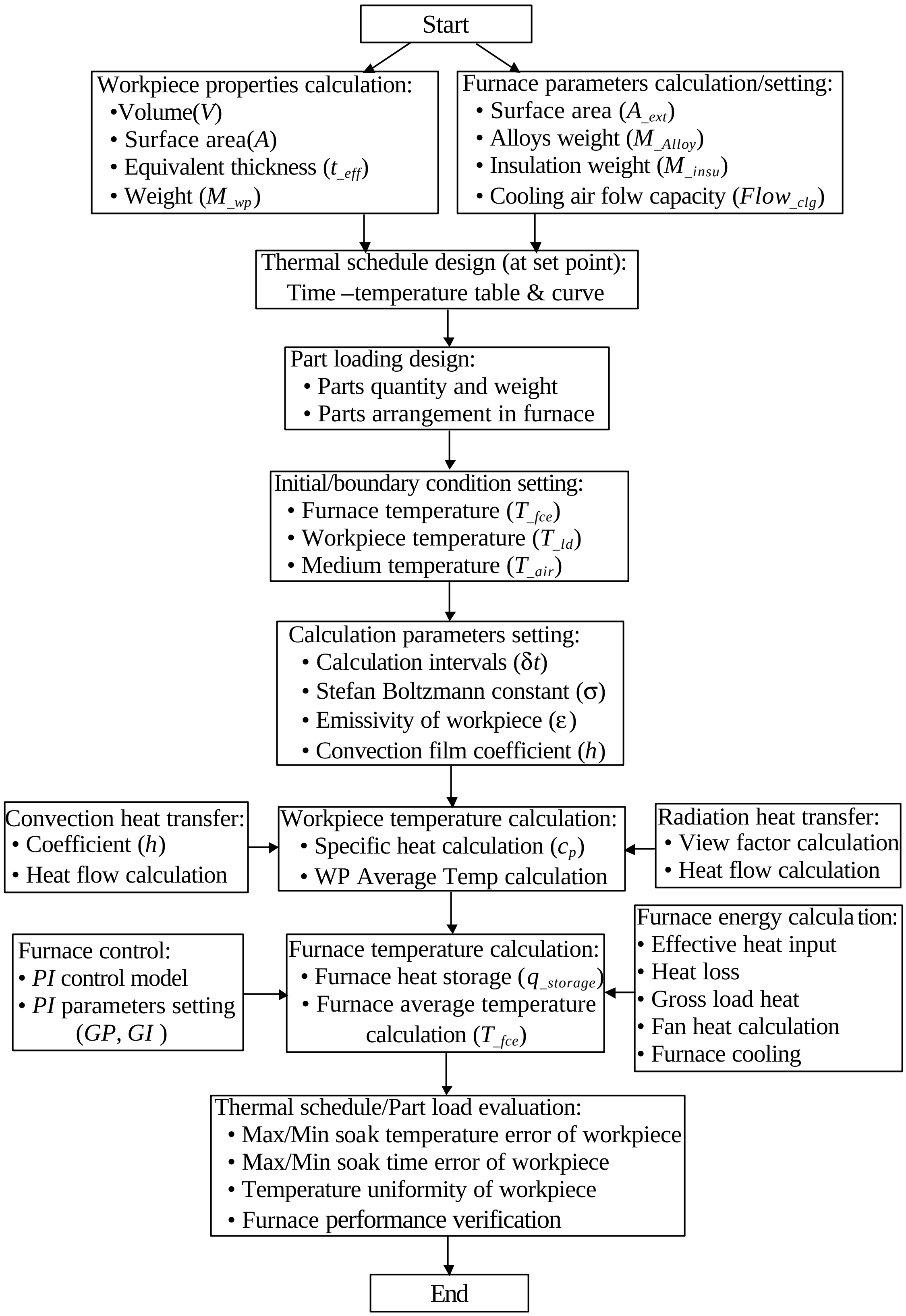


Figure 2.20. Flowchart for temperature of loaded furnace

The furnace model developed has many parameters which are included in the database. The effect of the various parameters are analyzed and studied.

2.6 Workpiece temperature calculation

There are five main factors that affect the workpiece temperature during heat treating cycle, including part properties, thermal schedule, radiation heat transfer, and convection heat transfer, as shown in figure 2.21.

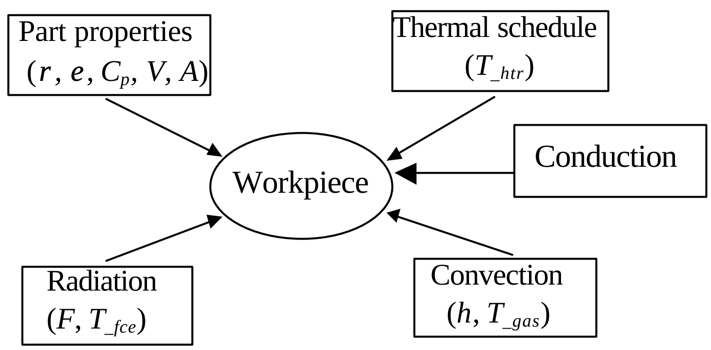


Figure 2.21 The effect of workpiece

The temperature history of workpieces in the heat treating furnace is a three dimensional conduction heat transfer process with hybrid convection/radiation boundary conditions. Part load patterns and the thermal schedule design are the main work in the heat treatment process design used to guarantee the heat treatment quality.

In the heat treating process, the workpieces are subjected to both convection and radiation heat transfer. Apply the energy balance equation to the workpiece, then,

$$E_{storage} = E_{convection} + E_{radiation} \tag{70}$$

Where $E_{storage}$ is the heat storage in the workpiece. $E_{convection}$ and $E_{radiation}$ are the heat obtained from convection and radiation heat transfer, respectively. Let the volume and surface area of workpiece are V and A. the energy terms in equation (70) can be calculated using following equation:

(1) Convection at ambient temperature T_{mediun}:

$$E_{convection} = h \cdot A \cdot \left(T_{medium} - T\right) \tag{71}$$

where h is the convection heat transfer coefficient, T is the temperature of WP, T_{medium} is the medium temperature in furnace.

(2) Radiation at heat source temperature T_{heater}:

$$E_{radiation} = e \cdot s \cdot F \cdot A \cdot \left(T_{heater}^4 - T^4\right) \tag{72}$$

where e is emissivity, s is Stefan Boltzmann constant, F is view factor between heater and workpiece, workpiece to workpiece, T_{heater} is the heater temperature.

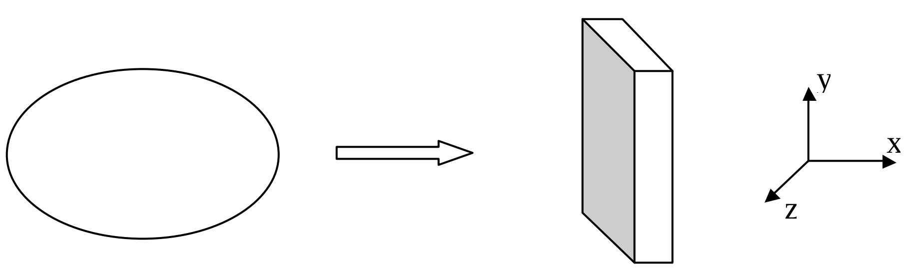
(3) Heat storage interior workpiece:

$$E_{storage} = r \cdot c \cdot V \frac{dT}{dt} \tag{73}$$

where ? is the density of workpiece, c is the specific heat, and t is the time. Combine equation (71), (72) and (73) into (70), then

$$r \cdot c \cdot V \cdot \frac{dT}{dt} = h \cdot A \cdot \left(T - T_{medium}\right) + e \cdot s \cdot F \cdot A \cdot \left(T^4 - T_{heater}^4\right) \tag{74}$$

Since the workpiece are taken as the uniform heating body, we can imagine an equivalent workpiece or "visual workpiece" to replace the real workpiece, as shown in figure 2.22. In this way the calculation can be further simplified.



(a) Real WP (b) Equ. WP

Figure 2.22. Equivalent workpiece

let $V = A \cdot t_{\_equ}$, where $t_{\_equ}$ is the equivalent thickness of workpiece.

Apply finite difference method to the left-side of equation (74), then

$$\frac{\partial T}{\partial t} = \frac{T^{k+1} - T^{k}}{d\,t} + \mathrm{O}(d\,t) \tag{75}$$

where k is the time step. Combine equation (74) and (75). Rearrange the equation (74), then at time step k, the equation becomes,

$$T^{k+1} = T^{k} + \frac{d\,t}{r \cdot c \cdot t_{\_equ}}\left[h \cdot \left(T^{k}_{medium} - T^{k}\right) + e \cdot s \cdot F \cdot \left(\left(T^{k}_{heater}\right)^{4} - \left(T^{k}\right)^{4}\right)\right] \tag{76}$$

Equation (76) can be used to calculate the temperature of workpiece with uniform temperature distributions at any time in a heat treating cycle.

(2) About radiation heat transfer and view factor calculation

Because the workpieces are located in the different positions in the furnace, the surface temperature around the workpiece is different. We can present this effect by the view factor.(Refer section 2.3).

(3) Workpiece interior temperature and core temperature:

It is noted that equation (76) is a simple and effective method to the small size parts. As for the large size parts or big equivalent thickness parts, the temperatures on the surface and in the center are big different. We need to calculate both of them. The temperature at an interior point can be calculated using both FEM analysis and analytical method.

For the analytical method, The other method is “visual sphere” method (Refer 2.2) is a useful way used to calculation the center temperature in a workpiece.

Chapter 3: System Structure, Interface and Database

3.1 System function and objectives

CAHTPS is a software tool used to simulate the parts heating process design and predict the heat-treating results. The simulating results can be used to evaluate the part loading pattern or thermal schedule.

There are five modules in the system:

- Process design module, including part load design, thermal schedule design, part and furnace definition, and some process parameters definition;
- Temperature calculation and evaluation module, including both workpiece and furnace temperature calculation;
- Database/Knowledge system, including data search, data management for workpiece, furnace, part loads, and thermal schedule;
- Output, the results process and graphic/evaluation output;
- CAD based user interface: used for information input/output and interactive

The system main functions include:

- The simulation of heating process of workpieces in loaded furnace;
- The calculation of the furnace average temperature for various types of furnaces;
- The calculation of energy balance for furnace heat-treating process;
- The design and optimization of the thermal schedule and part loading; and
- Database management system for heat-treat process design.

The objective of this research is to establish a knowledge-based computer-aided heat treat planning software system for the heat treatment process optimization. The system can be used to predict the temperature history of workpieces under given part loading pattern, thermal schedule and work conditions. And provides the necessary information for the optimization of part loading and thermal schedule in heat treating process, and hence get the uniform quality of the product and promote the productivity and efficiency.

3.2 System structure

The software consists of mainly five function modules: workpiece definition, furnace definition, load pattern, thermal schedule and calculation & report. The file management and database&database management serves the foundation of the software. Its structure is shown in Fig. 3.1. The contents included in each module are listed in Table 3.1.

The entry of the software and its main interface are shown in Fig.3.2 and Fig. 3.3 respectively.

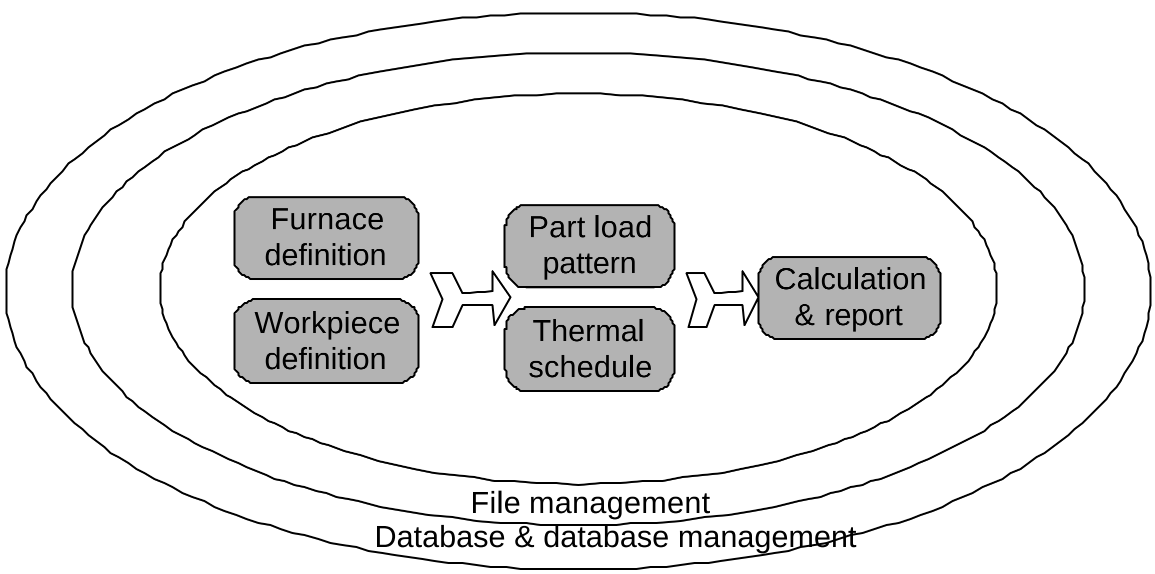


Fig. 3.1 Software structure

Table 3.1. Software main structure and contents

Workpiece definition	Furnace definition	Load pattern	Thermal schedule	Results and report	Database management
• Workpiece name Workpiece material type • Workpiece material • Material surface condition • Weight • Material emissivity f(T) • Workpiece shape & size definition: critical values, • Shape picture • Surface external surface area • Total surface area • Workpiece shape classification	• Furnace name • Atmosphere • Fuel • Preheated air temperature • Excess air • Furnace shape & size • Operating temperature • Gross load • Power • Heating method • Vacuum or not • Cooling condition • Recirculation fan • Accessories weight & material • Furnace wall material & thickness	• Fixture shape • Fixture number, rows, columns, layers • Workpiece number in each fixture: rows, columns and layers • Total workpiece quantity • Total load weight	• Input method I: time-temperature points • Input method II: ramps and levels • PID control constants	• Initial conditions • Calculation • Temperature-time curves • Heat rate-time curves • Fuel flow rate- time curve • Report	• Material • Furnace • Fuel/gas • Atmosphere • Workpiece • User

3.3 System Interface

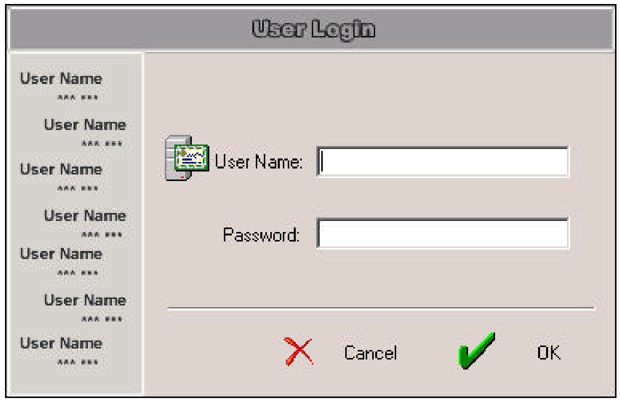


Fig. 3.2 User login

Fig. 3.3 Main interface

3.3.1 Workpiece definition

Workpiece definition includes workpiece material and weight definition, workpiece material emissivity edition and Workpiece shape &size definition, which are shown in Figs. 3.4-3.6. Workpiece material, material properties and workpiece shape are loaded from database directly. The thermal properties such as density, specific heat and conductivity are disposed behind the surface. Because emissivity is very important and values from references vary greatly, user can change the value from the interface.

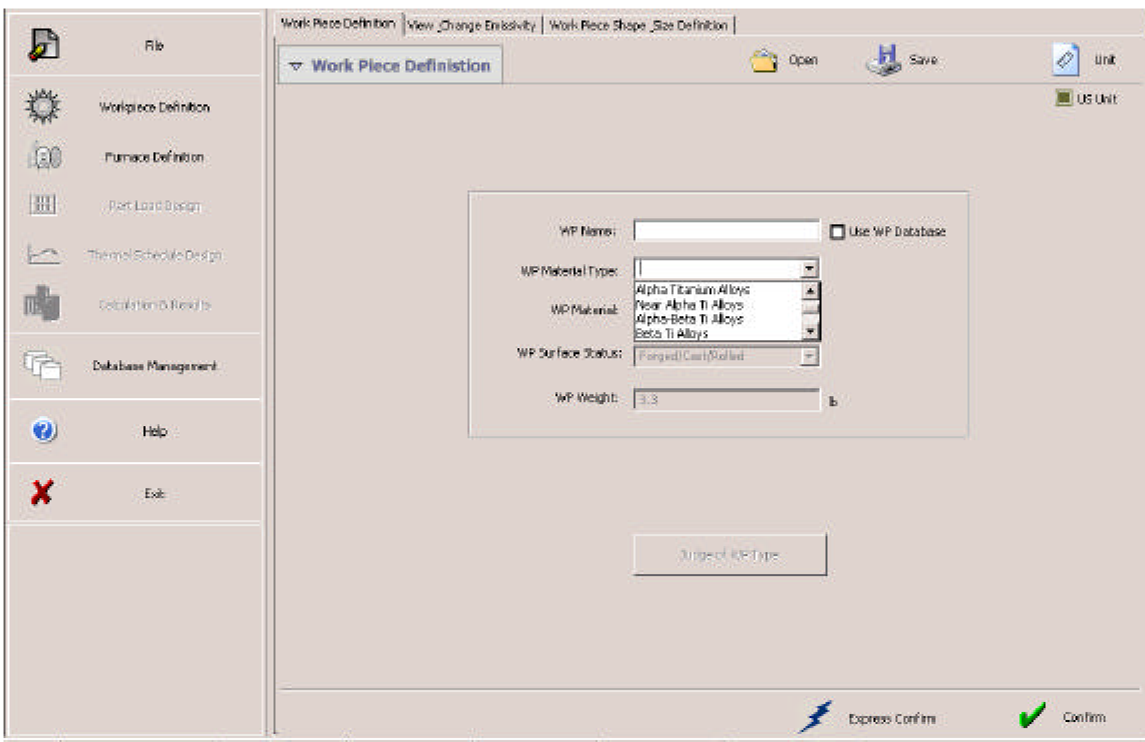


Fig. 3.4 Workpiece definition page1

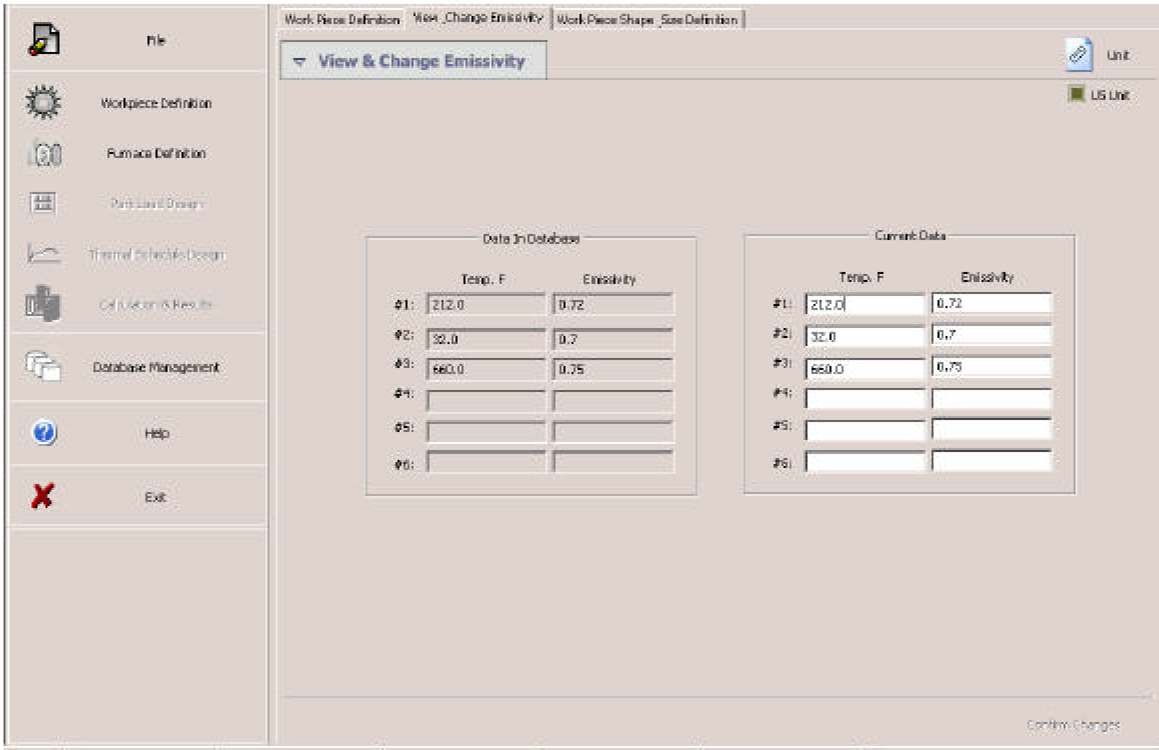


Fig. 3.5 Workpiece definition page2—workpiece material emissivity

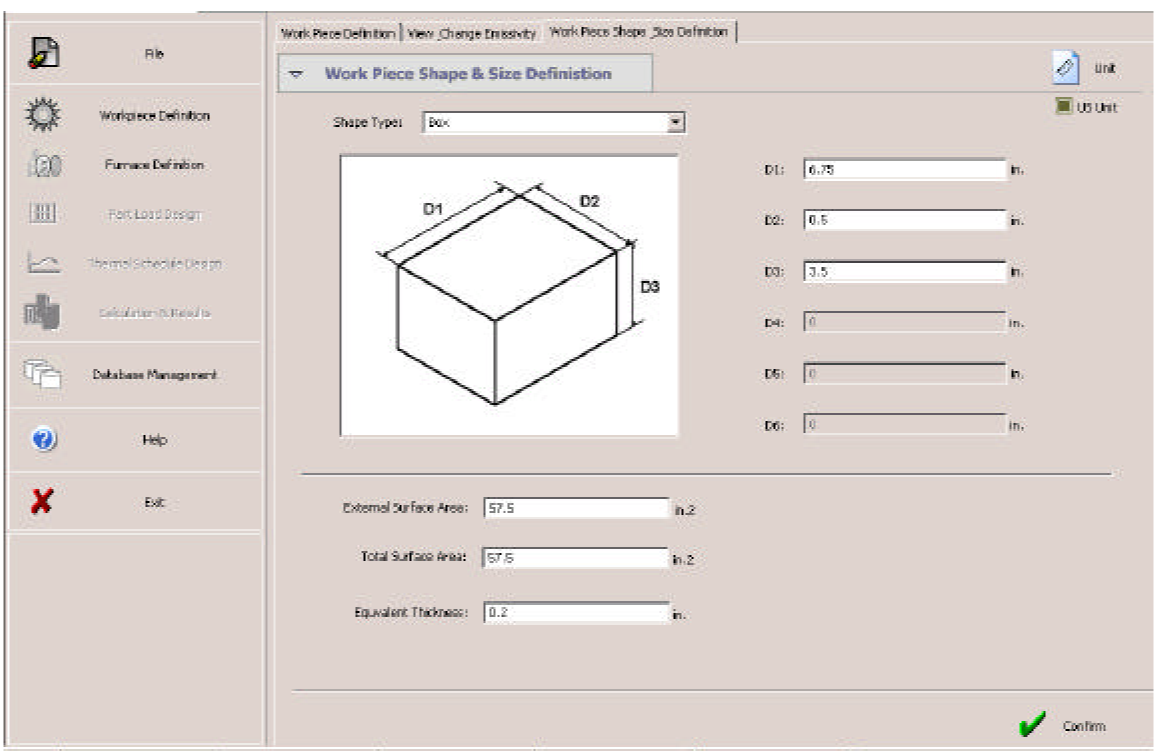


Fig. 3.6 Workpiece definition page3—workpiece shape and size definition

3.3.2Furnace definition:

Furnace definition includes four pages. Furnace image and all the other three pages are loaded directly from the furnace database. User can check and edit the values according to users' request, as shown in Figs. 3.7-3.10. Fuel, atmosphere settings are independent on the furnace database. Fuel type, atmosphere and other material selections are directly lined with respective database.

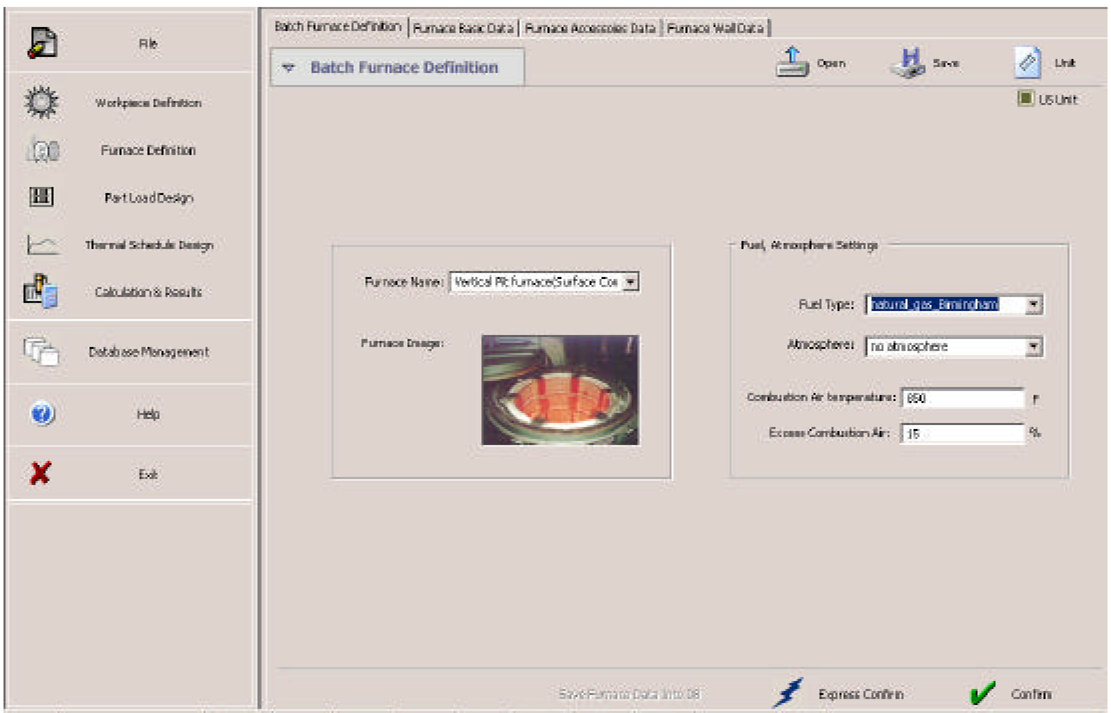


Fig. 3.7 Furnace definition page1

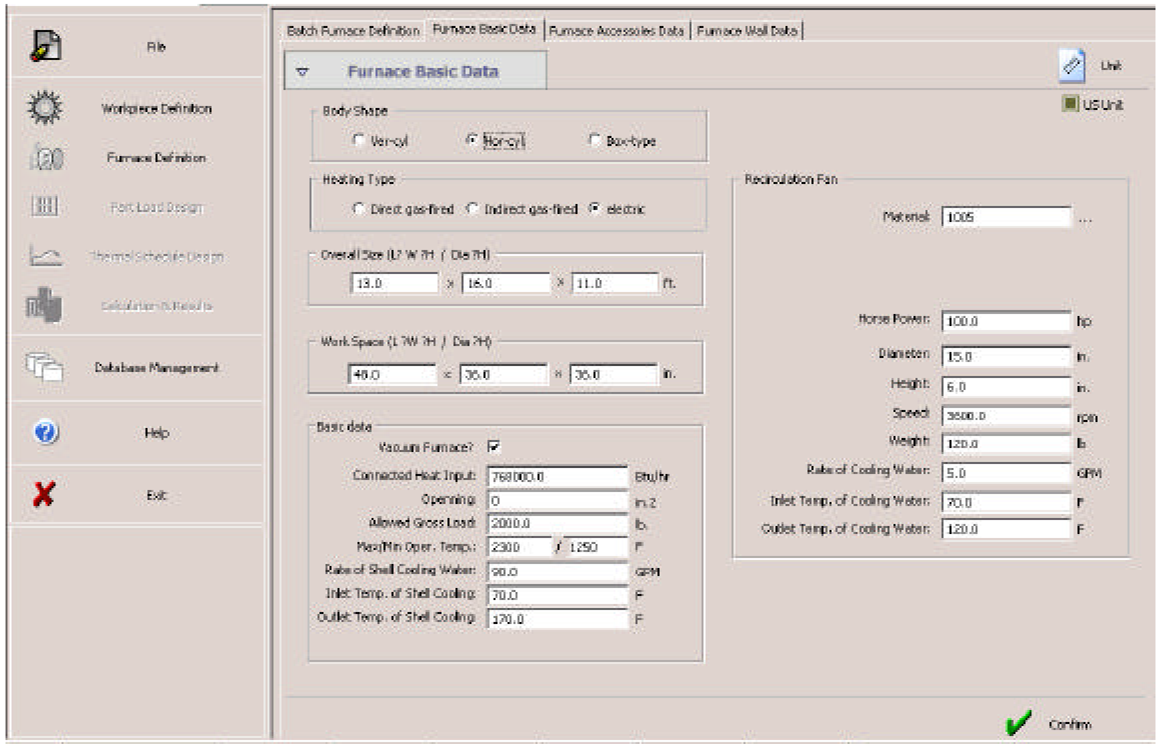


Fig. 3.8 Furnace definition page2

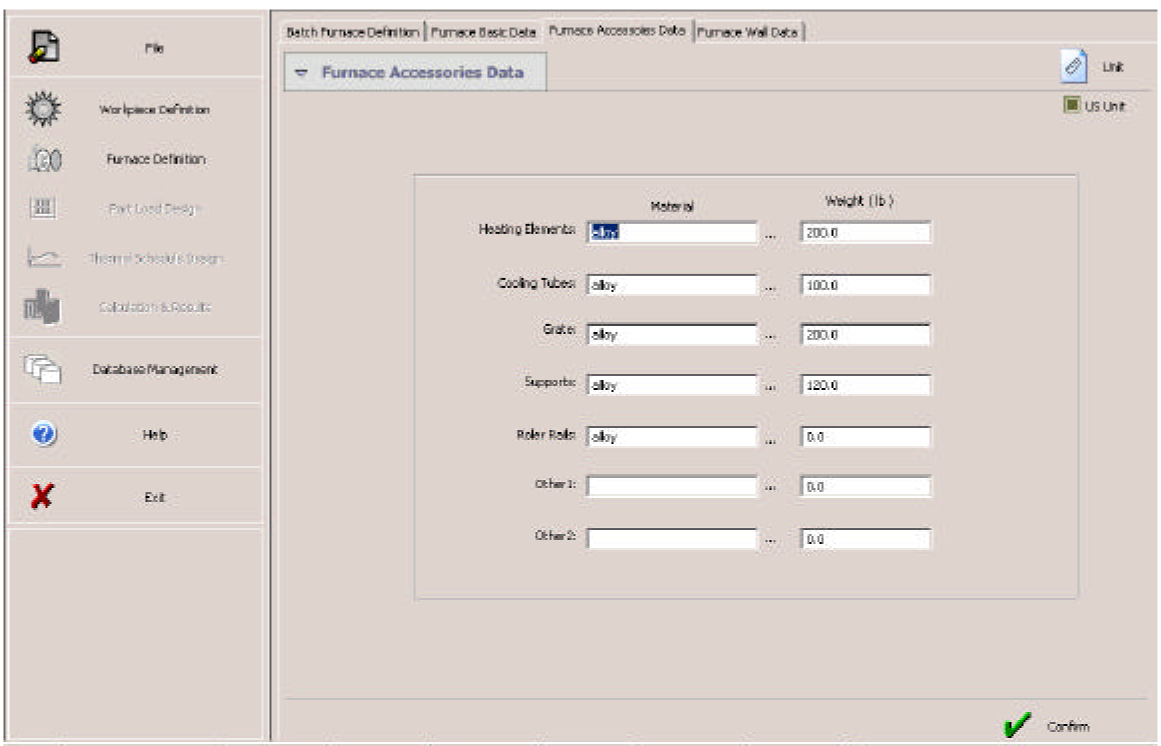


Fig. 3.9 Furnace definition page3—furnace accessories

Fig. 3.10 Furnace definition page4 --- furnace wall

3.3.3Load pattern:

Load pattern are classified into rectangular and round fixture shape and arranged and randomly packed categories. In this version only arranged load pattern is presented. It is made up of fixture definition and workpiece arrangement in fixtures. Fixture pattern includes rows, columns and layers. Part configuration includes rows, columns and layers of workpieces in each fixture.

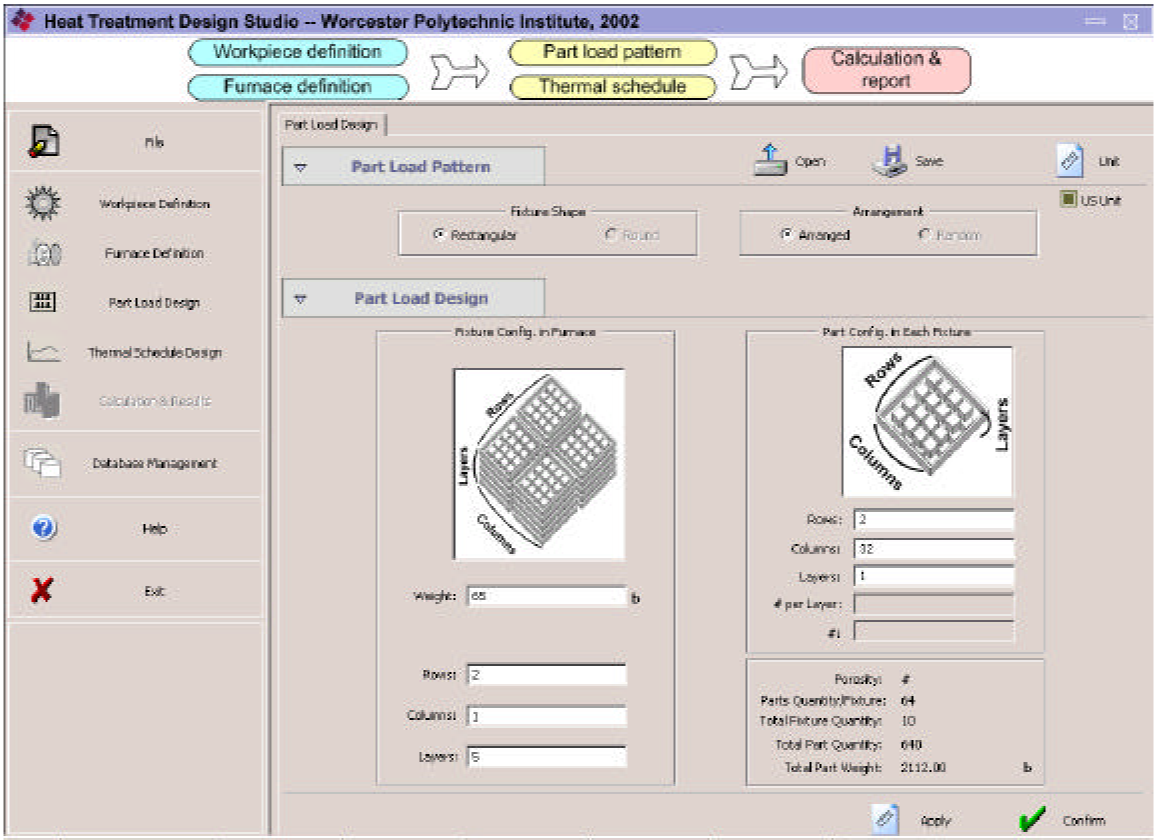


Fig. 3.11 Load pattern definition

3.3.4 Thermal schedule:

Two methods of input of thermal schedule are given, one is by points of time and temperature, the other is by ramps and levels. PID control is included in this page. There is an option for PID control, yes or no. If the answer is yes, PID constants are needed. For some old furnaces or small furnaces used in the lab there is always no PID control.

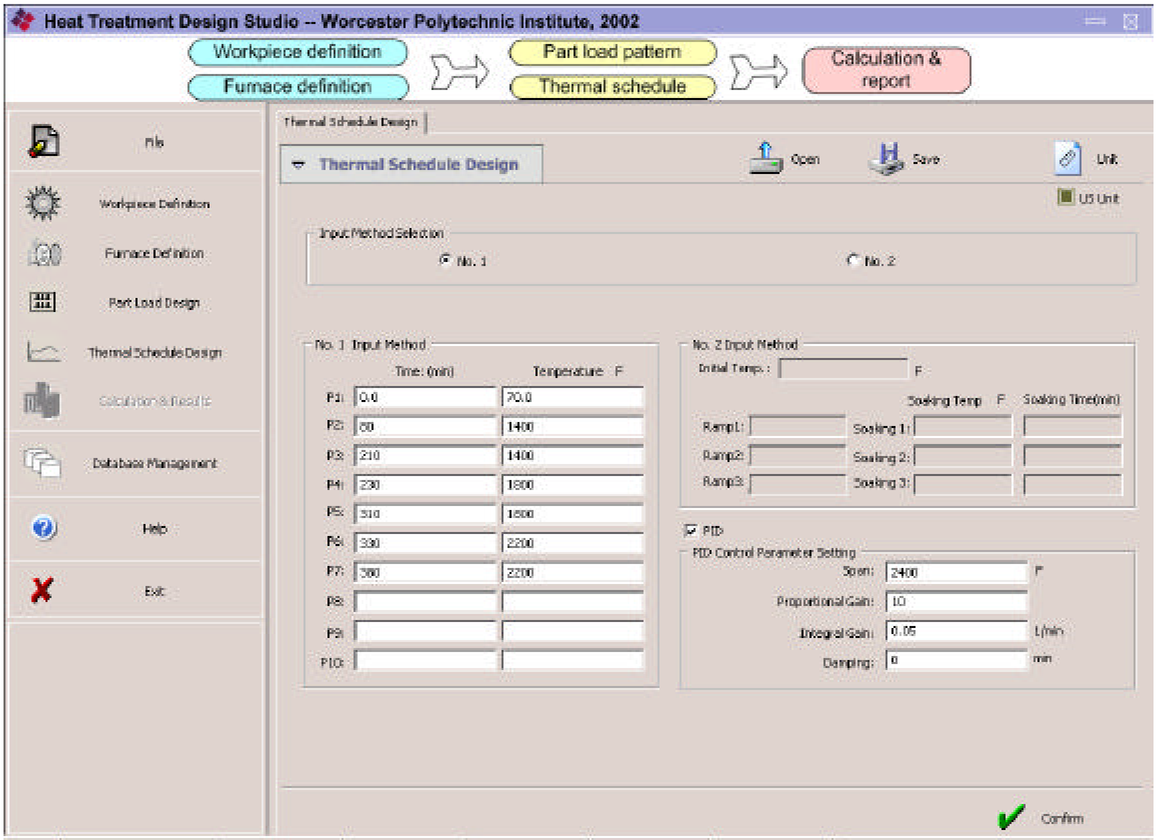


Fig. 3.12. Thermal schedule and PID control

3.3.6 Results & reports

The calculation page is illustrated in Fig. 3.14.

1) Results:

Results include:

- Temperature histories of critical parts (Static curves given directly) and any part (Dynamic curves given indirectly)
- Rate changes of all heat terms
- Fuel flow rate – time curve (for gas-fired furnace)

They are shown in Figs. 3.13-3.17. Static curves include set point temperature (thermal schedule), furnace temperature, fastest workpiece temperature, slowest workpiece temperature, and temperatures of the six centers of edges and faces. For the user's convenience, any workpiece temperature –time curve can be plotted by just giving the row, column and layer number.

The curves can be highlighted by thickening or zoomed in. The curves can also be saved into bitmap files.

2) Report file

The input information and calculation results can be saved into text file as shown in Fig. 3.18.

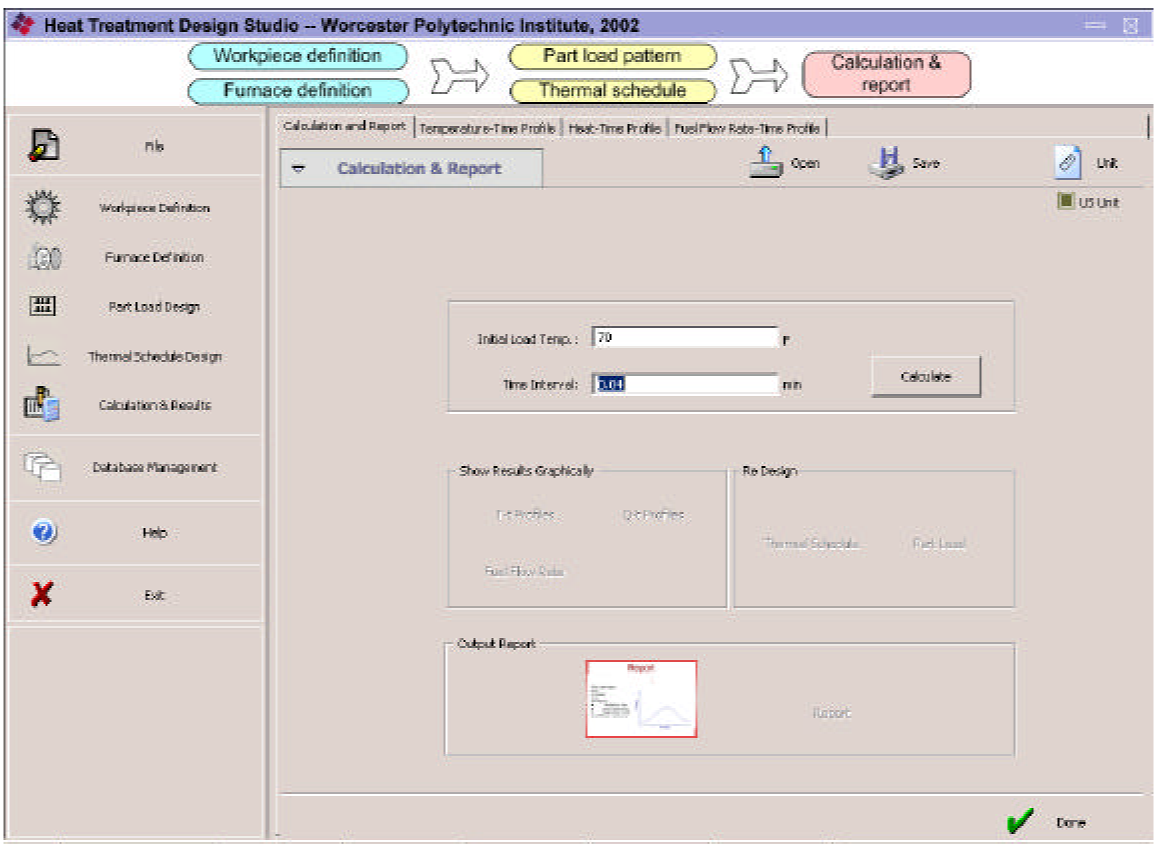


Fig. 3.13 Calculation and report page

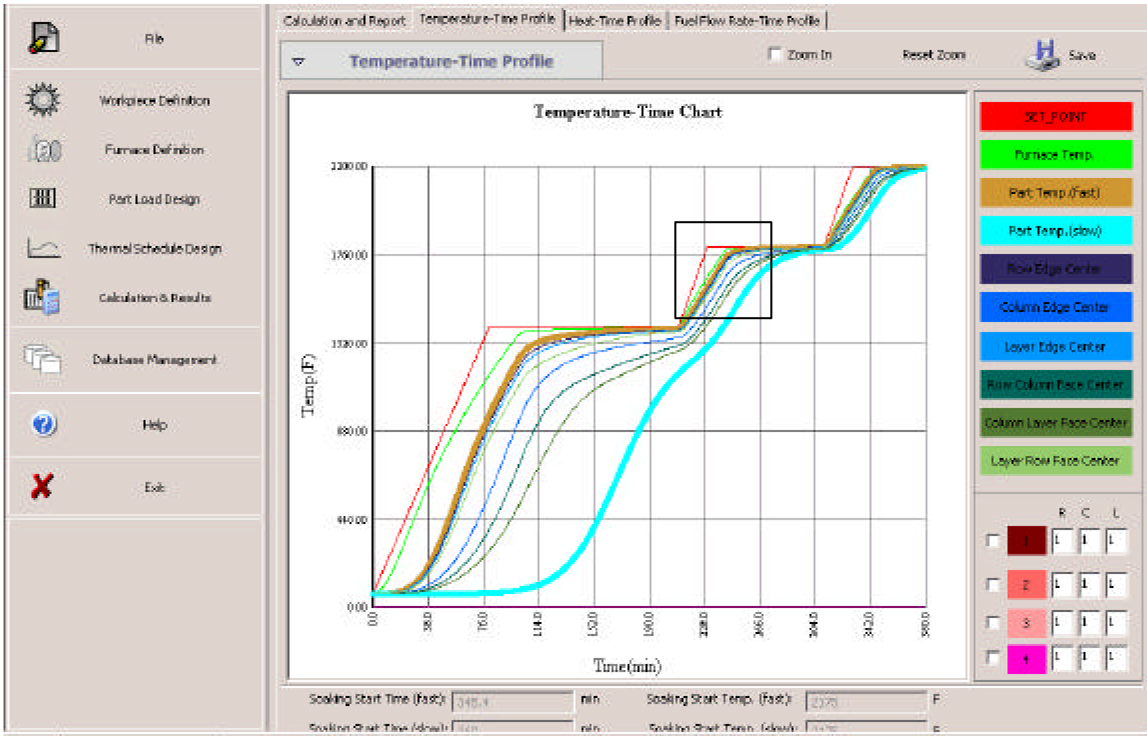


Fig. 3.14 Temperature—time profiles

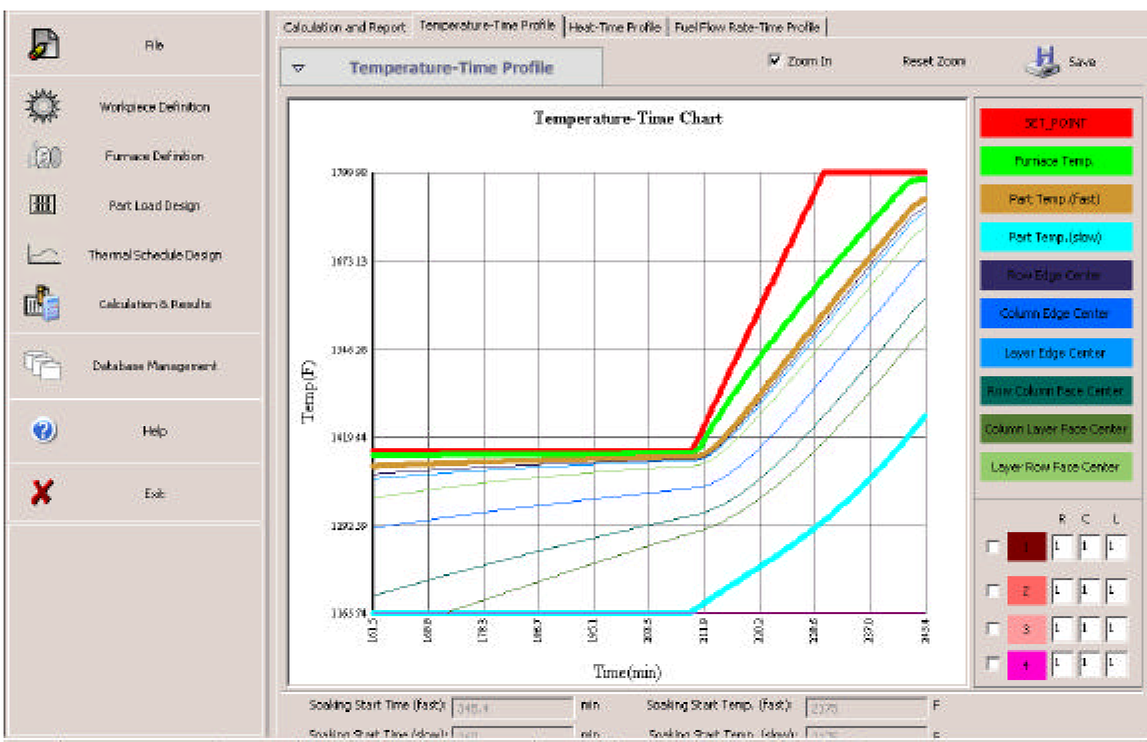


Fig. 3.15. Zooming of curves

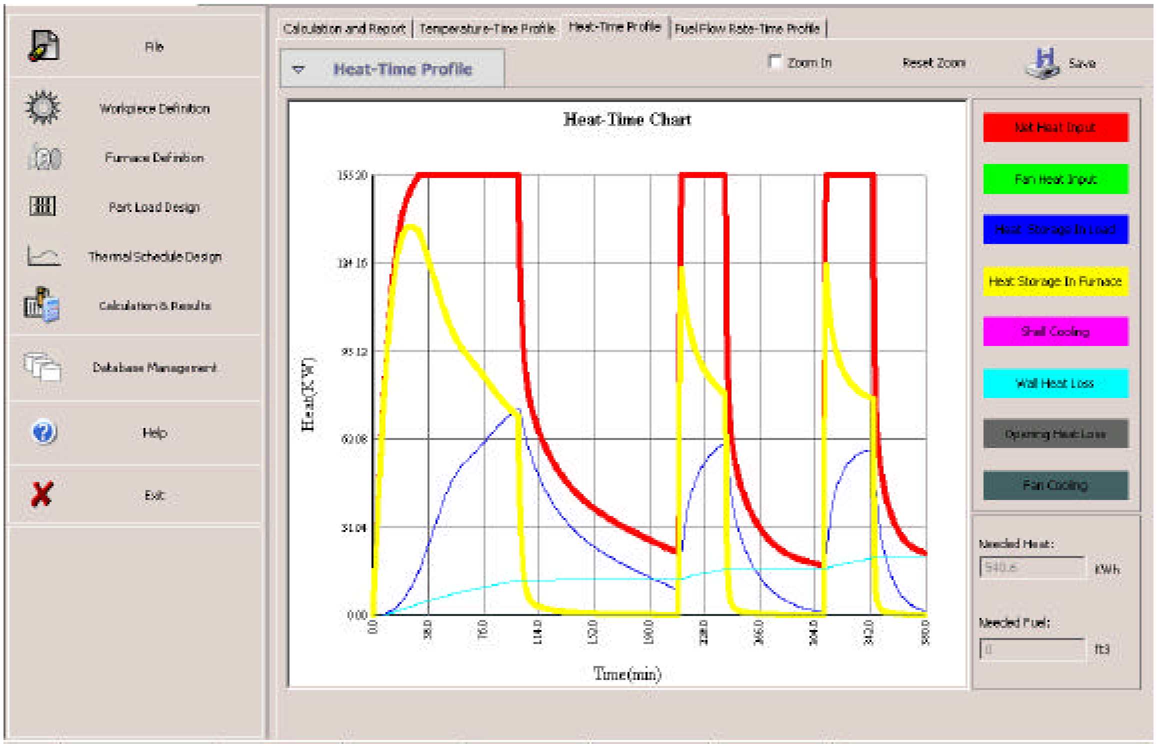


Fig. 3.16 Heat rate—time profiles

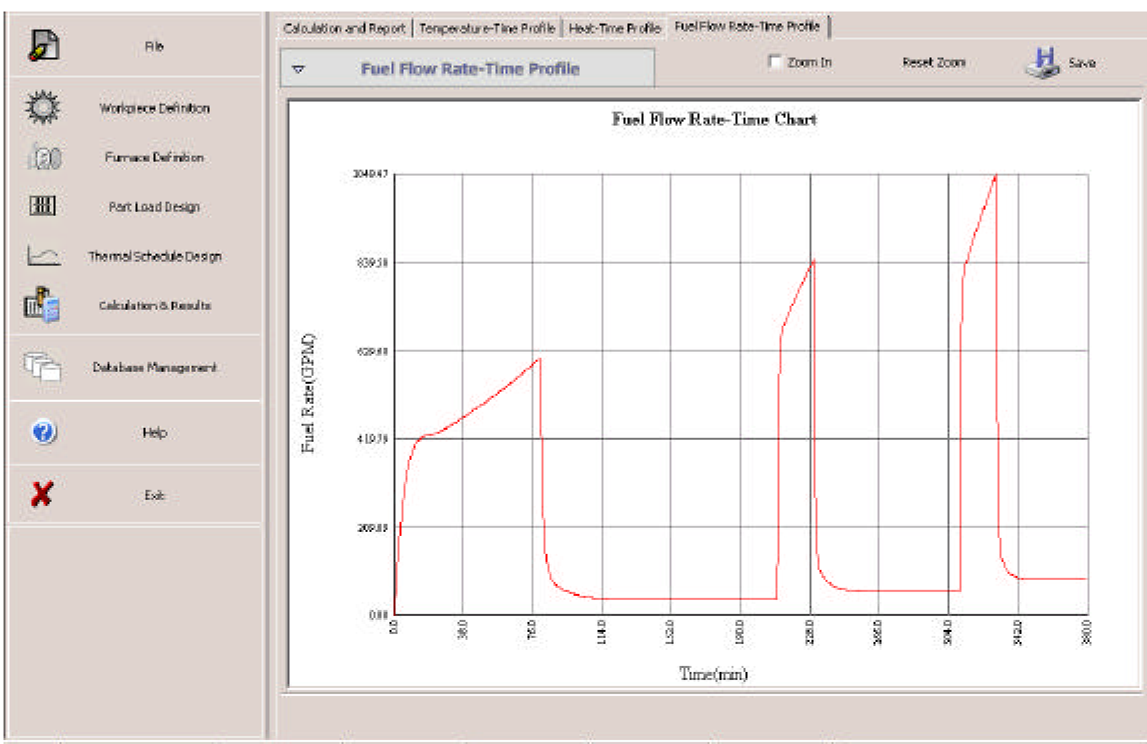


Fig. 3.17 Fuel flow rate—time curve

report - Notepad

File Edit Format Help

```
                HEATING PROCESS ANALYSIS OF blade'S HEATING
DATE:   4/18/2002
COMPANY:
USER:
1. INPUT:
  1) WORKPIECE INFORMATION:
    WORKPIECE NAME:                  blade
        MATERIAL TYPE:               Stainless Steel
        MATERIAL:                    403
        WORKPIECE UNIT WEIGHT (lbs):                      3.3
        WORKPIECE EXTERNAL SURFACE AREA (FT2):            0.4
        WORKPIECE TOTAL SURFACE AREA (FT2):               0.4
        WORKPIECE EQUIVALENT THICKNESS (FT):              0.0
        WORKPIECE SURFACE FINISH:                          Forged/Cast/Rolled
        WORKPIECE EMISSIVITY:
                TEMPERATURE(F)    EMISSIVITY
                     32.0           0.70
                    212.0           0.72
                    660.0           0.75
  2) FURNACE INFORMATION:
        FURNACE NAME: vertical Pit furnace(Surface Combustion))
        FURNACE SHAPE:  vertical cylindrical Furnace
        HEATING METHOD:  INDIRECT GAS-FIRED
        FUEL: natural_gas_Birmingham
                HEAT CONTENT OF FUEL (Btu/ft3):                              1002.0
                PREHEAT TEMPERTURE OF COMBUSTION AIR (F):                     850.0
                EXCESS COMBUSTION AIR ():                                      15.0%
        ATMOSPHERE:  no atmosphere
        FUNACE EXTERNAL SIZE(ft*ft*ft):              14.6      16.6      0.0
        FUNACE WORKSPACE(ft*ft*ft):                   5.7       6.0      0.0
        VACUUM: NO
        FURNACE CONNECTED HEAT INPUT(Btu/hr):           8600000.0
        FURNACE MAXIMUM & MINIMUM OPERATION TEMPERATURE (F):       1900.0    1400.0
        OPENING AREA (ft2):                                   0.0
        ALLOWED GROSS LOAD WEIGHT(lbs):                   18000.0
        COOLING RATE OF FURNACE SHELL (GPM):                  0.0
                INLET & OUTLET TEMPERATURE (F):               0.0         0.0
        RECIRCULATION FAN:
                HORSEPOWER (HP):                              0.0
                DIAMETER (ft):                                0.0
                HEIGHT (ft):                                  0.0
                SPEED (rpm):                                  0.0
                WEIGHT (lbs):                                 0.0
                RATE OF COOLING WATER (GPM):                  0.0
                INLET & OUTLET TEMPERATURE (F):              70.0        70.0
        WEIGHT OF HEATING ELEMENTS (lbs):            4050.0
        WEIGHT OF COOLING TUBES (lbs):               1680.0
        WEIGHT OF GRATE (lbs):                       1100.0
        WEIGHT OF SUPPORTS (lbs):                       0.0
        WEIGHT OF ROLLER RAILS (lbs):                   0.0
        WEIGHT OF OTHER 1 (lbs):                      660.0
```

```
        WEIGHT OF OTHER 2 (lbs):                        0.0
        FURNACE WALL MATERIALS & THICKNESS (in):
                FURNACE ROOF:
                                 0.8
                                 0.0
                                 0.0
                                 0.0
                                 0.0
                FURNACE SIDE WALLS:
                                 0.8
                                 0.0
                                 0.0
                                 0.0
                                 0.0
                FURNACE BOTTOM:
                                 0.8
                                 0.0
                                 0.0
                                 0.0
                                 0.0
  3) LOAD PATTERN INFORMATION:
        FIX SHAPE:              RECTANGULAR
        LOAD PATTERN:           ARRANGED
        WEIGHT OF FIXTURE (lbs):                  65.0
        FIXTURE SIZE (ft*ft*ft):                   2.8        2.8       2.8
        ROWS, COLOMNS, LAYERS OF WORKPIECE IN EACH FIXTURE:   2    32    1
        ROWS, COLOMNS, LAYERS OF FIXTUREs:                    2     1    5
        TOTAL QUANTITIES OF WORKPIECES IN EACH FIXTURE:     64
        QUANTITIES OF  FIXTURES:                           10
        QUANTITIES OF  WORKPIECES:                        640
        QUANTITIES OF  WORKPIECES:                        640
        TOTAL WEIGHT OF  WORKPIECES (lbs):             2112.0
  4) THERMAL SCHEDULE INFORMATION:
        TIME (min)  & TEMPERATURE (F):
             0.0          70.0
            80.0        1400.0
           210.0        1400.0
           230.0        1800.0
           310.0        1800.0
           330.0        2200.0
           380.0        2200.0
        MAXIMUM TEMPERTURE (F) OF SET POINT & TIME (min)    2200.0      380.0
  5) PID CONSTANTS: SPAN (F)  PG  IG(1/min)  DG(min):     2400.0       10.0      0.050      0.0
  6) INITIAL CONDITIONS: INITIAL LOAD TEMPERATURE (F):      70.0
  7) TIME STEP (min):       0.009
```

```
2. RESULTS:
       HEAT TERMS                               TOTAL HEAT (MBtu)   &    RATIO IN TOTAL HEAT (%):
       TOTAL HEAT INPUT                                  11.6              100.0%
       FAN HEAT INPUT                                     0.0                0.0%
       HEAT ABSORPTION BY LOAD                            0.6                5.6%
       HEAT STORAGE IN THE FURNACE                        6.5               56.2%
       HEAT LOSS FROM WALL                                1.5               12.9%
       HEAT LOSS FROM OPENING                             0.0                0.0%
       FURNACE SHELL COOLING                              0.0                0.0%
       FAN BEARING COOLING                                0.0                0.0%
       NET HEAT INPUT                                     8.7               74.7%
       FORCED CONVETION COEFFICIENT          0.0
       FORCED CONVETION NUSSEL NUMBER        0.0
       NATURAL CONVECTION COEFFICIENT        0.0
       NATURAL CONVETION NUSSEL NUMBER       5.1
       TEMPERATURE DIFFERENCE BETWEEN FASTEST WORKPIECE AND THERMAL SCHEDULE (F):                1.0
       TIME TO REACH HIGHEST LAOD TEMPERTURE (F):                                              380.0
       SOAKING START TIME OF FASTEST HEATED WORKPIECE(min):                                     333.2
       SOAKING START TEMPERATURE OF FASTEST HEATED WORKPIECE (F):                             2175.0
       TEMPERATURE DIFFERENCE BETWEEN SLOWEST WORKPIECE AND THERMAL SCHEDULE (F):                1.0
       SOAKING START TIME OF SLOWEST HEATED WORKPIECE (min):                                   335.7
       SOAKING START TEMPERATURE OF SLOWEST HEATED WORKPIECE (F):                             2175.0
       NEED FUEL (ft3):                                                                       11672.1
```

Fig. 3.18 Report file

3.3.7 Management of analysis case environment

The whole calculation environment, i.e., all the inputs consisting from the interface and database can be saved into files. Therefore the analysis of an old case can be done just by load from calculation environment from the saved files. In the file menu there are new design, loading a existed design and saving design three functions. Pages with respect to each menu item can also be saved into file separately. And the file can be loaded into the pages as well.

3.3.8 Unit change

There two unit systems, Metric and US, can be selected. The change between these two systems can be performed at any time by just pressing the button at the right top corner of each dialog. The values and the units as well will change when unit system is changed. The user can input the values under their favorite unit system, even different unit system for items on the same page. An example is shown in Figs. 3.8 and 3.19.

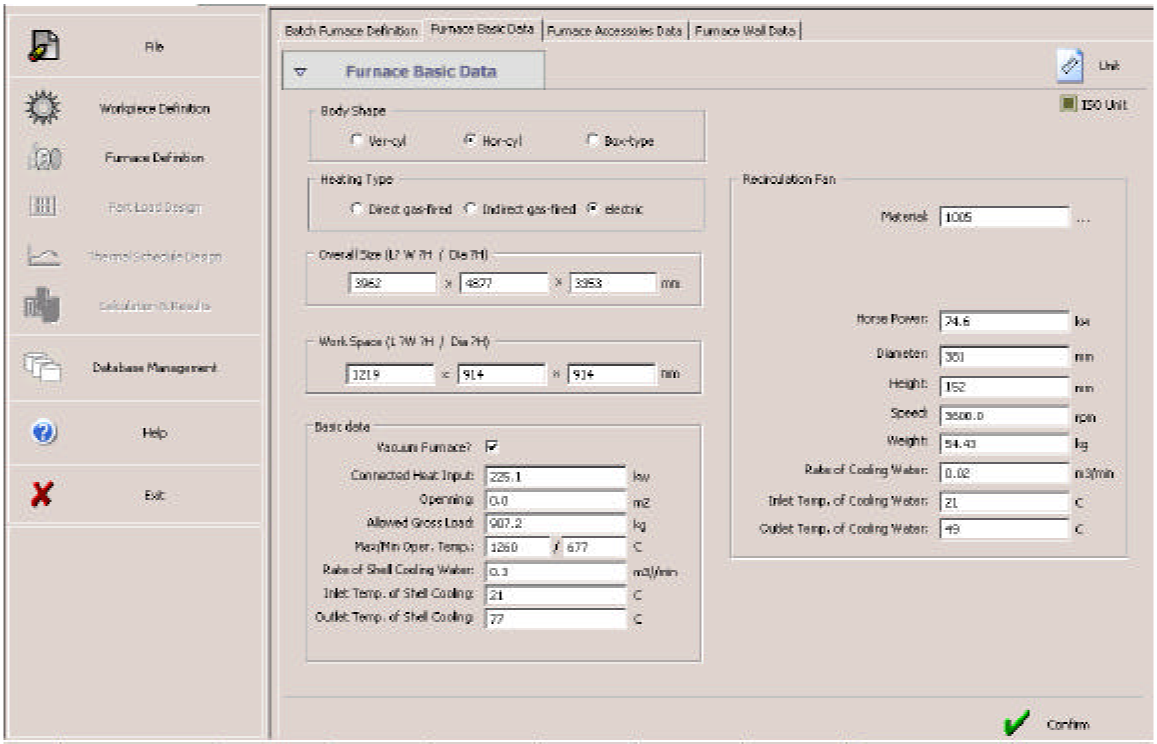


Fig. 3.19 Unit change

3.3.9 *Online help*

The help file is made into html files, when the user press the help key in each dialog the relative help file will appear in web style.

3.4 Database and database management

3.4.1 Use of Database

Every system cannot function independently on the programs. It needs to have storage capability and retrieval capability of data used as inputs to the programs. This data stored is to be kept in a proper format for editing and additions. This storage of data in an organized manner with relationships is called a database.

The CAHTPS works on many data values of material properties, furnace materials and etc. This data is stored in an easy format for editing and adding using Microsoft Access. The database is developed with the relationships among the various properties. The database management system makes it easy to add new data and edit the existing data.

3.4.1 Contents of the database

The CAHTPS database contents the following:

1. Workpiece material and properties [15-26,28]
2. Workpiece shape
3. Furnace Data (Case studies, Surface Combustion)
4. Furnace atmosphere [26,25]
5. Furnace fuels [26,29]

3.4.2 Structure

As mentioned earlier, in the database contents various types of data values and some of these values are interdependent and inter-related (specific heat, thermal conductivity dependent on temperature). The data in a database is stored in form of tables. Each table has set entities which represent a column in a table. Each table contains records stored in it which are input by the user. One or more of the entities in a table maybe related to other table entities. The relationship between all the tables is shown below in Fig3.20.

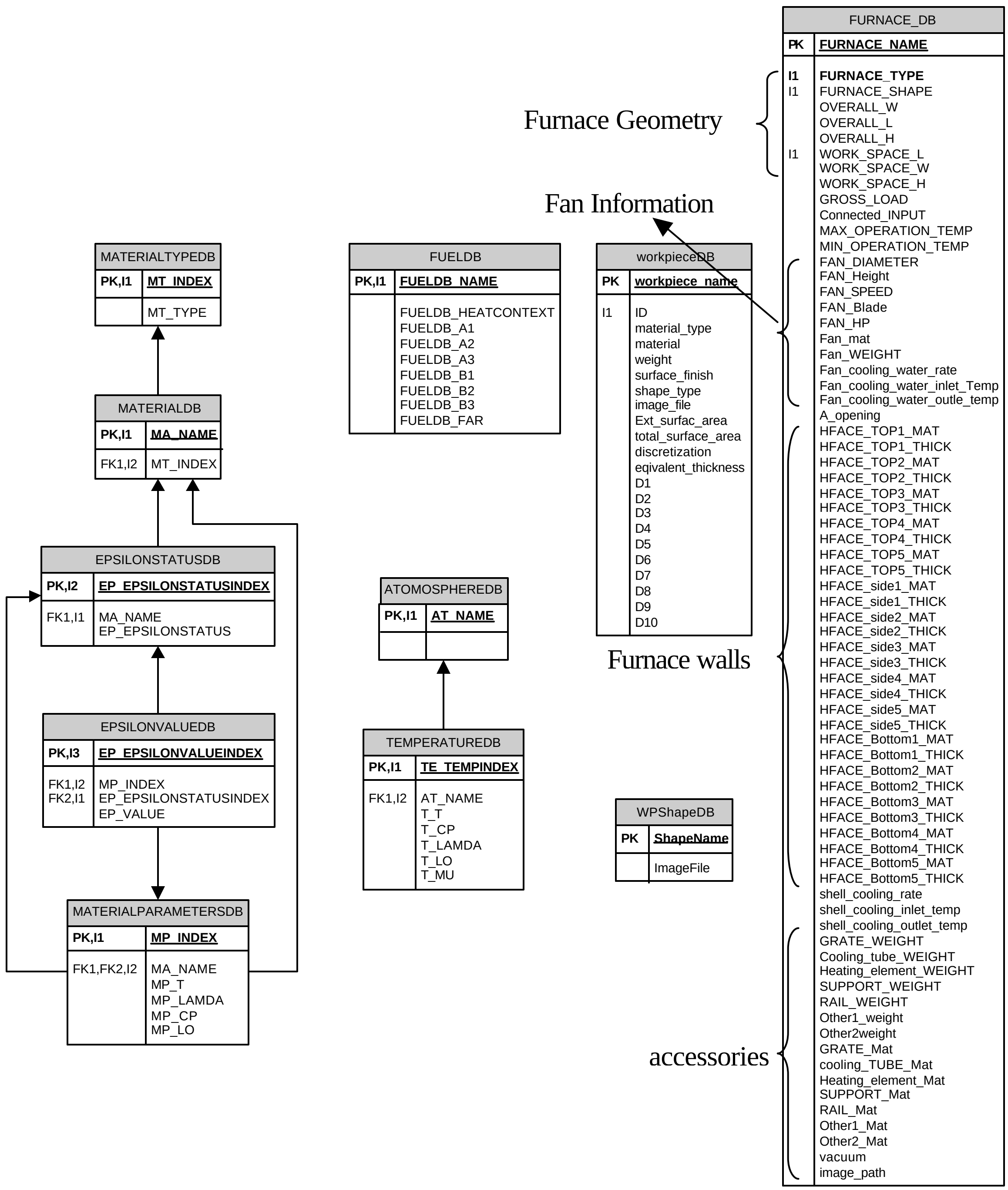


Figure3.20 Database Structure

As seen from above Fig 3.20 some of the tables are related to each other, whereas some tables are single (FURNACE_DB) or have only one to one relation with another table.

3.4.3 Materials and properties database

The material DB consists of all kinds of metals as shown below in figure 3.22. The materials database is used for defining the workpiece material, the fixture material, the furnace accessories material and the furnace wall material. Different properties of the materials are required to be input in the system for calculations. The property values are stored in the database and can be viewed and modified as required by the user. The database currently holds data of more then 2000 materials and its properties.

MT_INDEX	MT_TYPE
1	Carbon Steel
2	Alloy Steel
3	Tool Steel
4	Stainless Steel
6	Cast Aluminum
7	Wrought Aluminum
8	Pure/Low Alloy Nickel
9	Nickel-copper Alloy
10	NonMetals
11	Ni-Cr & Ni-Cr-Fe Alloy
12	Fe-Ni-Cr Alloy
13	Controlled Exp Alloy(Ni)
14	Ni-Fe Alloys
15	Pure Titanium Alloys
16	Alpha Titanium Alloys
17	Near Alpha Ti Alloys
18	Alpha-Beta Ti Alloys
19	Beta Ti Alloys
20	Zinc Alloys
21	Other Alloys

Figure 3.21: Types of materials included in the database

Materials database

Steel & alloys

A complete list of steel materials classified as carbon, alloy, stainless and tool steels is stored in the database. The AISI nomenclature is used for the identification.

Aluminum & alloys

Both cast and wrought aluminum alloys are included in the database. ANSI designation system is used in the database.

Nickel alloys

Nickel copper, Ni-Cr, Ni-Cr-Fe, Controlled expansion Ni alloys & Ni-Fe alloys are included in the database.

Nonmetals

Nonmetals contain all the furnace wall materials and insulations used. The most commonly used insulations and furnace walls materials are included in the database.

Titanium & alloys

Pure, alpha, near alpha, alpha beta and beta titanium alloys are included in the database.

Other alloys

Other alloys include other commonly used alloys like molybdenum, tungsten and tantalum alloys.

Material Properties

The various material properties included in the database are:

Specific heat (MP_CP)

Thermal Conductivity (MP_LAMDA)

Density (M_LO)

Emissivity (EP_VALUE, also function of surface finish EPSILONSTAUSINDEX)

Non Metals properties

The above properties of the materials are a function of temperature MP_T and hence temperature dependent values are input in the database, the temperature scale for different materials is different. The material properties are useful to calculate the heat transfer and storage in the load. The walls materials properties are useful to determine the heat storage in the furnace and the heat loss in the furnace.

MT_INDEX	MT_TYPE
1	Carbon Steel

MA_NAME
1005

MP_INDEX	MP_T	MP_LAMDA	MP_CP	MP_LO
1	210	33.42	0.1185	491

EP_EPSILONVALUEINDEX	EP_EPSILONSTATUSINDEX	EP_VALUE
1060	8	0.8
1061	9	0.6
1062	10	0.2
1063	11	0.08
(AutoNumber)		

MP_INDEX	MP_T	MP_LAMDA	MP_CP	MP_LO
2	570	28.56	0.1371	491
3	930	23.7	0.1692	491
4	1110	20.7	0.18	491
5	1290	19.13	0.2485	491
6	1380	17.4	0.26	491
7	1560	16.5	0.2055	491
8	1830	15.95	0.165	491
(AutoNumber)				

Figure 3.22: Material properties included in the database

Specific Heat

Units: *Btu (therm)/lb-°F*

Conversion used: 1 Btu (therm)/lb-°F = 4184 J/Kg-K

The data in the database is collected from the references listed in the end. A general plot of the specific values is shown below from 122 deg F to 1652 deg F. As observed from the curves, the variation in the specific heat values with temperature, 8 points were selected to input in the database.

Material 5132

Temp F	Cp (BTU/lb-F)
122	0.12
212	0.12
302	0.13
392	0.13
482	0.13
572	0.13
662	0.14
752	0.14
842	0.16
932	0.16
1022	0.18
1112	0.18
1202	0.20
1292	0.36
1382	0.22
1472	0.22
1562	0.14
1652	0.14

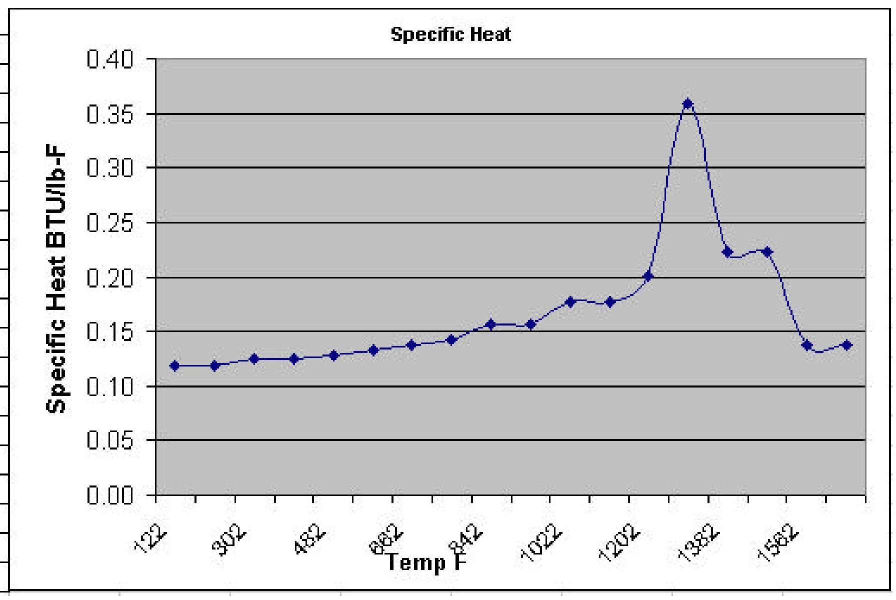


Figure 3.23: Specific heat values and curves (given data)

The 8 points selected to be included in the database are 210, 570, 930, 1110, 1290, 1380, 1560 & 1830. Some temperature values of some materials were not available from the references, hence interpolated or curve values were input into the database.

Some materials do not have the list of values for all the temperature scale. Hence interpolated values are input in the system. Also for some materials with no values available from the references, the values of material with similar or close composition are assigned to these materials. Materials are grouped and the materials in one group are assigned the same values.

Thermal Conductivity

Units: *Btu/h.ft. °F*

Conversion used: 1 W/m.K = 0.5782 *Btu/h.ft. °F*

The data in the database is collected from the references listed in the end. A general plot of the thermal conductivities values is shown below from 122 deg F to 1830 deg F.

Material 1008	
Temp F	Lamda (BTU/hr-ftF)
32	59.50
212	57.80
392	53.20
572	49.40
752	45.60
932	41.00
1112	36.80
1292	33.10
1472	28.50
1832	27.60
2192	29.70

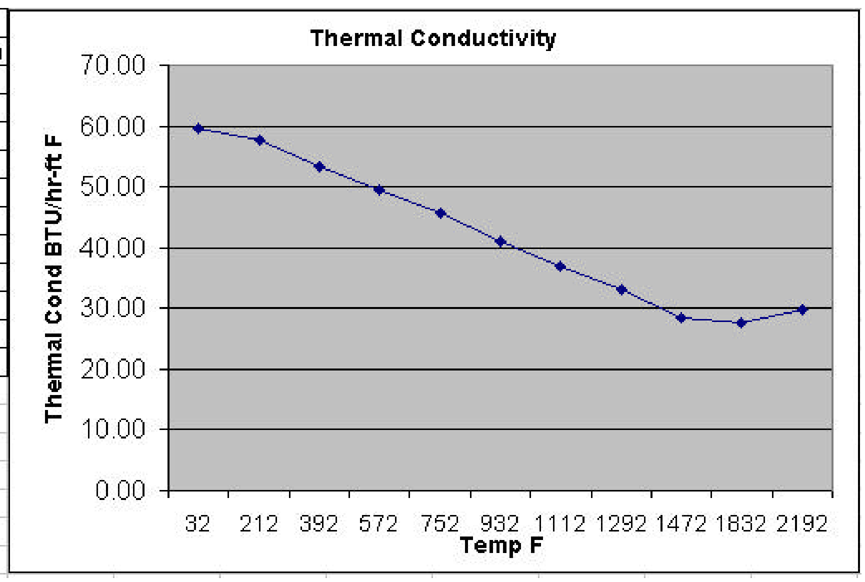


Figure 3.24: Thermal conductivities values and curve

The temperature values for thermal conductivities recorded in the database are as specific heat (210, 570, 930, 1110, 1290, 1380, 1560 & 1830)

As observed from the above curve, thermal conductivity of a material decreases with increase in the temperature and follows a liner path.

A similar interpolation technique as followed for the specific heat values is followed to get the values of thermal conductivities as some points.

Density

Units: lb/ft^3

The density of all the materials is considered to be constant with temperature. Hence a constant value at all points of temperature is input in the database. These values can be edited and changed as per the user requires.

MT_INDEX	MT_TYPE
1	Carbon Steel

MA_NAME
1005

MP_INDEX	MP_T	MP_LAMDA	MP_CP	MP_LO
1	210	33.42	0.1185	491
2	570	28.56	0.1371	491
3	930	23.7	0.1692	491
4	1110	20.7	0.18	491
5	1290	19.13	0.2485	491
6	1380	17.4	0.26	491
7	1560	16.5	0.2055	491
8	1830	15.95	0.165	491
(AutoNumber)				

MA_NAME
1006
1008
1010
1011
1012

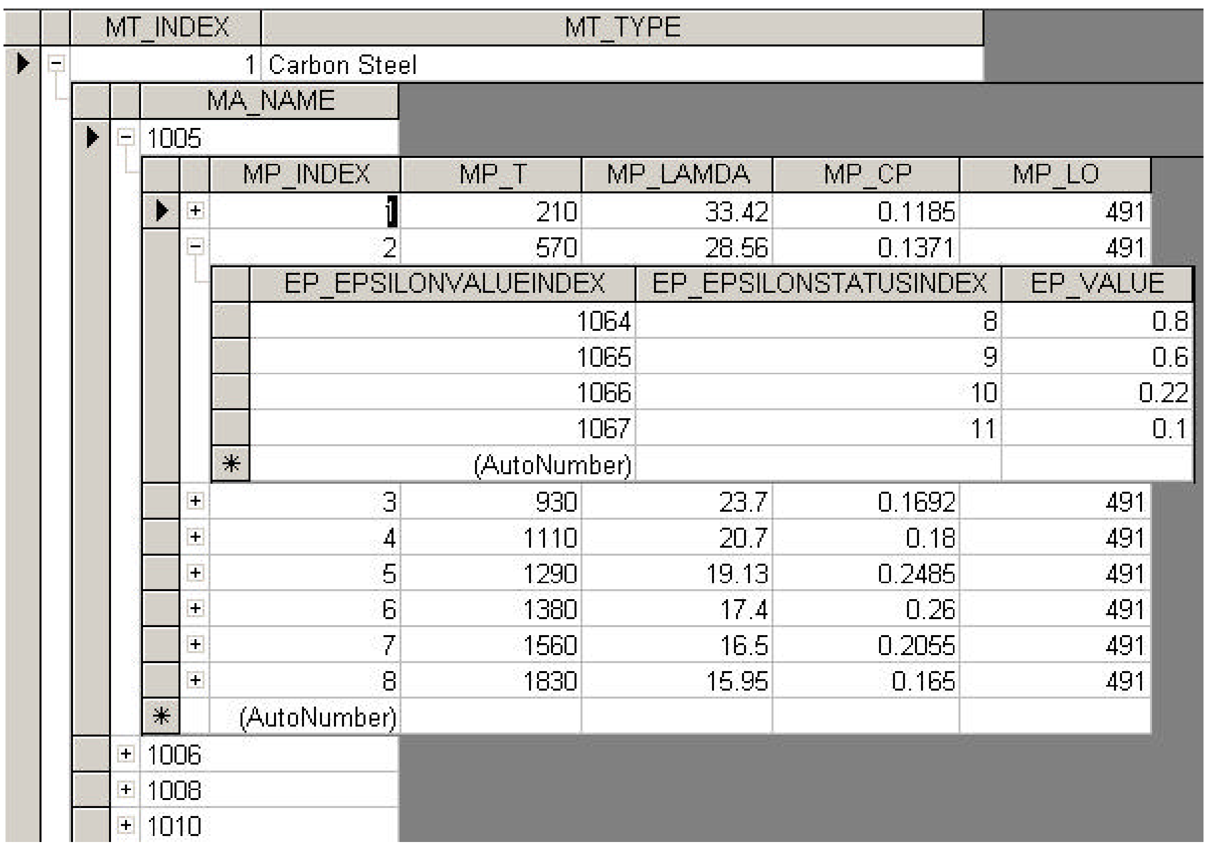
MP_INDEX	MP_T	MP_LAMDA	MP_CP	MP_LO
41	210	34.86	0.1185	491
42	570	28.91	0.1371	491
43	930	23.12	0.1692	491
44	1110	23.41	0.18	491
45	1290	22.54	0.2485	491
46	1380	20	0.26	491
47	1560	17.4	0.2055	491
48	1830	15.78	0.165	491
(AutoNumber)				

Figure 3.25: The density is considered constant with temperature for steels

Emissivity

The emissivity of the material is recorded as to be temperature as well as surface finish. The various surface finishes are

1. Forged/cast
2. Machined
3. Smooth (Smooth finish by machining operations milling, turning or sand polished)
4. Polished (polishing or finishing operation honing, lapping etc)



MT_INDEX	MT_TYPE
1	Carbon Steel

MA_NAME
1005

MP_INDEX	MP_T	MP_LAMDA	MP_CP	MP_LO
1	210	33.42	0.1185	491
2	570	28.56	0.1371	491

EP_EPSILONVALUEINDEX	EP_EPSILONSTATUSINDEX	EP_VALUE
1064	8	0.8
1065	9	0.6
1066	10	0.22
1067	11	0.1
(AutoNumber)		

MP_INDEX	MP_T	MP_LAMDA	MP_CP	MP_LO
3	930	23.7	0.1692	491
4	1110	20.7	0.18	491
5	1290	19.13	0.2485	491
6	1380	17.4	0.26	491
7	1560	16.5	0.2055	491
8	1830	15.95	0.165	491
(AutoNumber)				

MA_NAME
1006
1008
1010

Figure 3.26: Emissivity values a function of surface finish and temperature

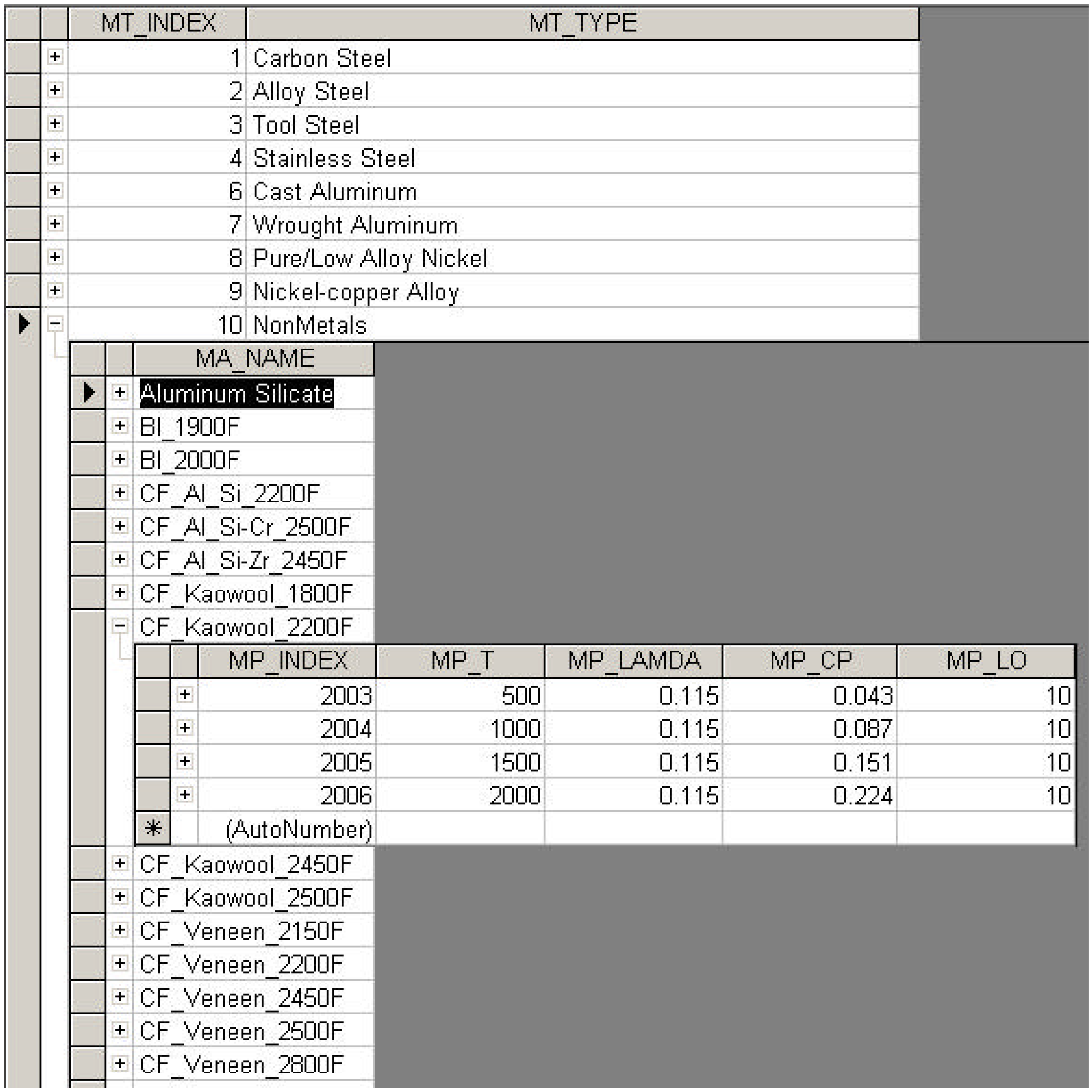
The Non metals properties

The non metals contain the refractory materials properties like kaowool, fire bricks etc used to deifne the furnace walls and the insulations.

The properties of these materials listed are:

1. Specific Heat
2. Density
3. Thermal Conductivity

All the above properties are function of temperature as shown in below Fig 3.27.



MT_INDEX	MT_TYPE
1	Carbon Steel
2	Alloy Steel
3	Tool Steel
4	Stainless Steel
6	Cast Aluminum
7	Wrought Aluminum
8	Pure/Low Alloy Nickel
9	Nickel-copper Alloy
10	NonMetals

MA_NAME
Aluminum Silicate
BI_1900F
BI_2000F
CF_Al_Si_2200F
CF_Al_Si-Cr_2500F
CF_Al_Si-Zr_2450F
CF_Kaowool_1800F
CF_Kaowool_2200F
CF_Kaowool_2450F
CF_Kaowool_2500F
CF_Veneen_2150F
CF_Veneen_2200F
CF_Veneen_2450F
CF_Veneen_2500F
CF_Veneen_2800F

MP_INDEX	MP_T	MP_LAMDA	MP_CP	MP_LO
2003	500	0.115	0.043	10
2004	1000	0.115	0.087	10
2005	1500	0.115	0.151	10
2006	2000	0.115	0.224	10
(AutoNumber)				

Figure 3.27 Non metal materials and properties

3.4.4 Workpiece shapes database

The workpiece shapes database is used to define the geometry of the workpiece so as to calculate the volume and other geometric parameters for calculations. Heat treatment is carried out on a variety of types of workpieces with different shapes and sizes. The geometry of the workpieces can be divided into two following types:

Standard shapes

These shapes include the most common standard shapes like the cube, sphere, cylinder etc. The various dimensions input by the user are used to calculate the volume, area and other parameters.

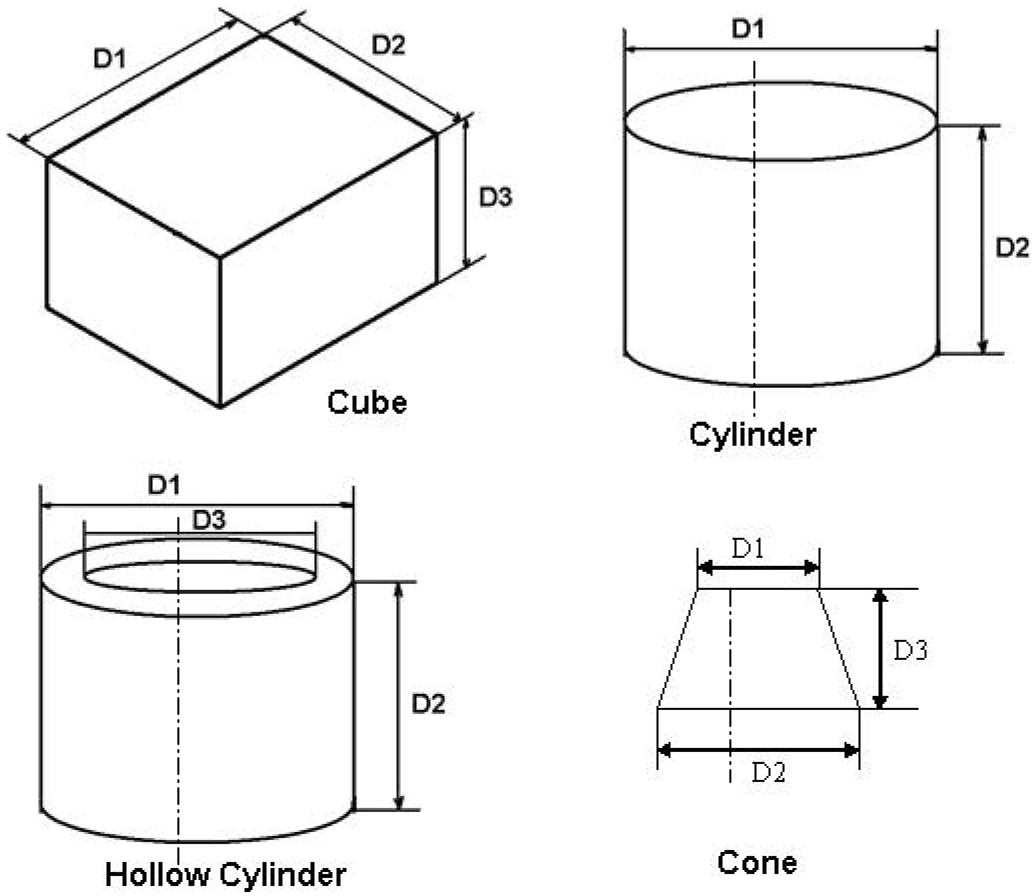


Figure 3.28 Some standard workpiece shapes

Special shapes

Some kinds of workpieces cannot be represented by standard shapes, like step shafts, hollow step shafts and etc. Hence we have some special shapes which can be used to define the workpieces with non standard or additional features. Give below is some of the special shapes included in the database.

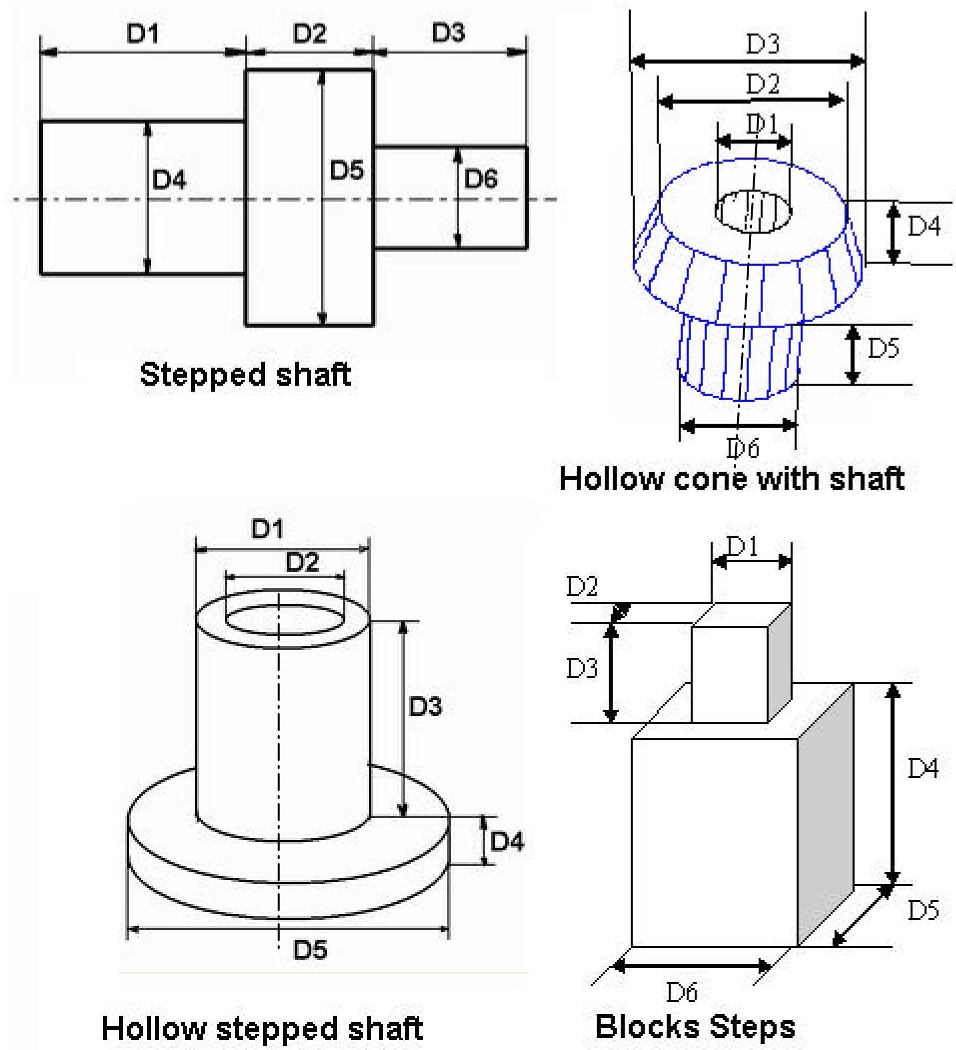


Figure 3.29 Special shapes for workpieces

3.4.5 Furnace data

The furnace database is used to store the furnace information of a furnace. This stored information can be used different times. If furnace being used for the process is same and if the information is stored in the database, the used can directly get the information from the database instead of typing all the information each time for a case.

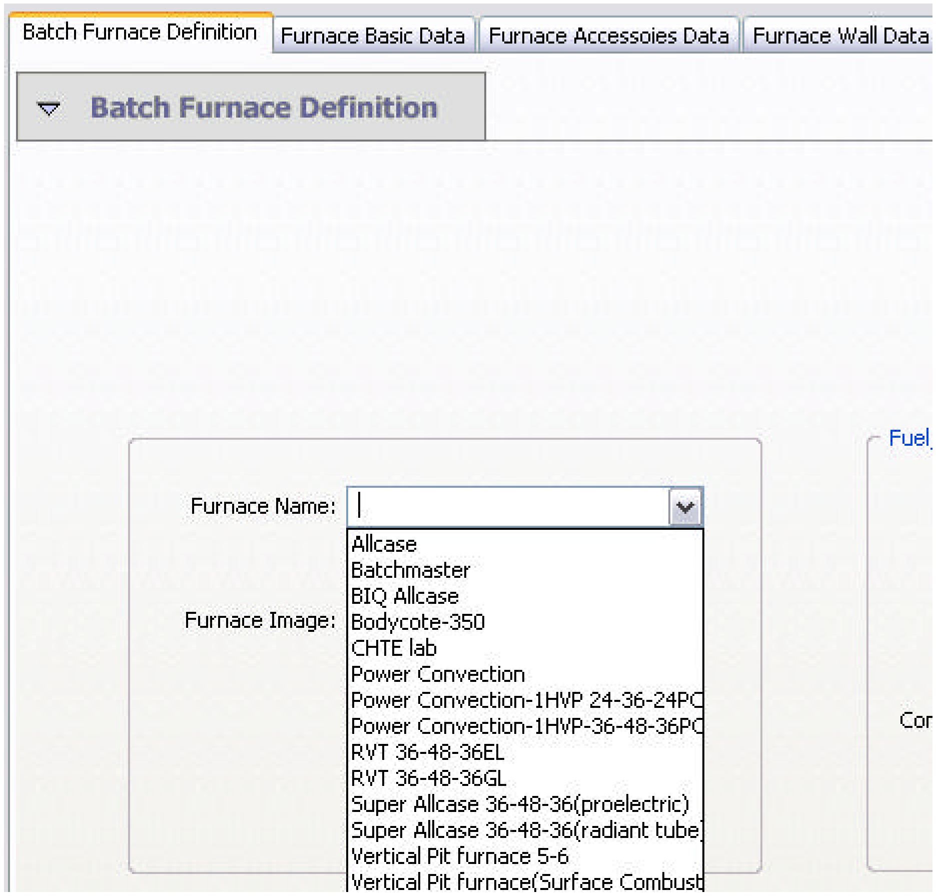


Figure 3.30: List of the furnaces along with the basic data, accessories data, stored in the CAHTPS database shown in the system interface for easy use

The furnace data in the database contains all the detailed information of the furnace (the type, shape, wall specifications, size, geometry, workspace, capacity, maximum & minimum temperatures, load capacity, accessories & their weights and etc).

FURNACE_NAME	TYPE	SHAPE	TOTAL_WIDTH	TOTAL_LEN	TOTAL_HT	WorkSpace_L
Allcase	2	3	11	10.5	18.5	36
Batchmaster	1	3	7	10.5	11	36
Bodycote-350	3	2	6.8	6.7	0	36
CHTE lab	3	3	0.65	0.7	0.6	4
Power Convection	3	2	13	16	11	36
Power Convection-1HVF	3	2	13	19.3	10	24
Power Convection-1HVF	3	2	16	20	11	36
RVT 36-48-36EL	3	3	96	96	0	36
RVT 36-48-36GL	3	3	96	96	0	36
Super Allcase 36-48-36(	3	3	11.25	10.85	10.8	36
Super Allcase 36-48-36(	2	3	11.25	10.85	10.8	36
Vertical Pit furnace 5-6	2	1	16	11.5	0	60
Vertical Pit furnace(Surf	2	1	16.6	14.6	0	68

Figure 3.31: Furnace data stored in the database

3.4.6 Furnace atmosphere

The various atmospheres used in the furnace are stored in the database. The properties of these gases required for the calculation are also included in the database. The users can add or edit the atmosphere data.

The list of atmospheres included in the database is shown below in the Fig 3.33.

AT_NAME
air
Ammonia
Argon
Carbon dioxide
Carbon monoxide
DX(Lean)
DX(Rich)
Helium
Nitrogen
no atmosphere
Oxygen
RX

Figure 3.32: List of atmosphere gases included in the database

Properties of atmosphere

The properties of the atmosphere included in the database for calculations are specific heat, conductivity, density and dynamic viscosity. All these properties are temperature dependent as shown in the Fig 3.33 below.

AT_NAME: air

TE_TEMPINDEX	T_T	T_CP	T_LAMDA	T_LO	T_MU
1	100	0.240277097	0.01503	0.08071937	0.0462
2	500	0.244815134	0.026	0.046571268	0.0675
3	1300	0.249592015	0.03122	0.038455632	0.101
4	2200	0.261056528	0.037	0.028467156	0.124
(AutoNumber)					

AT_NAME: Ammonia

TE_TEMPINDEX	T_T	T_CP	T_LAMDA	T_LO	T_MU
5	100	0.518	0.014	0.043	0.0396
6	225	0.538	0.022	0.033	0.046
7	300	0.555	0.027	0.0305	0.053
8	400	0.58	0.032	0.0266	0.0594
(AutoNumber)					

Argon

Carbon dioxide

Figure 3.33: Atmosphere properties

The properties of the atmospheric gases are specific heat (T_CP), thermal conductivity (T_LAMDA), density (T_LO) and dynamic viscosity (T_MU) all a function of temperature (T_T). The atmosphere properties are essential to calculate the heat convection by these gases.

3.4.7 Furnace fuels

Some common fuels used in the furnace are stored in the database. The user can add and edit this database. The list of fuels input in the database and the properties of the fuels included (heat content and etc) are shown below in Fig 3.35.

FUELDB_NAME	FUELDB_HEATCONTEXT	FUELDB_A1	FUELDB_A2	FUELDB_A3	FUELDB_B1	FUELDB_B2	FUELDB_B3	FUELDB_FAR
Acetylene	1498	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	11.91
Blast Furnace Gas	92	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	0.68
Butane(Natural Gas)	3225	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	30.47
Butylene	3077	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	28.59
Carbon Monoxide	323	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	2.38
Carburetted Water G	550	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	4.6
Coke Oven Gas	574	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	4.99
Digester(Sewage Ga	690	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	6.41
Ethane	1783	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	16.68
Hydrogen	325	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	2.38
Methane	1011	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	9.53
natural_gas _Pittsbu	1129	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	10.6
natural_gas_Birming	1002	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	9.4
natural_gas_Groning	941	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	8.41
Natural_gas_Kansas	974	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	9.31
Natural_gas_Los An	1073	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	10.05
Producer(Wellman-G	167	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	1.3
Propane	2572	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	23.82
Propene (Propylene)	2322	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	21.44
Sasol(South Africa)	500	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	4.13
Water Gas(bitumino	261	0.904	-0.0001894	-1.605E-08	-0.01104	0.0001816	7.322E-09	2.01

Figure 3.34: Furnace fuel and properties

The heat input for the gas furnace is calculated from the formulae given below:

$$AH1(T) = a_1 + a_2 T + a_3 T^2$$

$$AH2(T) = b_1 + b_2 T + b_3 T^2$$

$$AHC(T_{fce}, T_{ca}, X_{ca}) = AH1(T_{fce}) + AH2(T_{ca})(1 + X_{ca}) - AH2(T_{fce}) X_{ca}$$

a_1 = *FUELDB_A1*, a_2 = *FUELDB_A2*, a_3 = *FUELDB_A3*

b_1 = *FUELDB_B1*, b_2 = *FUELDB_B2*, b_3 = *FUELDB_B3*

FUELDB_HEATCONTEXT is the heat content of the fuel.

The database management functions are shown in Figs. 3.36-3.40. In the database management records can be changed, deleted and added.

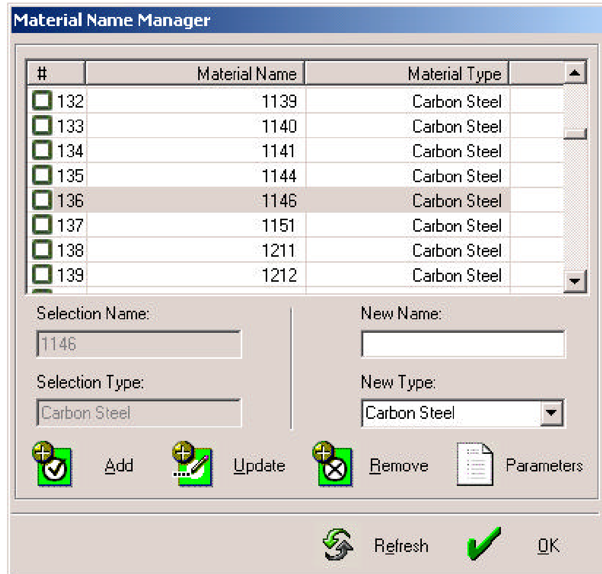


Fig3.35. Material type management

Fig. 3.36 Material name management

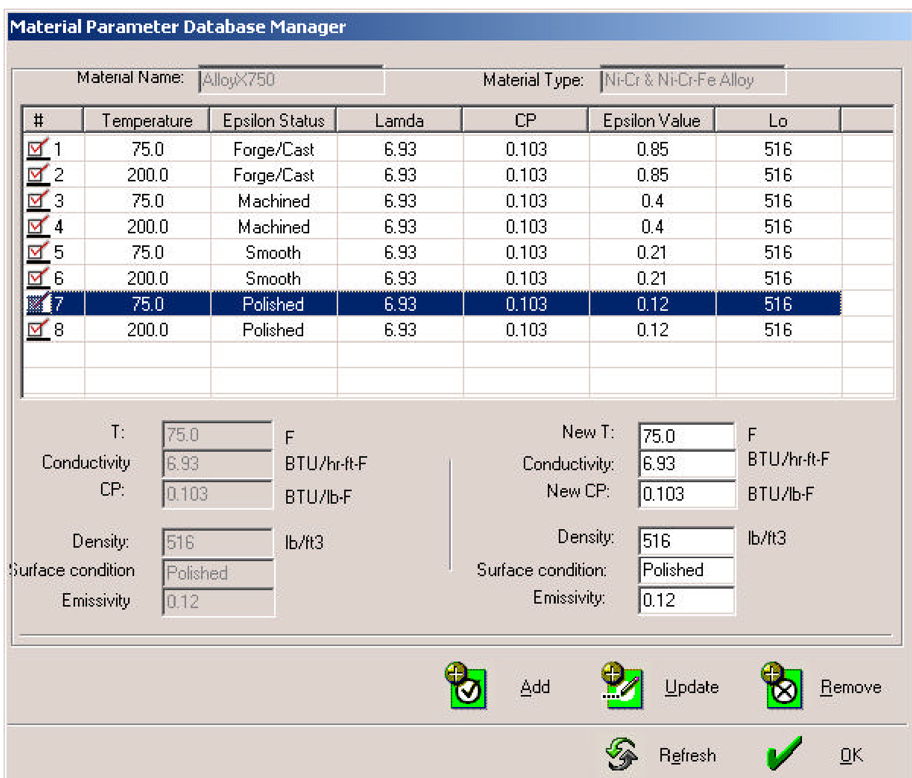


Fig.3.37 Material thermal properties management

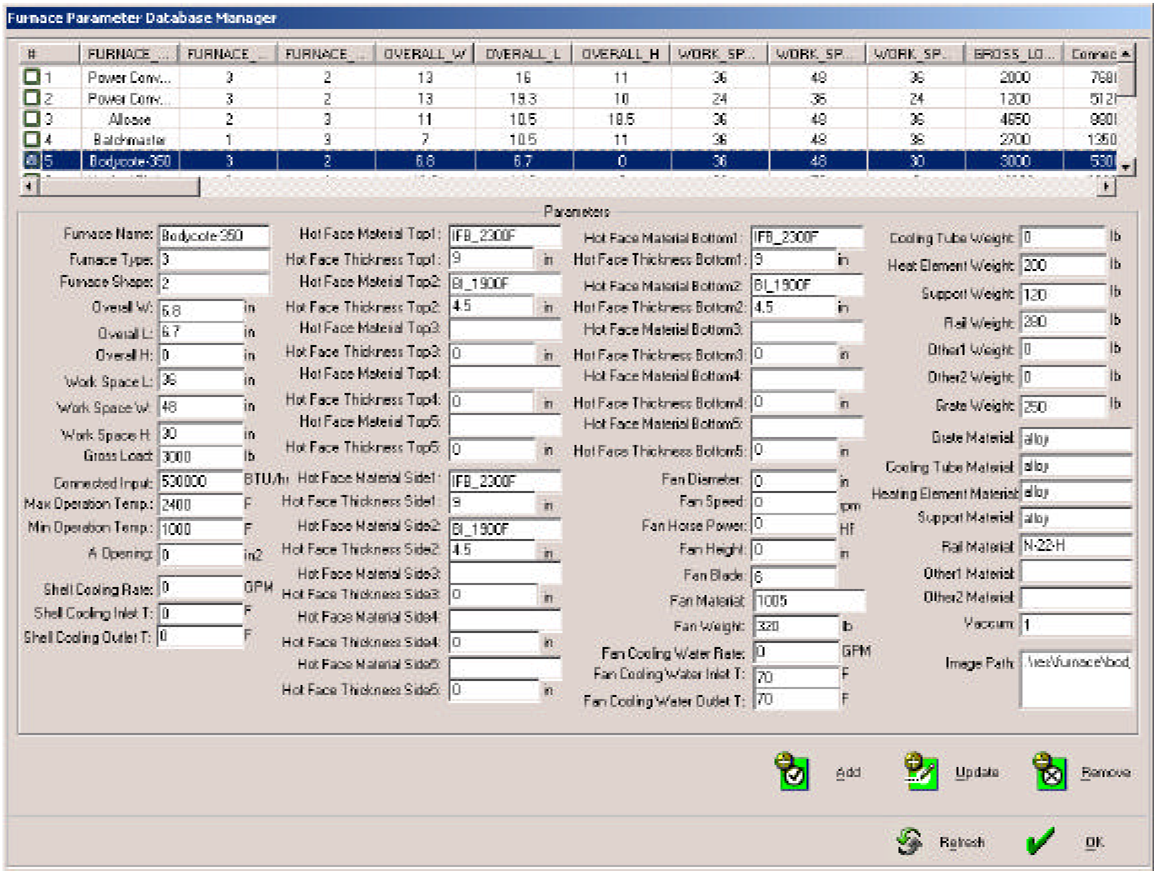


Fig. 3.38 Furnace database management

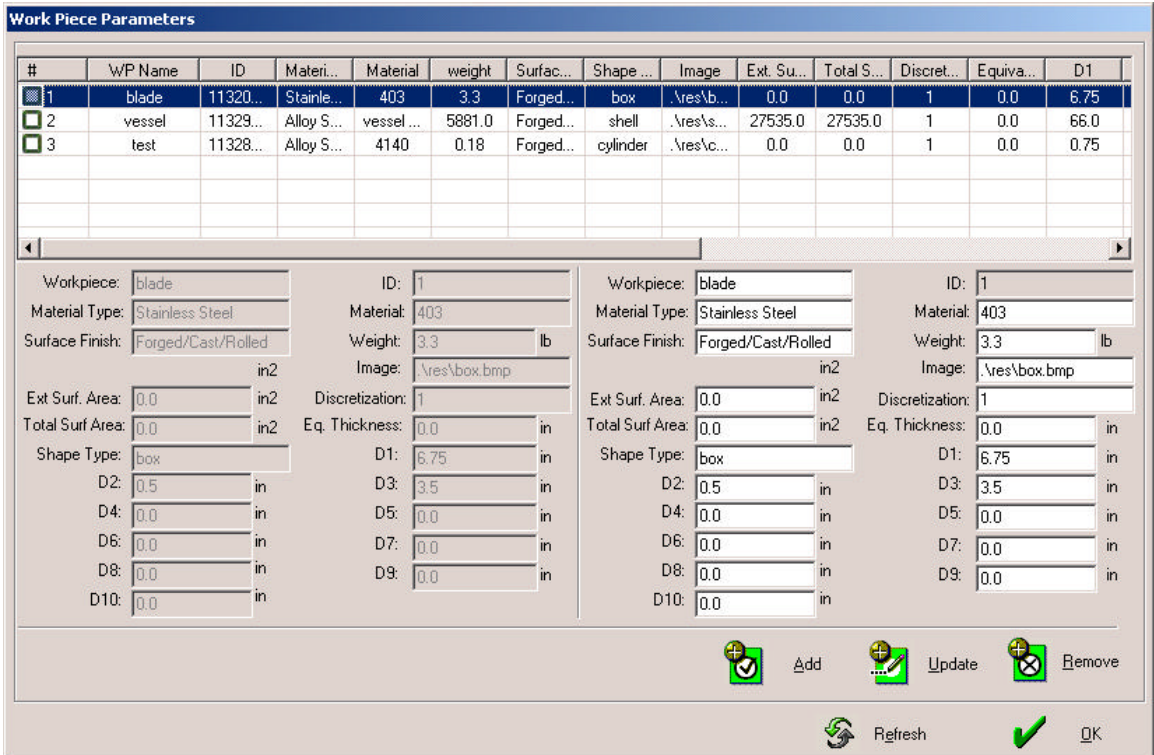


Fig. 3.39 Workpiece database management

Chapter 4 System Validation and Testing (Case Studies)

4.1. Purpose:

The models developed based on various heat transfer principles are integrated to form CAHTPS. The validation of the system is carried out by case studies so as to:

- Test the system capability and accuracy.
- Identify the scope of application of the system.
- Effects of change in the load quantity are studied and recommendations given for the thermal schedule redesign.
- Effects of change in arrangement are studied and the optimal load pattern is determined from the calculated temperature values.

4.2. General Information

The following cases studies are carried out to validate the temperature calculation model for CAHTPS, also the effect of different loads and the loading pattern was to be studied.

The furnace for the case studies 1 &2 is shown below:

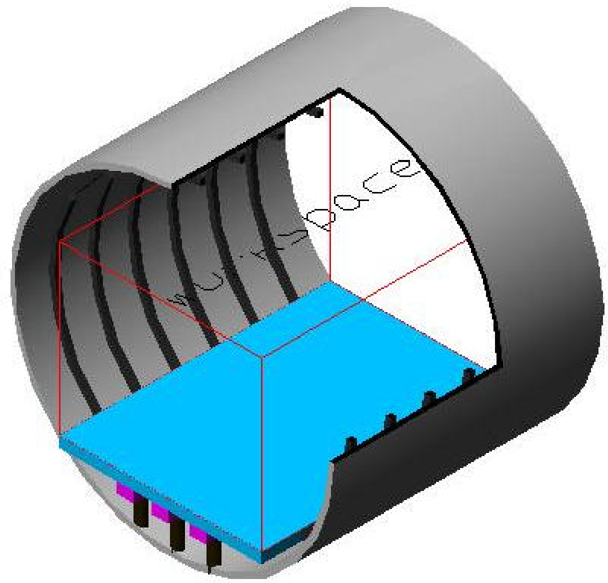


Fig 4.1 Furnace geometry and workspace

Manufacturer: ABAR BM889

Model: HR50 (Horizontal, Refer to Appendix A)

Total Size: 50 Diameter × 48”

Workspace: 36” × 48” × 30” ht

Heat input/Electric KW: 330Amps, 480Volts, 3Ph, and 60Hz

Heaters: Graphite Heating Elements (18 Qty, 54” length, 170lbs)

Insulation: 1” Fiber Form, 1” Kaowool, 9” Firebrick

Maximum operating temperature: 2400°F

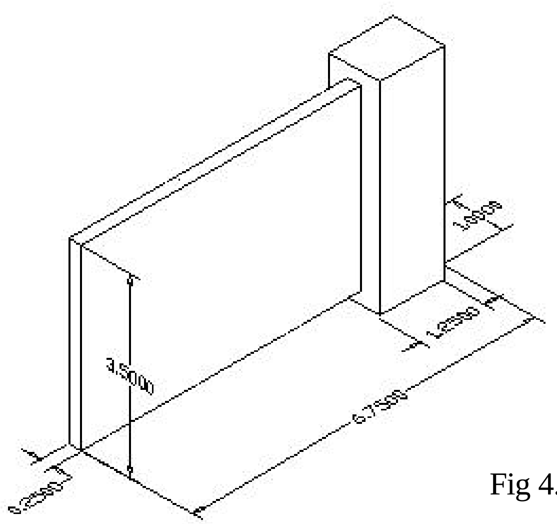
Minimum operating temperature: 1000°F

Gross Load: 3000 lbs

Fixture/Supports: 3 Molly Rails (42’X3” × 2”, 100Lbs, Cp = 0.16BTU/lb.F),

12 support bars (2”Dia × 8”Ht, 100 lbs)

The workpieces used for the case studies are:



Weight: 3.3 lbs
Material: Steel 403 CB

Density = 490 lbs/Ft^3

Surface Area: 57.125 in^2

Volume: 9.8125 in^3

Fig 4.2: Workpiece 1, used for case study 1
(Simplified and loading orientation)

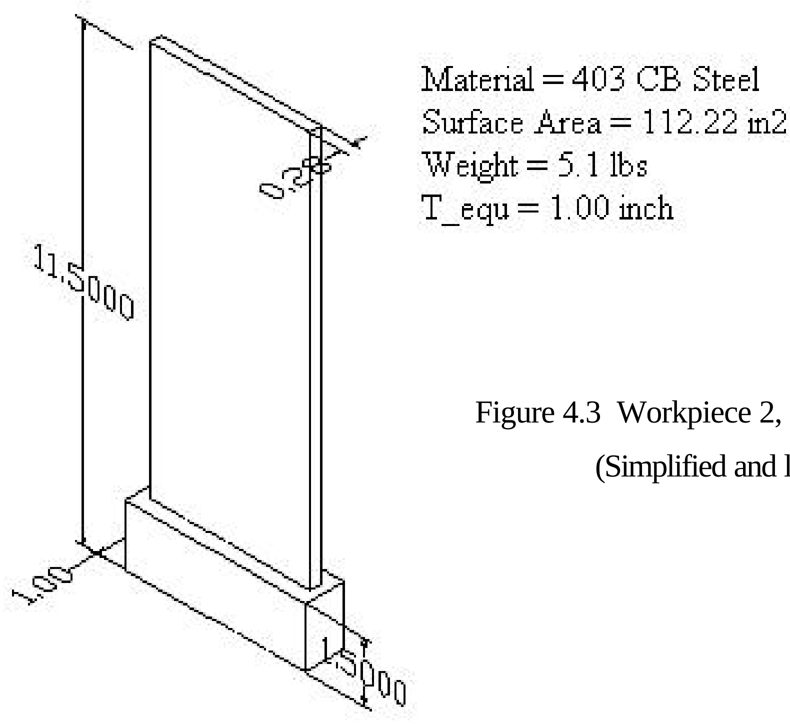


Figure 4.3 Workpiece 2, used for case study 2
(Simplified and loading orientation)

A different type and quantity of the above workpieces are used in the 2 case studies. A brief description of the case studies is given below in table 4.1.

Table 4.1 Case studies

	Case1	**Case2**
Workpiece Quantity	492	523
Type	1	2
Basket size	34"X22"X4.5"	17"X22"12"
Basket Quantity (Each Basket wt)	8 (55)	8 (50)
Total weight	2200 lbs	3100 lbs

Load terminology

The temperatures calculated by the system are at the six centers the 3 edges and 3 faces. The various locations are shown below in the Fig 4.4.

1. Edge1 center
2. Edge2 center
3. Edge3 center
4. Face1 center
5. Face2 center
6. Face3 center

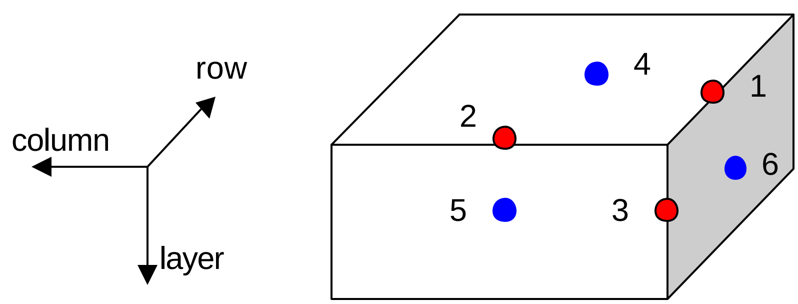


Figure 4.4 Load points

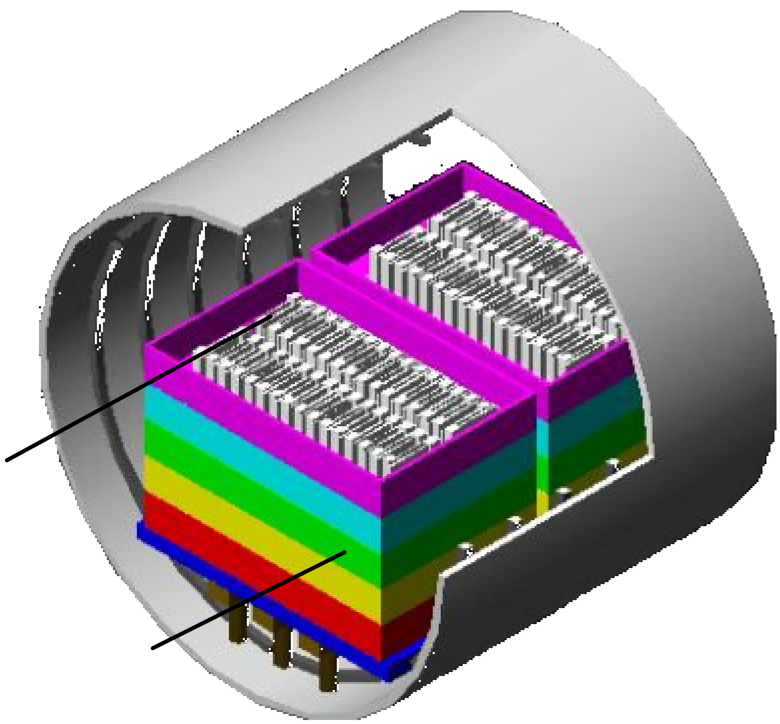
4.3. Case Study 1

General Case

The objective of this case study is to compare the measured and the calculated temperature values and determine the accuracy

In this case, the workpiece I is used as the load. The quantity being 492. The loading pattern of the workpieces in the basket is shown below in figure 4.5:

The thermocouples are located in the center in three baskets in a column. The first TC is located in the center of the top basket, the second at the center of the center basket and the third at the center of the bottom basket shown in Fig 4.5.



Basket size: 34”X22”X4.5”

Quantity of basket: 8

Loading: 2 row, 1 column & 4 layers

Figure 4.5 Workpiece arrangement, thermocouple positions & Furnace Loading

Observations and calculations

Using the above furnace data and the workpiece data as input to the system, the temperature values for the load were calculated.

The measured temperature values at the top layer of the load (edge2) and the center of the load (face2) are given below in table 4.2. Also the calculated temperature values by the system are given in the table. The difference between these two and the RMS values are given in the table 1 below. The % variation of the calculated temperature values from the measured temperature values at each time step is also shown in table 4.2.

Table 4.2 Measured and calculated values, RMS values and % variation (Units: Time (mins), Temperature (°F))

Time	SetPoint	Furnace	Fast	Slow	Meas1	CalEdge2	Meas2	CalFace2	DiffEdge	DiffFace	SqrEdge	SqrFace	%Var	%Var
0	70	70	70	70	70	70	70	70	0	0	0	0	0.0	0.0
15	320.5	212.9	76.9	70	80	71.9	72	70.9	8.1	1.1	65.61	1.21	10.1	1.5
30	571.7	480.9	138.8	70.1	95	90	80	79.3	5	0.7	25	0.49	5.3	0.9
45	823	743.8	338.4	70.9	150	153.6	120	109.1	-3.6	10.9	12.96	118.81	-2.4	9.1
60	1074.3	970.3	667.6	73.8	290	298.1	150	179.1	-8.1	-29.1	65.61	846.81	-2.8	-19.4
75	1325.5	1168.5	965.5	83.1	500	541.5	260	310.8	-41.5	-50.8	1722.25	2580.64	-8.3	-19.5
90	1409.9	1342.3	1206.9	112.8	800	851.7	420	530.3	-51.7	-110.3	2672.89	12166.1	-6.5	-26.3
105	1409.9	1394.8	1334.7	204	960	1099.1	665	815.4	-139.1	-150.4	19348.8	22620.2	-14.5	-22.6
120	1409.9	1399.9	1366.8	397.5	1050	1212.3	810	1028	-162.3	-218	26341.3	47524	-15.5	-26.9
135	1409.9	1402.7	1381.9	660.8	1130	1270.3	940	1143.1	-140.3	-203.1	19684.1	41249.6	-12.4	-21.6
150	1409.9	1404.4	1390.7	917.4	1190	1303.9	1050	1211.6	-113.9	-161.6	12973.2	26114.6	-9.6	-15.4
165	1409.9	1405.7	1396.7	1111	1250	1330.4	1145	1267.8	-80.4	-122.8	6464.16	15079.8	-6.4	-10.7
180	1409.9	1406.7	1401	1235.6	1300	1354.7	1215	1315.9	-54.7	-100.9	2992.09	10180.8	-4.2	-8.3
195	1409.9	1407.4	1404	1310.3	1330	1374.5	1275	1351.9	-44.5	-76.9	1980.25	5913.61	-3.3	-6.0
210	1509	1479.9	1438.1	1354.6	1380	1401.7	1320	1382.7	-21.7	-62.7	470.89	3931.29	-1.6	-4.8
225	1809.1	1691.8	1641.4	1434.7	1560	1559.5	1425	1507.5	0.5	-82.5	0.25	6806.25	0.0	-5.8
240	1809.9	1804.6	1788.1	1600.7	1655	1727.5	1540	1679.8	-72.5	-139.8	5256.25	19544	-4.4	-9.1
255	1809.9	1807	1802.8	1728.5	1720	1778.6	1650	1760.1	-58.6	-110.1	3433.96	12122	-3.4	-6.7
270	1809.9	1807.9	1806.5	1780.3	1745	1797.5	1705	1791	-52.5	-86	2756.25	7396	-3.0	-5.0
285	1809.9	1808.2	1807.8	1798.8	1775	1804.6	1750	1802.4	-29.6	-52.4	876.16	2745.76	-1.7	-3.0
300	1809.9	1808.4	1808.2	1805.1	1786	1807.1	1763	1806.4	-21.1	-43.4	445.21	1883.56	-1.2	-2.5
315	2034.4	2006.5	1975.8	1860.2	1935	1928.8	1870	1899.7	6.2	-29.7	38.44	882.09	0.3	-1.6
330	2110	2106.6	2100.2	2017.5	2045	2072.7	2000	2051.7	-27.7	-51.7	767.29	2672.89	-1.4	-2.6
345	2110	2108.1	2107.1	2088.7	2080	2100.7	2050	2096.1	-20.7	-46.1	428.49	2125.21	-1.0	-2.2
360	2110	2108.4	2108.2	2104.4	2090	2106.9	2075	2105.9	-16.9	-30.9	285.61	954.81	-0.8	-1.5
375	2110	2108.5	2108.5	2107.7	2105	2108.2	2102	2108	-3.2	-6	10.24	36	-0.2	-0.3
											109117	245497		
									RMS Values		***64.783***	***97.171***		

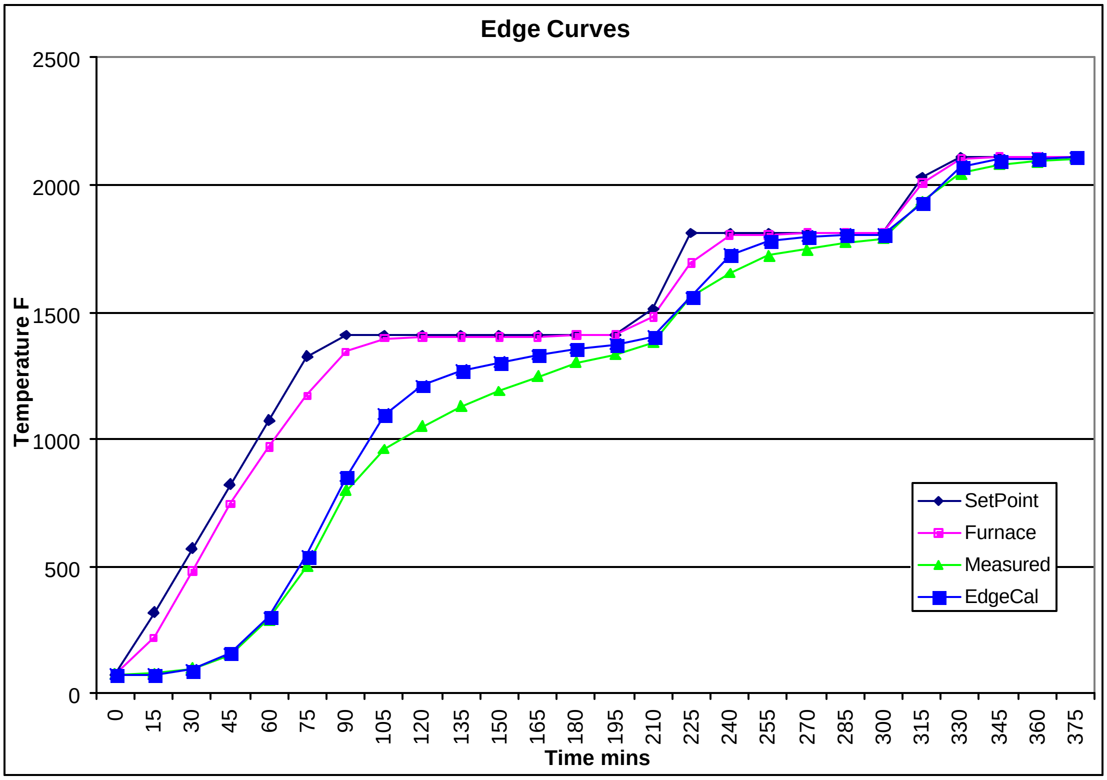


Figure 4.6 Comparing measured and calculated edge value curves

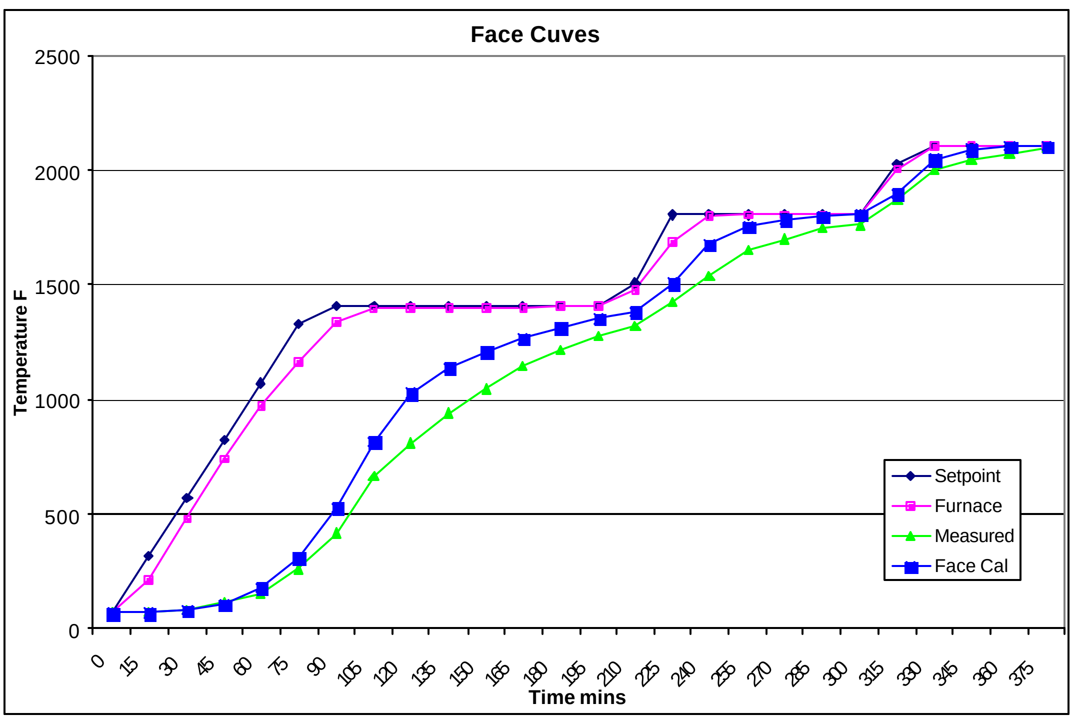


Figure 4.7 Comparing measured and calculated face value curves

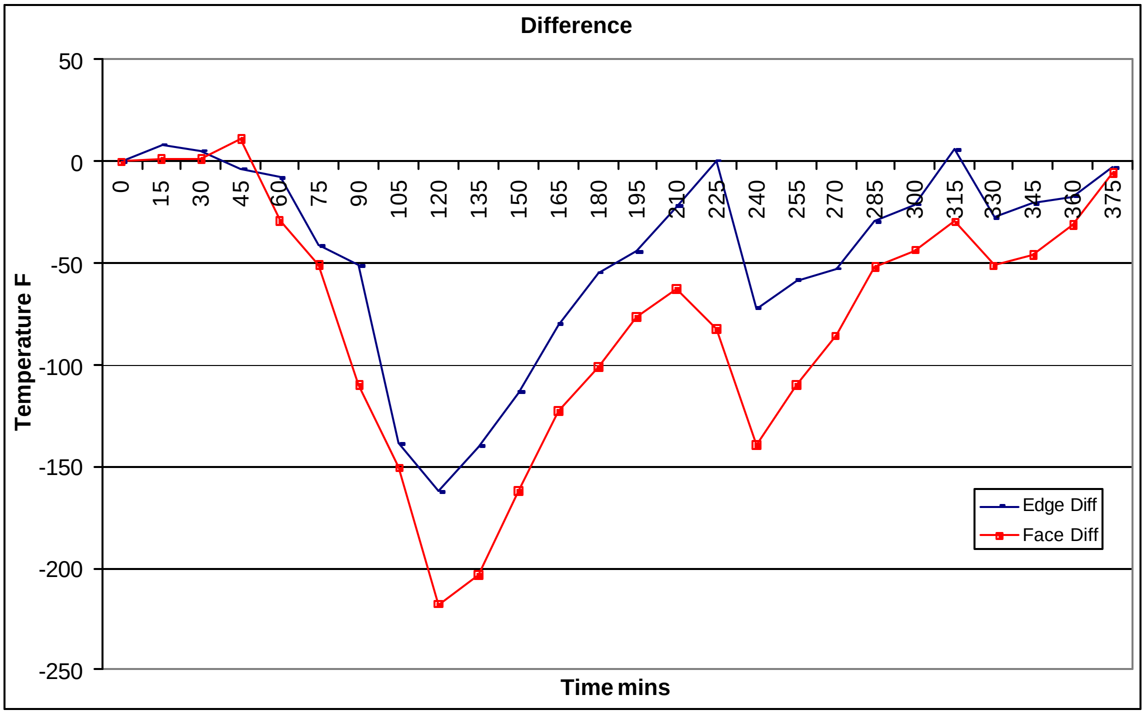


Figure 4.8 The Difference

Results and conclusions:

An observation of the measured edge and face curve values (Fig 4.6 &4.7)obtained by system calculations, show that the differences between the two values are higher below the first holding period (1410°F), a variation of about 15% in the edge curves and 25% in the face curves is observed.

After the initial holding period, the variation decreases below 10% for both the edge and face curves. A variation of less than 5% is observed in the final 100 mins of the thermal schedule.

4.4 Change in loading arrangement

The CAHTPS has the capability to analyze the effects by change in the loading pattern of the load. This change in the load patterns effects are shown and discussed below.

With the given basket size (34”X22”X4.5”), workpiece size, & the workpieces can be arranged inside he basket in 2 ways as shown below in Fig 4.9. The loading arrangement in all the baskets is changed from:

2 rows, 31 columns, 1 layer → 15 rows, 4 columns, 1 layer

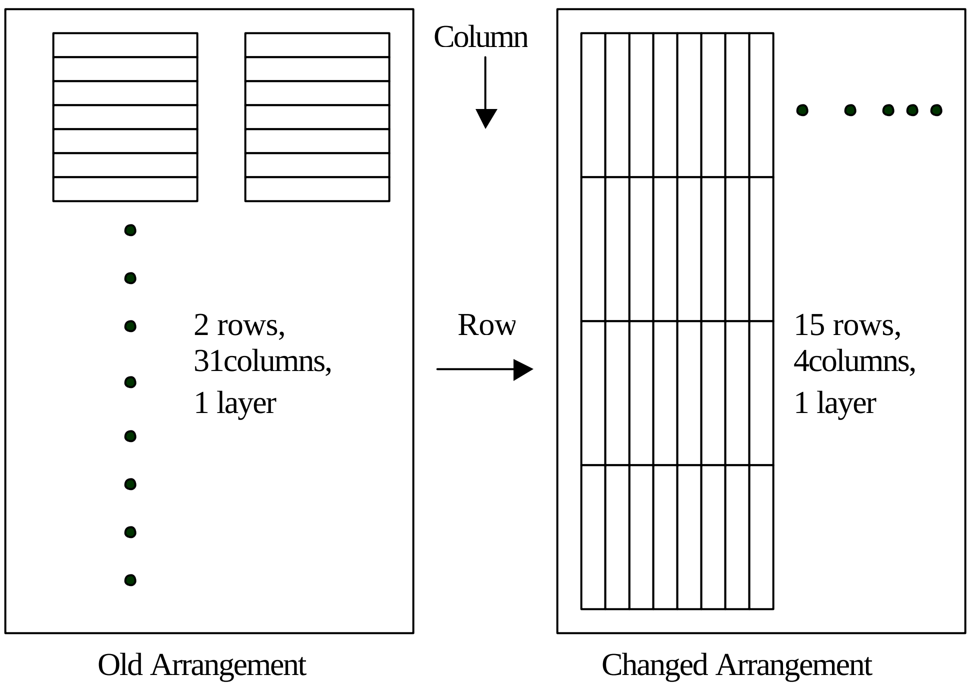


Figure 4.9 Old and New arrangements

Calculations and Observations

Using the same furnace and workpiece and thermal schedule input to the CAHTPS, the change in the loading pattern temperature values were calculated.

The values of temperature obtained earlier with the old pattern and by change in the loading pattern are shown below, in table4.2 & Figs 4.10, 4.11 & 4.12.

A plot of the two same points in the loads (the face 2 & edge 2) is used to compare the results for both the loading pattern Fig 4.10 & 4.11. Also the plot of the fastest workpiece and the slowest workpiece in both the cases are calculated and plotted below Fig 4.12.

As observed from the temperature curves of the edge and face (Figs 4.10 &4.11), it can be concluded that the new arrangement is better then the old/normal arrangement since the parts heat up faster comparatively.

But an observation of the fast and slow curves plotted in Fig 4.12 we can see that although there is very less difference in the fast temperature curves, a large difference in slow part temperature curves is observed. The new arrangement's slow part is lagging behind the normal arrangement curve.

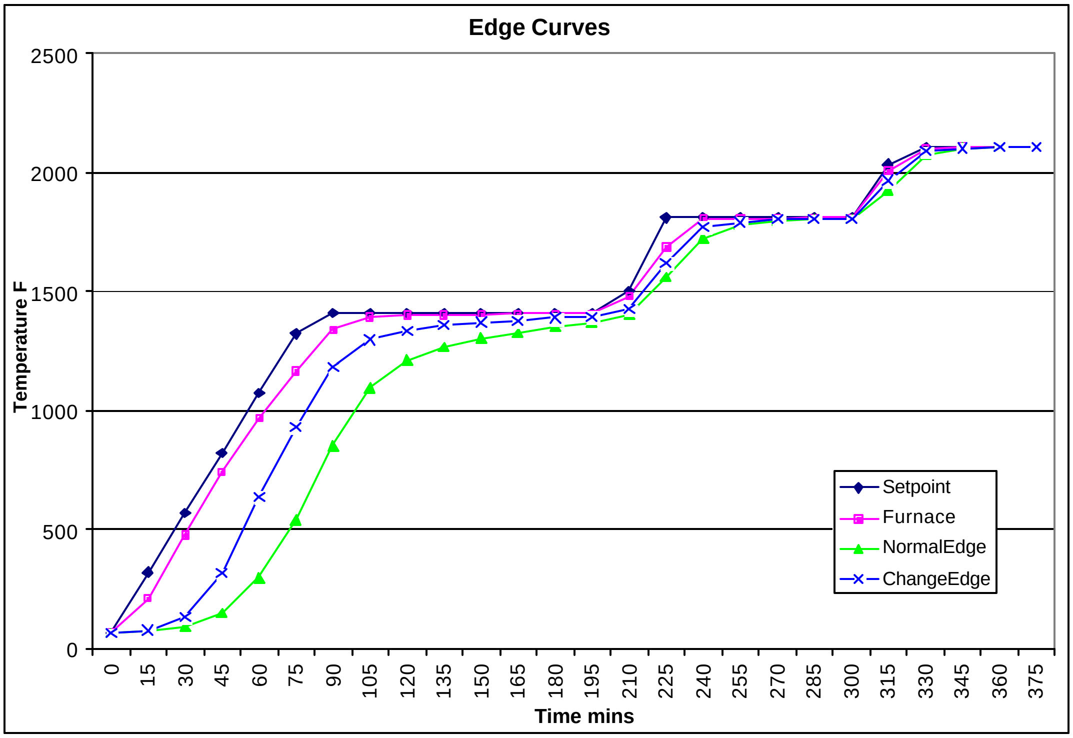


Figure 4.10 Edge curves

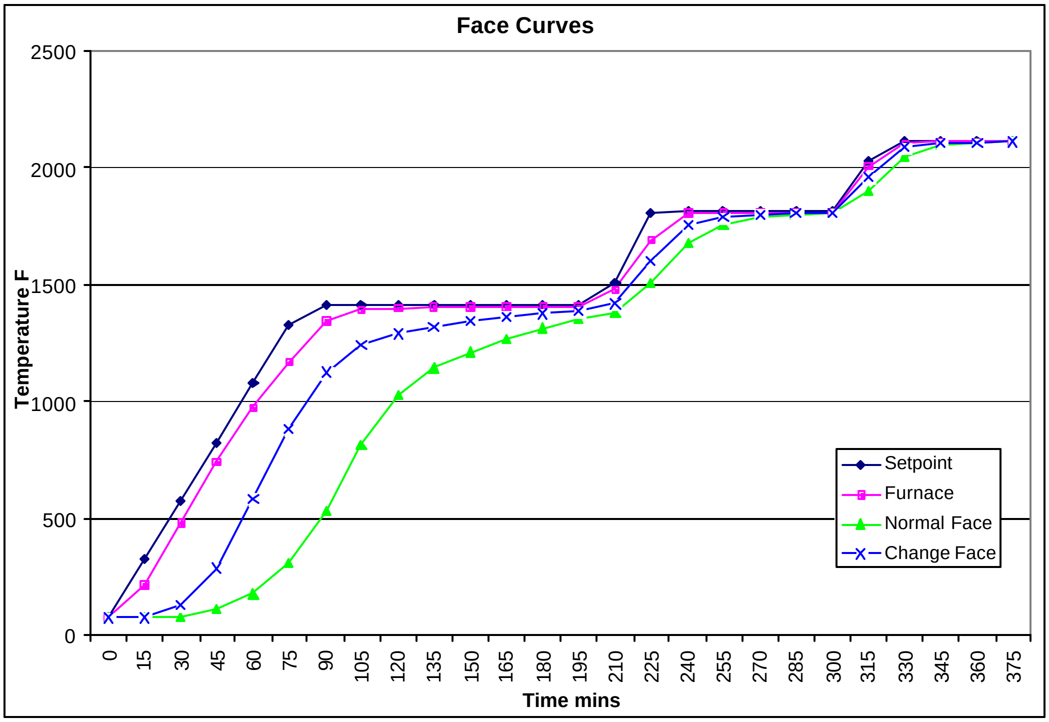


Figure 4.11 Face curves

Table 4.3 Calculated values for change in arrangement (Units: Time (mins), Temperature (°F))

Time	SetPoint	Furnace	Fast	FastRCL	Slow	SlowRCL	CalEdge2	ChangeRCL	CalFace2	changeRCL
0	70	70	70	70	70	70	70	70	70	70
15	320.5	212.9	76.9	76.8	70	70	71.9	76.3	70.9	75.4
30	571.7	480.9	138.8	138.6	70.1	70.1	90	133.2	79.3	124.7
45	823	743.8	338.4	337.3	70.9	70.5	153.6	318.4	109.1	287.6
60	1074.3	970.3	667.6	667	73.8	72.2	298.1	637.3	179.1	586.4
75	1325.5	1168.5	965.5	968.2	83.1	77.3	541.5	935.5	310.8	882.2
90	1409.9	1342.3	1206.9	1219.9	112.8	92.8	851.7	1184.5	530.3	1123.6
105	1409.9	1394.8	1334.7	1326.3	204	137.3	1099.1	1296.3	815.4	1239.4
120	1409.9	1399.9	1366.8	1358.4	397.5	234.2	1212.3	1335.3	1028	1287.7
135	1409.9	1402.7	1381.9	1374.9	660.8	389.5	1270.3	1356.9	1143.1	1320.1
150	1409.9	1404.4	1390.7	1384.8	917.4	584.4	1303.9	1370.8	1211.6	1344
165	1409.9	1405.7	1396.7	1391.3	1111	787.1	1330.4	1380.7	1267.8	1362
180	1409.9	1406.7	1401	1396	1235.6	967.9	1354.7	1388.3	1315.9	1375.5
195	1409.9	1407.4	1404	1399.5	1310.3	1111.3	1374.5	1394.2	1351.9	1385.5
210	1509	1479.9	1438.1	1433.6	1354.6	1216.3	1401.7	1427.9	1382.7	1418.7
225	1809.1	1691.8	1641.4	1635.6	1434.7	1323.4	1559.5	1623.5	1507.5	1602.5
240	1809.9	1804.6	1788.1	1782.8	1600.7	1490.7	1727.5	1772.9	1679.8	1755.2
255	1809.9	1807	1802.8	1799.5	1728.5	1648.3	1778.6	1795.1	1760.1	1787.8
270	1809.9	1807.9	1806.5	1804.6	1780.3	1736.1	1797.5	1802.8	1791	1799.8
285	1809.9	1808.2	1807.8	1806.8	1798.8	1777.2	1804.6	1806	1802.4	1804.8
300	1809.9	1808.4	1808.2	1807.7	1805.1	1795.1	1807.1	1807.4	1806.4	1806.9
315	2034.4	2006.5	1975.8	1975.6	1860.2	1840.4	1928.8	1968.7	1899.7	1956.5
330	2110	2106.6	2100.2	2098.1	2017.5	1979.7	2072.7	2093.7	2051.7	2086.1
345	2110	2108.1	2107.1	2106	2088.7	2067.8	2100.7	2104.9	2096.1	2103.1
360	2110	2108.4	2108.2	2107.8	2104.4	2096.8	2106.9	2107.5	2105.9	2107
375	2110	2108.5	2108.5	2108.3	2107.7	2105.2	2108.2	2108.2	2108	2108.1

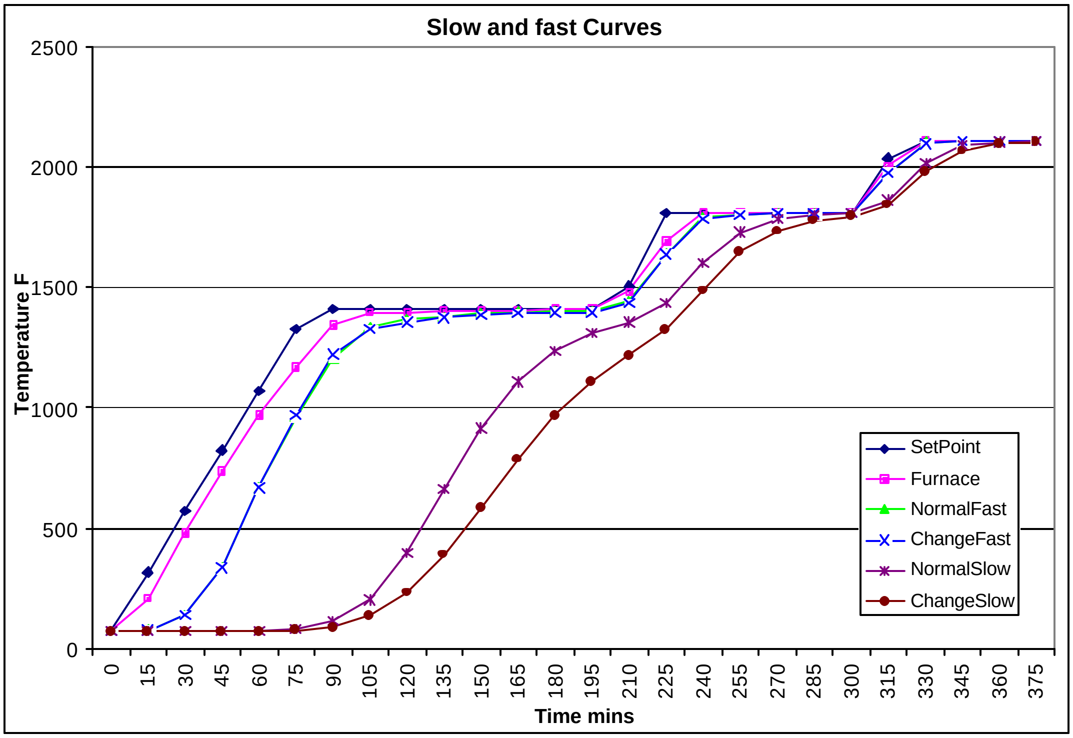


Figure 4.12 Fast and Slow curves for arrangement change

Results and Conclusions

Although it is observed from the edge and the face curves (Figs 4.10 & 4.11) that the new loading arrangement is better, since it heats up the parts faster. No significant change is observed in the fast part curves. But from the slow part temperature curves it can concluded, that although the edge and face temperatures reach the faster then the normal/old ones, the slowest part temperature lags behind by a very high range as compared to the normal loading. In fact the slow part in the new arrangement doesn't even come within the temperature tolerance range at the end of the initial soaking period (the lower limit value being 1350), the slow part (new arrangement) temperature is 1210°F, well below the range limit. There is a large variation in the fastest and slowest part showing no uniformity of temperature.

Hence even if the edge and face part reaches the temperature limit faster, the slow part curve lagging values recommend that this loading pattern is not better then the earlier pattern used.

4.5 Change in load quantity

The CAHTPS has the capability to analyze the effects by change in the load quantity (492 to 620 parts). This change in the load quantity effects are shown and discussed below. The same thermal schedule used earlier for 492 parts is used so as to find the new thermal schedule required for the increased load.

Calculations and observations

Using the same furnace, workpiece data and thermal schedule input to the CAHTPS, the change in the load quantity temperature values were calculated. Earlier the loading arrangement had only 4 layers of baskets, it has being increased to 5 layers.

The values of temperature obtained using the 492 load and thermal schedule for the 620 load are shown below, in table4.4.

As observed there is no significant change in furnace, edge and the fast curves (Fig 4.13). But some variation in the edge curves and large variations in the face curves are observed as shown in Fig 4.14. The temperature values for the face and the slow curves during the end of the initial soaking period are given below table 4.4.

Table 4.4 Temperature values at end of holding period

Time(mins)	Set Point (°F)	Face Normal (°F)	Face 620 (°F)	Slow Normal (°F)	Slow 620 (°F)
80	1410	385	333	93	78
205	1410	1375	1330	1345	1245

Redesign the thermal schedule

As observed from the table 4.4 and the plots of the face and edge (Fig 4.13 &4.14) curves, the temperature values at these points at the end of the first soaking period are observed to be below the lower limits, hence a incremental of 15 mins to the initial soaking period in the thermal schedule (Fig 4.15) is given and the effects are shown below.

Table 4.5 Redesigned thermal schedule

Old TS Time mins	Old TS Temperature (°F)	New TS Time (mins)	New TS Tempearture (°F)
0	70	0	70
80	1410	80	1410
205	1410	220	1410
225	1810	240	1810
300	1810	315	1810
320	2110	335	2110
375	2110	375	2110

Table 4.6 Change in load temperature values (Units: Time (mins), Temperature (°F))

Time	SetPoint	FurnaceN	Furnace620	FastN	Fast620	Slow	Slow620	Edge2N	edge2620	FaceN	face2620
0	70	70	70	70	70	70	70	70	70	70	70
15	320.5	212.9	212.7	76.9	76.9	70	70	71.9	72.1	70.9	70.9
30	571.7	480.9	479.7	138.8	138.6	70.1	70.1	90	91.8	79.3	78.8
45	823	743.8	736.7	338.4	336.1	70.9	70.4	153.6	160.3	109.1	106.7
60	1074.3	970.3	949.2	667.6	652.7	73.8	71.5	298.1	309.9	179.1	169.2
75	1325.5	1168.5	1133.2	965.5	935.5	83.1	74.7	541.5	550.3	310.8	278.9
90	1409.9	1342.3	1293.9	1206.9	1161.5	112.8	84	851.7	841.5	530.3	447.5
105	1409.9	1394.8	1390.7	1334.7	1321.7	204	110.5	1099.1	1091.9	815.4	680.2
120	1409.9	1399.9	1397.8	1366.8	1362.2	397.5	181.7	1212.3	1210.9	1028	908.5
135	1409.9	1402.7	1401.2	1381.9	1378.7	660.8	334.6	1270.3	1267.6	1143.1	1060.8
150	1409.9	1404.4	1403.3	1390.7	1387.9	917.4	582	1303.9	1300.2	1211.6	1144
165	1409.9	1405.7	1404.7	1396.7	1394.1	1111	862	1330.4	1323.5	1267.8	1202.3
180	1409.9	1406.7	1405.9	1401	1398.6	1235.6	1079.4	1354.7	1343.3	1315.9	1257
195	1409.9	1407.4	1406.8	1404	1401.9	1310.3	1213.8	1374.5	1361.5	1351.9	1305.7
210	1509	1479.9	1476.9	1438.1	1435.8	1354.6	1293.9	1401.7	1391.1	1382.7	1349.2
225	1809.1	1691.8	1673.2	1641.4	1626	1434.7	1377.9	1559.5	1546.2	1507.5	1467.6
240	1809.9	1804.6	1802.9	1788.1	1782.3	1600.7	1531.2	1727.5	1715.7	1679.8	1635.2
255	1809.9	1807	1806.4	1802.8	1801.1	1728.5	1685	1778.6	1771.9	1760.1	1735
270	1809.9	1807.9	1807.6	1806.5	1805.7	1780.3	1759.8	1797.5	1793.3	1791	1778.6
285	1809.9	1808.2	1808.1	1807.8	1807.4	1798.8	1789.9	1804.6	1802.5	1802.4	1796.9
300	1809.9	1808.4	1808.3	1808.2	1808.1	1805.1	1801.4	1807.1	1806.2	1806.4	1804.1
315	2034.4	2006.5	1997.4	1975.8	1968.9	1860.2	1845.1	1928.8	1926.4	1899.7	1886.8
330	2110	2106.6	2105.9	2100.2	2098.4	2017.5	1988.6	2072.7	2068.9	2051.7	2033.2
345	2110	2108.1	2107.9	2107.1	2106.6	2088.7	2077.3	2100.7	2098.5	2096.1	2089.1
360	2110	2108.4	2108.3	2108.2	2108.1	2104.4	2101	2106.9	2106.1	2105.9	2103.8
375	2110	2108.5	2108.5	2108.5	2108.4	2107.7	2106.7	2108.2	2107.9	2108	2107.4

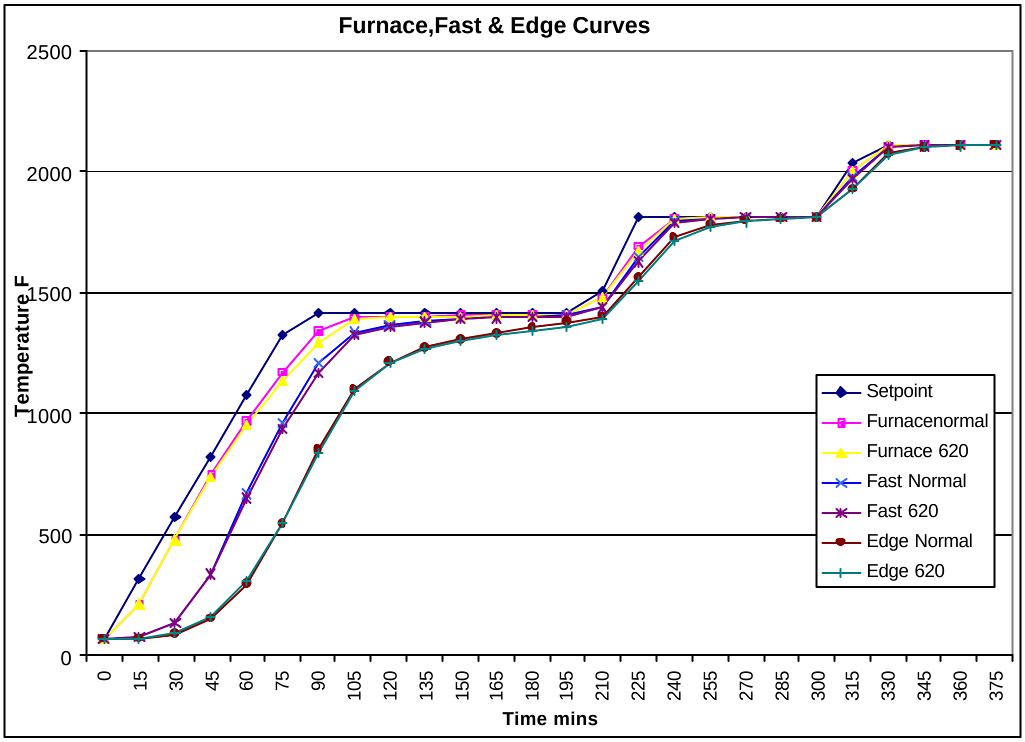


Figure 4.13 Furnace, Fast & Edge curves

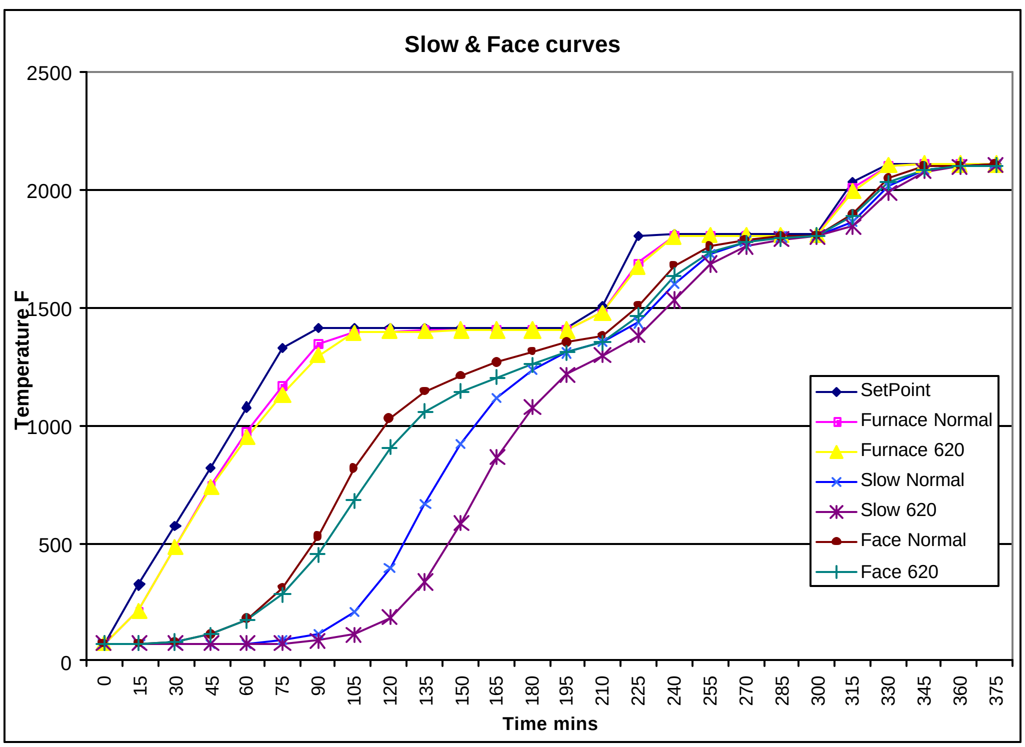


Figure 4.14 Slow & Face curves

Table 4.7 Change Thermal Schedule temperature values (Units: Time (mins), Temperature (°F))

Time	SetPointN	Setpt(TSch)	Furn620N	FurnaceTSCh	Slow620N	SlowTSCH	face620 N	faceTS ch
0	70	70	70	70	70	70	70	70
15	320.5	320.5	212.7	212.7	70	70	70.9	70.9
30	571.7	571.7	479.7	479.7	70.1	70.1	78.8	78.8
45	823	823	736.7	736.7	70.4	70.4	106.7	106.7
60	1074.3	1074.3	949.2	949.2	71.5	71.5	169.2	169.2
75	1325.5	1325.5	1133.2	1133.2	74.7	74.7	278.9	278.9
90	1409.9	1409.9	1293.9	1293.9	84	84	447.5	447.5
105	1409.9	1409.9	1390.7	1390.7	110.5	110.5	680.2	680.2
120	1409.9	1409.9	1397.8	1397.8	181.7	181.7	908.5	908.5
135	1409.9	1409.9	1401.2	1401.2	334.6	334.6	1060.8	1060.8
150	1409.9	1409.9	1403.3	1403.3	582	582	1144	1144
165	1409.9	1409.9	1404.7	1404.7	862	862	1202.3	1202.3
180	1409.9	1409.9	1405.9	1405.9	1079.4	1079.4	1257	1257
195	1409.9	1409.9	1406.8	1406.8	1213.8	1213.8	1305.7	1305.7
210	1509	1409.9	1476.9	1407.4	1293.9	1293.5	1349.2	1342.9
225	1809.1	1509	1673.2	1478.9	1377.9	1341.4	1467.6	1374.8
240	1809.9	1808.9	1802.9	1677.5	1531.2	1407.3	1635.2	1484.9
255	1809.9	1809.8	1806.4	1803.4	1685	1550	1735	1646.3
270	1809.9	1809.8	1807.6	1806.5	1759.8	1693.9	1778.6	1740
285	1809.9	1809.8	1808.1	1807.6	1789.9	1763.3	1796.9	1780.7
300	1809.9	1809.8	1808.3	1808	1801.4	1791.1	1804.1	1797.6
315	2034.4	1809.8	1997.4	1808.2	1845.1	1801.9	1886.8	1804.3
330	2110	2034.1	2105.9	1997.7	1988.6	1845.3	2033.2	1887.1
345	2110	2109.8	2107.9	2105.9	2077.3	1988.9	2089.1	2033.4
360	2110	2109.8	2108.3	2107.8	2101	2077.3	2103.8	2089.1
375	2110	2109.8	2108.5	2108.2	2106.7	2101	2107.4	2103.7

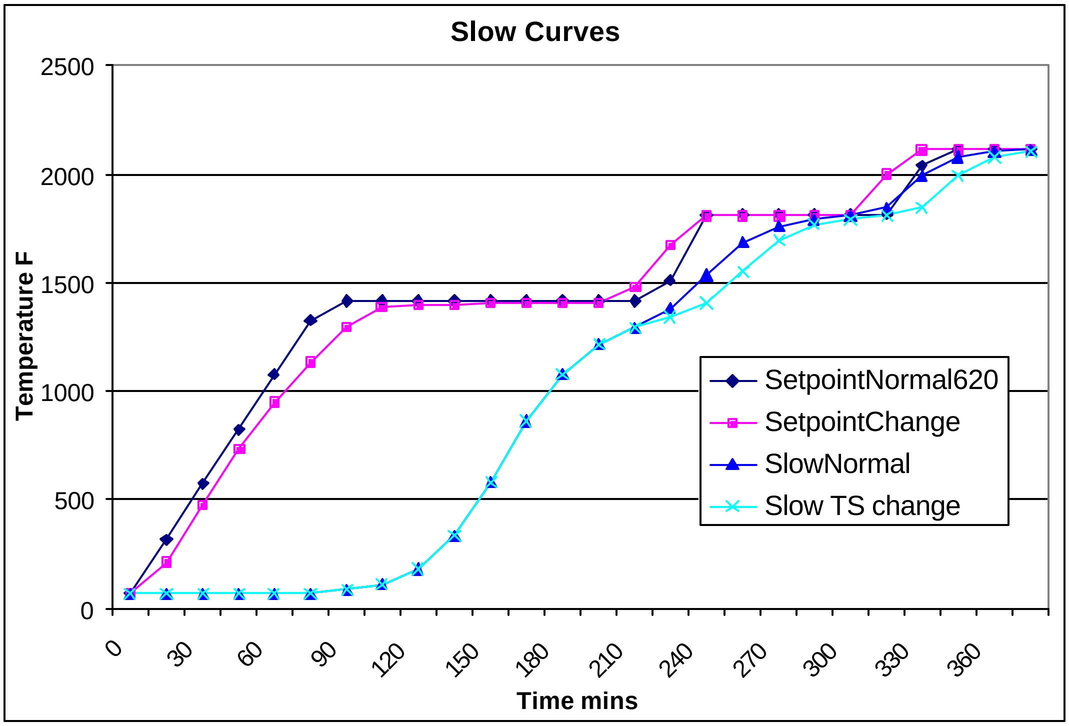


Figure 4.15 Slow curves

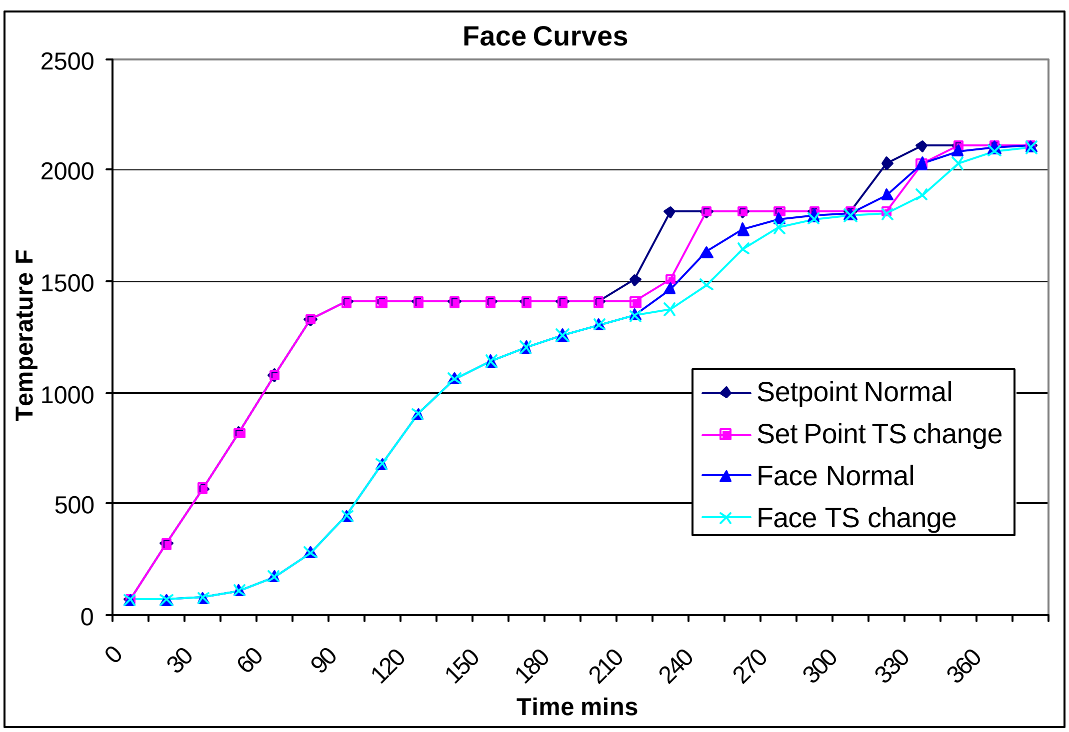


Figure 4.16 Face Curves

Results and conclusions

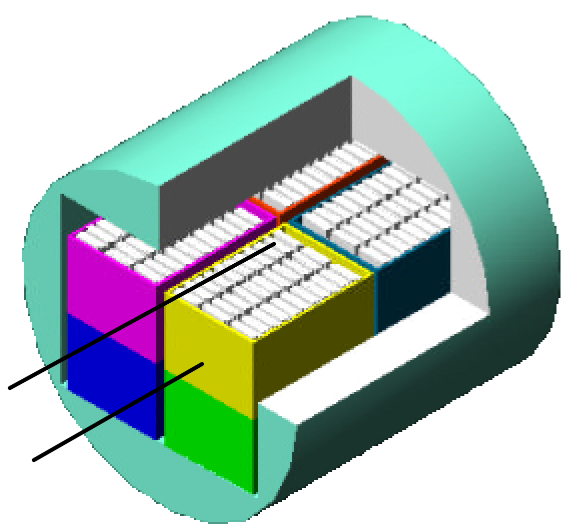
With a prolonged soaking period of 15 mins, the temperature values of the face and the slow part (Fig 4.15 & 4.16) are observed to be above the lower limit. Also since the end soaking time is more then sufficient for 492 loads; the whole load can be heated to the same temperature range within the same time periods. This means the time required for 492 parts and 620 parts is approximately the same, with slight changes in the thermal schedule.

4.6 Case Study 2

The objective of this case study is to compare the measured and the calculated temperature values and determine the accuracy

In this case, the workpiece 2 is used as the load. The quantity being 523. The loading pattern of the workpieces in the basket is shown below Fig 4.17:

The thermocouples are located in the center of two baskets in a column. The first TC is located in the center of the top basket, the second at the center of the bottom basket.



Basket size:
17"X22"X12"
Quantity of basket: 8
Loading: 2 row, 2 column & 2 layers

Figure 4.17 Furnace Loading

Observations and calculations

Using the above furnace data and the workpiece data as input to the system, the temperature values for the load were calculated.

The thermocouple parts location in the load can be identified as row 11, column 2 & layer 1 for the top the second at row 11, column 2 & layer 2. The calculated temperatures at both these points are the same. Hence comparison of both the measured temperature values is done with this single calculated temperature values.

The measured temperature values at the top layer of the load and the bottom of the load are given below in table 4.8. Also the calculated temperature values by the system are given in the table. The difference between these two and the RMS values are given in the table 4.8 below. The % variation of the calculated temperature values from the measured temperature values at each time step is also shown in table 4.8.

Table 4.8 Measured and calculated values, RMS values and % variation (Units: Time (mins), Temperature (°F))

Time	SetPt	Furnace	Fast	Slow	CALC	Meas1	Meas2	Diff1	Diff2	Sqr1	Sqr2	% Var	% Var
0	70	70	70	70	70	70	70	0	0	0	0	0.00	0.00
15	330.2	218.2	78.6	70.4	70.4	75	72	4.6	1.6	21.16	2.56	6.13	2.22
30	591.2	495.9	156.2	74.5	74.6	85	75	10.4	0.4	108.16	0.16	12.24	0.53
45	852.4	757.2	391.3	89	89.3	130	80	40.7	-9.3	1656.49	86.49	31.31	-11.63
60	1113.4	978	709.6	121.7	123	275	125	152	2	23104	4	55.27	1.60
75	1374.4	1167.8	971.5	180.2	185.2	500	285	314.8	99.8	99099	9960.04	62.96	35.02
90	1409.9	1324.7	1184.4	270.7	287.4	815	450	527.6	162.6	278362	26438.8	64.74	36.13
105	1409.9	1389.6	1313.7	390.9	439.5	925	585	485.5	145.5	235710	21170.3	52.49	24.87
120	1409.9	1395	1350.7	518.8	622.3	1010	780	387.7	157.7	150311	24869.3	38.39	20.22
135	1409.9	1398.5	1369.7	653.6	810.9	1075	925	264.1	114.1	69748.8	13018.8	24.57	12.34
150	1409.9	1401.1	1381.3	795.4	979.2	1125	1035	145.8	55.8	21257.6	3113.64	12.96	5.39
165	1409.9	1403.1	1389.2	936.3	1109.4	1175	1115	65.6	5.6	4303.36	31.36	5.58	0.50
180	1409.9	1404.6	1394.8	1063.2	1202.6	1212	1175	9.4	-27.6	88.36	761.76	0.78	-2.35
195	1409.9	1405.8	1399	1166.3	1268.8	1240	1220	-28.8	-48.8	829.44	2381.44	-2.32	-4.00
210	1409.9	1406.7	1402	1243.9	1315.2	1265	1255	-50.2	-60.2	2520.04	3624.04	-3.97	-4.80
225	1409.9	1407.4	1404.1	1299.1	1347.1	1290	1285	-57.1	-62.1	3260.41	3856.41	-4.43	-4.83
240	1409.9	1407.8	1405.6	1337	1368.5	1334	1310	-34.5	-58.5	1190.25	3422.25	-2.59	-4.47
255	1709.1	1618.4	1567.1	1397.3	1423.5	1490	1385	66.5	-38.5	4422.25	1482.25	4.46	-2.78
270	1809.9	1786.7	1744.4	1516.4	1552.4	1600	1500	47.6	-52.4	2265.76	2745.76	2.97	-3.49
285	1809.9	1805.4	1795.6	1647.1	1685.7	1665	1585	-20.7	-100.7	428.49	10140.5	-1.24	-6.35
300	1809.9	1807.1	1803.5	1729.2	1754.2	1705	1655	-49.2	-99.2	2420.64	9840.64	-2.89	-5.99
315	1809.9	1807.9	1806.4	1771.7	1784.8	1740	1710	-44.8	-74.8	2007.04	5595.04	-2.57	-4.37
330	1809.9	1808.3	1807.6	1791.9	1798.2	1755	1745	-43.2	-53.2	1866.24	2830.24	-2.46	-3.05
345	1809.9	1808.5	1808.2	1801.2	1804.1	1790	1760	-14.1	-44.1	198.81	1944.81	-0.79	-2.51
360	1959.5	1948.8	1923.8	1841.8	1849.4	1955	1880	105.6	30.6	11151.4	936.36	5.40	1.63
375	2109.5	2097.8	2073.3	1949.9	1968.8	2040	1980	71.2	11.2	5069.44	125.44	3.49	0.57
390	2110	2107.4	2104.2	2050.6	2066.3	2070	2035	3.7	-31.3	13.69	979.69	0.18	-1.54
405	2110	2108.3	2107.5	2090.1	2096.5	2090	2058	-6.5	-38.5	42.25	1482.25	-0.31	-1.87
420	2110	2108.6	2108.3	2103	2105.2	2100	2074	-5.2	-31.2	27.04	973.44	-0.25	-1.50
435	2110	2108.7	2108.6	2107	2107.7	2101	2085	-6.7	-22.7	44.89	515.29	-0.32	-1.09
										921528	152333		
								RMS Values		**175.26**	**71.258**		

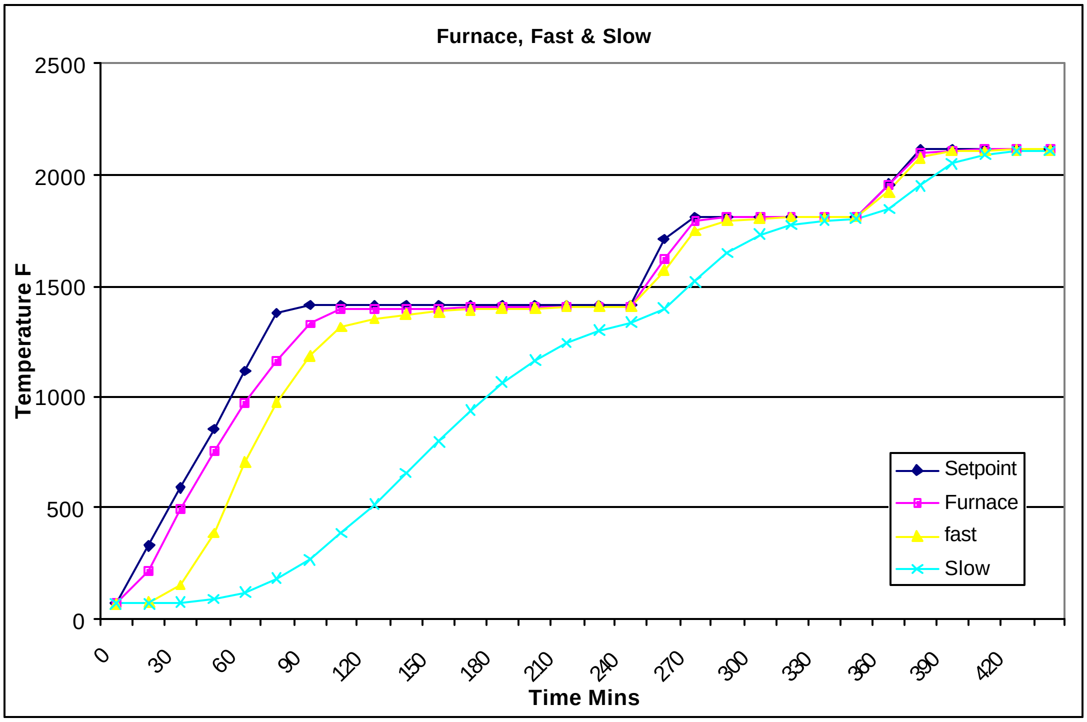


Figure 4.18 Furnace, fast and slow curves

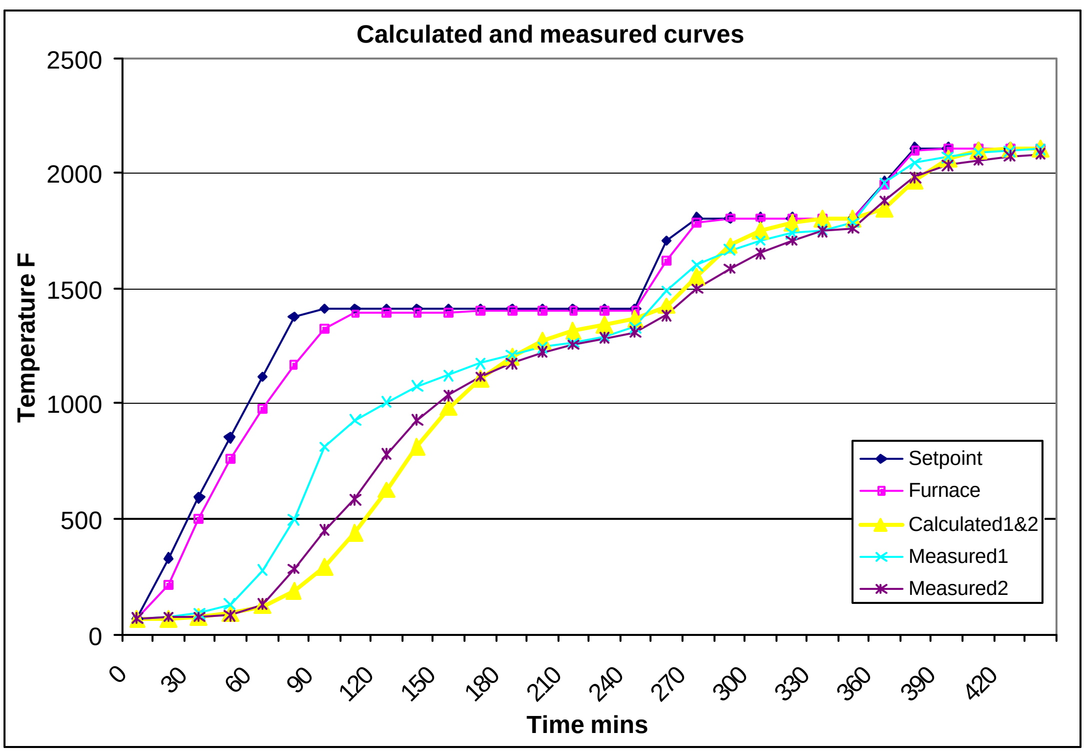


Figure 4.19 Comparing measured and calculated curves

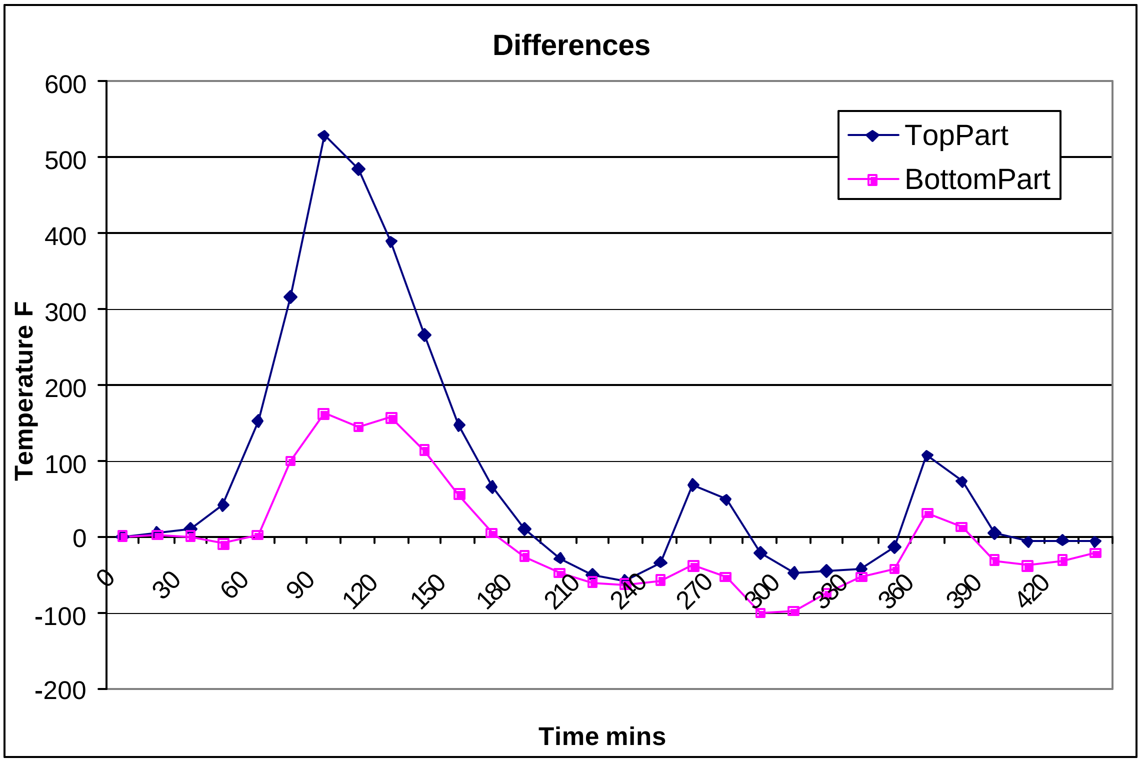


Figure 4.20 The Difference

Results and conclusions:

Observation of the measured values with the calculated ones (Fig 4.19 & 4.20), show that the differences between the two values are higher for the top part temperature before the end of the first soaking period (1410°F). After the initial holding period, the variation decreases below 5% for both measured values.

4.7 Change in loading arrangement

The CAHTPS has the capability to analyze the effects by change in the loading pattern of the load. This change in the load patterns effects are shown and discussed below. With the given basket size (17"X22"X12"), and workpiece size, the workpieces can be arranged inside he basket in 2 ways as shown below in Fig 4.21. The loading arrangement in all the baskets is changed from:

3 rows, 22 columns, 1 layer → 17 rows, 4 columns, 1 layer

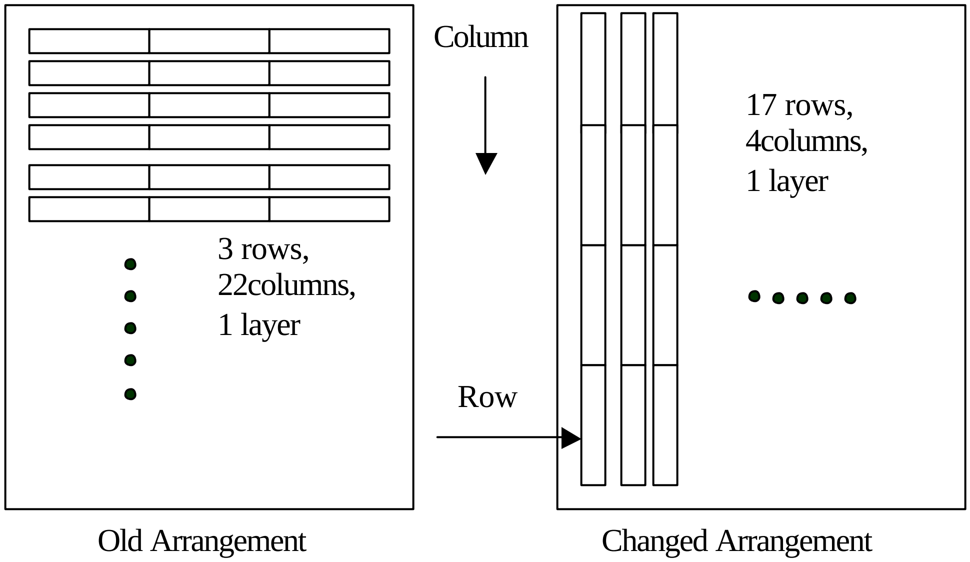


Figure 4.21 Old and New arrangements

Calculations and Observations

Using the same furnace and workpiece and thermal schedule input to the CAHTPS, the change in the loading pattern temperature values were calculated.

The values of temperature obtained earlier with the old pattern and by change in the loading pattern are shown below, in table 4.9.

A plot of the two same points in the loads (center of the front top basket) is used to compare the results for both the loading pattern. Also the plot of the fastest workpiece and the slowest workpiece in both the cases are calculated and plotted below (Fig 4.25& 4.26).

A large difference between the calculated points and the slow workpiece is observed during the initial phase. No significant difference in the fast workpiece temperature values is observed.

Results and Conclusions

As observed from the table 4.9 and the temperature curve(Fig 4.22 & 4.23), the center part in the top layer and the bottom layer of the new arrangement heats up faster as compared to the old arrangement. Also the slowest part in the new arrangement load heats up faster then the slowest part in the old arrangement load.

Hence it can be concluded that a change in the old load pattern will yield better temperature uniformity and reduction in time.

Table 4.9 Calculated values for change in arrangement (Units: Time (mins), Temperature (°F))

Time	Setpt	furnace	fastRCL	slowRCL	CALRCL	Fast	Slow	CALC	DiffFast	Diffslow	DiffCALC
0	70	70	70	70	70	70	70	70	0	0	0
15	330.2	218	78.6	70.6	70.6	78.6	70.4	70.4	0	-0.2	-0.2
30	591.2	494.5	156.9	76.4	76.7	156.2	74.5	74.6	-0.7	-1.9	-2.1
45	852.4	745.5	391.4	96.4	98.4	391.3	89	89.3	-0.1	-7.4	-9.1
60	1113.4	947.2	704.8	139.7	149.6	709.6	121.7	123	4.8	-18	-26.6
75	1374.4	1114.1	955.2	213.4	252.9	971.5	180.2	185.2	16.3	-33.2	-67.7
90	1409.9	1253.4	1148.1	322.7	443.5	1184.4	270.7	287.4	36.3	-52	-156.1
105	1409.9	1374.4	1301.8	472.1	721.9	1313.7	390.9	439.5	11.9	-81.2	-282.4
120	1409.9	1392.8	1361.8	654.4	982.1	1350.7	518.8	622.3	-11.1	-135.6	-359.8
135	1409.9	1398	1380.3	855.9	1141	1369.7	653.6	810.9	-10.6	-202.3	-330.1
150	1409.9	1401.7	1391	1049.5	1240.9	1381.3	795.4	979.2	-9.7	-254.1	-261.7
165	1409.9	1404.3	1397.8	1195.5	1307.7	1389.2	936.3	1109.4	-8.6	-259.2	-198.3
180	1409.9	1406	1402.2	1288.4	1350.7	1394.8	1063.2	1202.6	-7.4	-225.2	-148.1
195	1409.9	1407.1	1404.9	1342.8	1376.5	1399	1166.3	1268.8	-5.9	-176.5	-107.7
210	1409.9	1407.7	1406.5	1373.2	1391.2	1402	1243.9	1315.2	-4.5	-129.3	-76
225	1409.9	1408.1	1407.4	1389.7	1399.2	1404.1	1299.1	1347.1	-3.3	-90.6	-52.1
240	1409.9	1408.3	1407.9	1398.5	1403.6	1405.6	1337	1368.5	-2.3	-61.5	-35.1
255	1709.1	1611	1570.6	1449.7	1471.7	1567.1	1397.3	1423.5	-3.5	-52.4	-48.2
270	1809.9	1771.2	1739.9	1577.9	1624.3	1744.4	1516.4	1552.4	4.5	-61.5	-71.9
285	1809.9	1805.8	1800.4	1714.1	1749.9	1795.6	1647.1	1685.7	-4.8	-67	-64.2
300	1809.9	1807.6	1806.2	1776.4	1790.4	1803.5	1729.2	1754.2	-2.7	-47.2	-36.2
315	1809.9	1808.2	1807.8	1798.2	1802.9	1806.4	1771.7	1784.8	-1.4	-26.5	-18.1
330	1809.9	1808.4	1808.3	1805.3	1806.8	1807.6	1791.9	1798.2	-0.7	-13.4	-8.6
345	1809.9	1808.6	1808.5	1807.5	1808	1808.2	1801.2	1804.1	-0.3	-6.3	-3.9
360	1959.5	1948.2	1927.8	1856.8	1872.6	1923.8	1841.8	1849.4	-4	-15	-23.2
375	2109.5	2097.4	2078.7	1985.6	2013.2	2073.3	1949.9	1968.8	-5.4	-35.7	-44.4
390	2110	2107.8	2106.4	2081.4	2092.6	2104.2	2050.6	2066.3	-2.2	-30.8	-26.3
405	2110	2108.5	2108.3	2103.6	2105.9	2107.5	2090.1	2096.5	-0.8	-13.5	-9.4
420	2110	2108.6	2108.6	2107.7	2108.2	2108.3	2103	2105.2	-0.3	-4.7	-3
435	2110	2108.7	2108.7	2108.5	2108.6	2108.6	2107	2107.7	-0.1	-1.5	-0.9

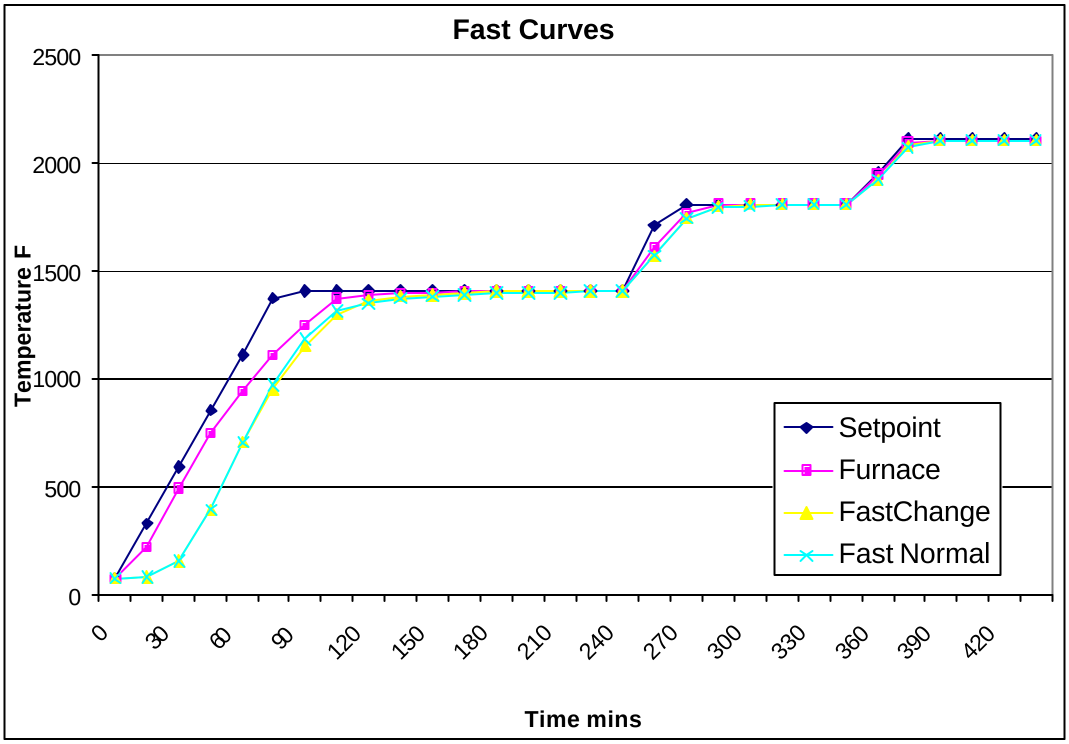


Figure 4.22 Fast curves

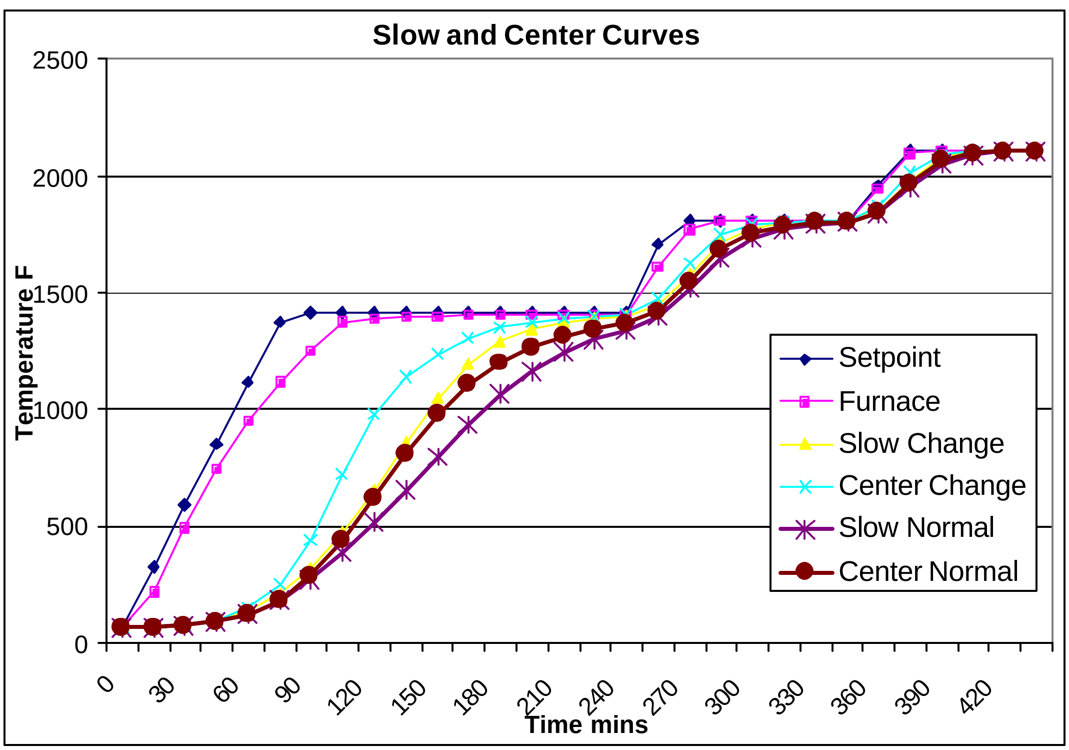


Figure 4.23 Slow and center of top basket curves

Chapter 5. Summary and Future Work

Summary

This thesis presented a computer- aided heat treatment planning system (CAHTPS) design and the various models used for the analysis. A number a cases studies were presented with different analysis results and compared with actual industrial results.

1. Physics-mathematical models based on the heat transfer theory for the various modes of heat transfer taking place between the furnace and the workpieces and among the workpieces itself are developed and the various parameters in the model are identified and classified.
2. The various model parameters and their effects are studied.
3. The various models are integrated to form a system to predict the temperature distribution inside the load of a furnace and hence can identify the temperature uniformity inside the load. The slowest part and the fastest part temperature can be obtained from the system.
4. A database containing the above model parameters and the various properties of materials as a function of temperature is developed for reference and use in the system.
5. The system application scope and accuracy of the system is tested.
6. The various effects due to change in load pattern and load quantity are studied and presented in the case studies.
7. The application scope is for a wide variety of workpieces of shapes and sizes. Different kinds of furnaces and load arrangements.

Future work

1. Some more cases studies with different kinds of furnace and conditions are to carried out.
2. Random loading pattern model for the load to be developed and analyzed by the case studies method.
3. System can be expanded to the cooling of the workpieces in the furnace with gas or air.
4. The database can be expanded to more materials and gases and furnaces.
5. The systems could be expanded for continuous furnaces.

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