Computer-aided Thermal Design of Furnace

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Abstract of thesis entitled

'Computer-aided Thermal Design of Furnace'

An energy balance of a furnace had been performed to develop a comprehensive mathematical model for the prediction of its temperature and heat flux distributions. The energy sources under consideration included combustion of the air/fuel intake, soot formation during the combustion processes, heat content of the exhaust gas, heat transfer by convection and radiation to the load and furnace enclosure, and conduction in the load and the furnace walls. The non-dimensional equation emerged from the experimental work of Lebedev[16] had been adopted to calculate the convection heat transfer. The Hottel's zone method[6,7,8] had been used for the radiation heat transfer calculation. The major difficulty in linking up the convection and radiation models directly to produce the overall heat transfer is the determination of the total exchange areas, which are the most important inputs in performing gaseous radiation in a grey enclosure. In addition, integral equations involved in solving the direct exchange areas are incompatible with the equations used for convection heat transfer when it is determined numerically. On the other hand, such integral equations used to estimate direct exchange areas are only available for very simple geometry such as cube or cylinder.

A numerical approach, the Monte Carlo method[2,3], had been applied to overcome this drawback and generate the total exchange areas (i.e. surface-surface, surface-gas and gas-gas) for the radiation calculations. However, the total exchange areas obtained by using the Monte Carlo method usually suffer from rather poor accuracy because of the random generation nature of the method. A least square smoothing technique[4,5], which is based on the concept of a better fulfillment of the Reciprocity Theorem, had been introduced to improve their accuracy. I had made a successful

contribution to apply a new and better approach for the calculation of gaseous radiation in a grey enclosure.

Based on the proposed model, I had also developed a computer programme, with the aid of Visual Basic to perform the following prediction for an oil-fired open flame furnace under both the transient and steady-state operations :

1. Combustion gas temperature distribution along axial length of the furnace ;
2. Temperature distribution of the furnace enclosure ;
3. Heat flux distribution in the furnace ;
4. Soot amount inside the combustion gas ;
5. Time required for a particular part of the furnace to reach a pre-set temperature.

My other contribution was to integrate all energy sources in the above model to predict the thermal performance of a furnace, especially during the transient operation which has rarely been investigated before the present study.

Results of the present study provided a very useful tool for the Design Engineers and Plant Engineers to predict and analyze the thermal performance of an oil-fired open flame furnace, including the start-up period, which is most critical for many industrial heating processes.

A numerical prediction had been made to test the applicability of the proposed methods and the programme developed. The sample furnace had been divided into 18 surface zones and 4 gaseous zones. The surface-surface, surface-gas, gas-surface and gas-gas total exchange areas had been calculated using the proposed smoothing Monte Carlo method. After integrating the other thermal models, a transient response curves had been obtained by the programme.

The proposed methods had been presented in local/international conferences[39,40]. A journal paper had been sent to The Journal of Heat and Mass Transfer[41], and was accepted for publication.

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1 Introduction

1.1 General Types of Furnaces

Furnace is an engineering equipment which is used to convert chemical energy of fuel into thermal energy for heating. It is widely applied to the industries such as steam production, heat treatment, paint curing or ceramic sintering. In a scientific point of view, a furnace can be defined as "a technological device isolated from its surroundings in which heat is the working energy"[1].

In term of heat transfer, the classification of the furnace can be based on the processes of heat production and transfer, or so-called the "energy processes", occurring inside the furnace chamber. These energy processes include (i) flame combustion, (ii) heat generation from electricity, (iii) heat from the burning out of metalloids from pig iron and sulphur from concentrates of non-ferrous metals, and (iv) the processes of heat transfer.

The energy processes can be divided into two classes: in the first class, heat is generated from the primary fuel in the furnace chamber and in the second class, heat is supplied to the furnace via indirect processes such as a heat exchanger.

Furnace in which the heat generation processes are both confined within some specific working zone within the stock is called "heat generating furnace". Examples are fuel-fired furnace and induction furnace.

Furnace in which the heat transfer processes are taking place outside the working location is called "heat exchanging furnace". In such furnace, the heat generator is not necessary inside the working space of the furnace, or be within the working space as an individual element. For this kind of furnace, the heat exchange processes between the element and the working zone determine the operating characteristics of the furnace.

For simplicity, Fig. 1.1 shows the fundamental classification of the furnaces.

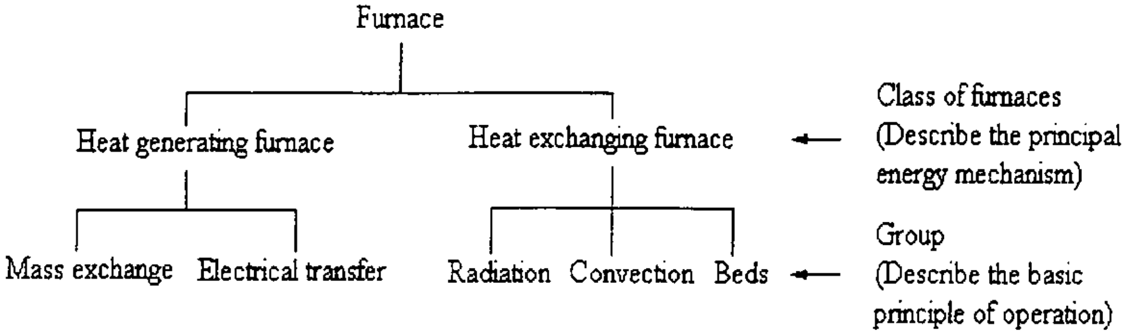


Fig 1.1 Classification of furnace

The present work will be concentrated on the oil-fired furnace because it is commonly used in the industry. However, thermal analysis of oil-fired furnace is most complicated among various kinds of furnaces.

1.2 Operating Principle of The Oil-Fired Furnace

Construction of an oil-fired furnace is shown in Fig. 1.2.

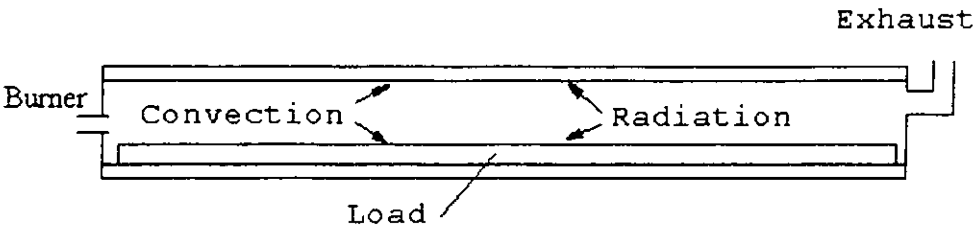


Fig. 1.2 Construction of Oil-Fired Furnace

In the oil-fired furnace, oil is burnt and a flame is generated by the burner. The combustion product usually contains carbon dioxide, carbon monoxide, water vapour, sulphur dioxode, soot, excess air or fuel depending on rich or lean combustion. The hot combustion gas will flow along the furnace and the fluid flow pattern produced shall be according to the burner type and air jet arrangement. Heat will transfer from the hot combustion gas to the furnace enclosure and the load by both convection and radiation. Conduction will be taken place within the furnace enclosure and the load. After heat being absorbed by the furnace enclosure, the furnace temperature will rise up from room temperature to the steady-state temperature, by going through the transient state of the furnace. Finally, the exhaust gas leaves the furnace and disperses to the atmosphere via a chimney.

1.3 Design Considerations of A Furnace

In furnace design, the following factors are necessary to be considered :

- Thermodynamics

  Combustion and heat transfer processes are both taking place inside the furnace and they affect the temperature distribution of the furnace directly. Therefore thermodynamics plays the most important role in furnace design.

- Mechanical structure

  For some large furnace such as the boiler in a power plant, the mechanical structure consideration is important to ensure that the structure is able to support the whole furnace. On the other hand, thermal stress analysis is another consideration in mechanical design.

- Fluid dynamics

  Convection is one of the major modes of the energy transfer. However, the convective heat transfer coefficient is highly dependent on the flow pattern inside the furnace. Hence, understanding of the furnace aerodynamics is essential. In addition, the temperature distribution within the furnace is also affected by the fluid flow pattern.

- System dynamics and control

  In many industrial applications, specification for the furnace temperature variation is very tight. A precise control system is required to control the temperature. Furthermore, the control system can alert the operators when an unexpected accident occurs such as overheating, leakage or mechanical failure.

- Environment control

  Nowadays, the environmental protection becomes more and more concerned. The constituent of the emission must be controlled carefully. Examples of method used are: (i) Lean combustion; (ii) sufficient primary and secondary air supply; and (iii) using light oil, natural gas or electricity as the primary energy source.

- Combustion noise control

  For some highly turbulent combustion, the noise produced must be considered as a factor in furnace design.

1.4 Thermal Design of A Furnace

Among these factors, thermal design is the most important criteria of the furnace to deal with the temperature distribution and heat transfer rate inside the furnace. Determination of the thermodynamics inside the furnace and its subsequent temperature distribution is a very complicated problem because the thermal behaviour within the furnace is affected by the following complex factors :

- Furnace geometry and material of construction

- Air/fuel supplies
- Combustion processes
- Heat transfer processes
- Aerodynamics inside the furnace

In order to carry out and optimize the thermal design of a furnace, a full understanding of these factors as well as their effect on the temperature and heat flux distributions is essentially important. In the past, thermal design of a furnace is very much relied on the designer's experience with the aid of the manuals, handbooks and experimental data. Such design method involves a tedious process during which mistakes can be easily involved. Also, information available to help the design process is very rare and may have limited applicability. In addition, hot spot and overheating may not be known before the actual operation of the furnace and accident may easily be occurred.

Nowadays, due to rapid development of personal computer and computer software, it becomes the preferred choice to handle engineering problems, including those related to heat transfer. Since thermal design of a furnace involves a lot of complicated parameters, therefore it is most preferable to carry out the design work with the aid of a computer programme in order to speed up the design process and reduce human errors.

In most of the oil-fired furnace, convection and radiation heat transfer rates are both important. For the radiation exchange calculation, total exchange areas are most critical inputs for the analysis. Furthermore, integral equations involved in solving the direct exchange areas are incompatible with the equations used for convection heat transfer when it is determined numerically. A promising approach to overcome this barrier is by using the Monte Carlo method[2,3]. It is a statistical sampling of events to determine the average behaivour of a system by using a pseudorandom number generator. For each trial, the process and the constraints are applied to match the physical problem. After a sufficient number of trials, the result can be used to simulate the physical situation.

However, accuracy of the obtained solution is normally barely satisfactory. The least square smoothing technique[4,5], which is based on the concept of a better fulfillment of the Reciprocity Theorem can be applied together with the Monte Carlo method to improve the results. A better accuracy can then be obtained in the prediction of the total exchange areas by considering both the conservation and reciprocity constraints.

1.5 Project Objectives

The present study will be performed to solve the problem of thermal design of furnace. The major objectives will be :

1. To assess the effect of the following factors on the furnace thermal performance :
    - Furnace geometry
    - Air/Fuel supplies
    - Combustion processes
    - Heat transfer processes including steady-state and transient operation
    - Thermal and optical properties of the furnace enclosure
    - Transient temperature variation of the furnace gas and enclosure
2. To select and integrate the important factors in the development of a mathematical model for the thermal design of a furnace. The developed model will account for

the heat transfer processes and temperature distribution in the furnace from starting up, through the transient period, to the steady-state operation.

3. To develop a user-friendly software to help the furnace design engineers to analyze the furnace performance when it is operating with certain parameters. The developed software will also be used to aid the design engineers to obtain the thermal design of a furnace to meet a particular purpose.
4. To iron out the incompatibility between the calculations of convection and radiation.

2 Literature Review

Heat transfer processes in a furnace are essentially convection and radiation, and their significance depend on the types of furnaces, burners and fuels used. Considerable investigations have been carried out to study these heat transfer mechanisms previously.

In 1968, Glinkov[1] discussed the basic theory of furnace from the engineering science viewpoint. In his study, furnaces were clearly defined and classified into two basic types, namely, the heat generating and heat exchanging. The operating theories and fundamental governing equations to predict a furnace's heat transfer performance were also proposed.

In 1958, Hottel [6,7] proposed the zone method to analyze the radiation heat transfer in an enclosure with allowance of non-uniformity temperature distribution in it. In his work, the enclosure was divided into regions called zones. In each zone, the radiation exchange between gas-gas, gas-surface and surface-surface were calculated by using the exchange areas. The thermal relationship between zones was then considered together with the conduction and convection heat transfer in the energy balanced equations, and the results were obtained by solving the system of simultaneous linear equations so developed. This method provided a good estimation of radiation in a grey enclosure, however, the gas medium being considered was limited to gaseous mixture without the existence of soot. In 1967, Hottel [8] extended the zone method to the "long furnace" model. For the zone near the burner, a considerable high turbulent mixing process occurred between fuel and air and the combustion was assumed to be taken place fully or partially. If a suitable condition is applied, for examples, to increase the turbulent mixing by increasing the air/fuel flow rate or to increase the swirl by increasing the number of fuel burner or air vent in appropriate position to improve the mixing process, or to stabilize the flame by using a suitable fuel burners or flame stabilizer, a more uniform stock temperature and thermofluid properties inside the zone can be achieved. Hottel assumed that this zone is behaving as a 'Well-Stirred' zone and the rest of the furnace can be modeled by the so-called 'plug-flow' zone.

Mixing process, ignition, stabilisation of flame and combustion of air/fuel mixture are main factors determining the thermal performance of a furnace, but they are affected by the aerodynamic behavior inside the furnace space. In 1967, Afrosimova[9] studied the aerodynamic pattern at the exit of a burner experimentally and obtained useful flow data for different degrees of swirl, which can be used for the prediction of convective heat transfer coefficient in a furnace.

In order to predict the convection in a furnace, the determination of heat transfer coefficient is vitally important. In 1970, Lucas[10] used mass transfer measurement together with a heat/mass analogy to find the heat transfer coefficient in industrial furnaces. He replaced the heat transfer surface in a furnace by a mass transfer surface and measured the mass transfer rate. The physical similarity was then used to determine the convective heat transfer coefficient. In 1972, Lucas[11] continued to study the prediction of the furnace's thermal performance. The Hottel's long furnace model was applied to predict the thermal performance of the shell boiler and suggested the following models of the furnace:

Combustion model –The stoichiomatric calorific values was used as the heat input to the furnace. The analysis of flame characteristics was highly dependent on the burner design and a semi-empirical study was adapted. He concluded from practical experience and experimental investigation that the flame volume in a shell boiler would be in the order of 0.2 m^2 for each MW of heat input. In addition, the heat of reaction liberated was represented by an exponential curve, which is approaching unity asymptotically. It was equal to zero at the burner throat and 99% at the end of the flame. For emissivity of the luminous flame, he assumed a value of 0.7 for a flame diameter of 3 ft by burning heavy oil and very low emissivity is obtained by burning lighter oil because of the low carbon concentration. Furthermore, an average temperature of $\overline{T^4}$ was used instead of the $(\overline{T})^4$ to evaluate the effective radiating temperature.

Convective heat transfer model – The convective heat transfer coefficient was taken as a constant of 5.68 kW/m^2K for the waterside and the Dittus-Boelter equation[12] was used inside the tube, i.e.

$$Nu = 0.023Re^{0.8}\,Pr^{0.33} \qquad \text{.... [2.1]}$$

Where

Nu = Nusselt number

Re = Reynolds number

Pr = Prandtl number

Radiative heat transfer model – Hottel's exchange areas was used to estimate the radiation heat transfer between the zones. For carbon particles formed by oil and gas flames, the diameter was less than 1m. For such a small size, the absorption coefficient is independent of its diameter and only a function of the carbon concentration, which can be expressed as:

$$K_a = f(\Lambda).\ f_v \qquad \text{.... [2.2]}$$

Where

K_a = Absorption coefficient, 1/m

f_v = Concentration of carbon particle, kg/m^3

Λ = Mean wave length, μm

and is defined as :

$$\Lambda = \frac{4110}{T_g} \qquad \text{.... [2.3]}$$

where

T_g = Effective radiating temperature in combustion product, K

In Lucas's analysis, he provided a systematic approach to separate the various physical criteria by different models such as combustion model, convection model and radiation model which had been used in many research projects later. In the combustion model, the heat released by combustion was assumed to equal to the stoichiomatric calorific value of the fuel. It is a reasonable assumption and will be adopted in the present research project.

In 1973, Johnson[13] extended Hottel's zone method to soot modeling and allowed the variation in gas absorption coefficient of the luminous flame. For the modeling of combustion gas consisting of soot particles, a weighted sum of grey gases was used to represent its emissivity. The emissivity of one grey gas (ε) could be expressed as :

$$\varepsilon_s = 1 - \exp(-BTcL) \qquad \text{.... [2.4]}$$

where :

$$\text{BTc} = \text{K}_a \qquad \text{.... [2.5]}$$

When the combustion gas is assumed to contain several grey gases, its emissivity (ε) could then be expressed as :

$$\varepsilon_s = \sum_n \left[a_{g,n}(T)\right] \cdot \left[1 - \exp\left(-K_{as,n} L\right)\right] \qquad \text{.... [2.6]}$$

To allow for the spatial variation of absorption coefficient, an averaging technique was adopted to find the average absorption coefficient along the path line.

In 1975, Truelove[14] published a comprehensive paper to describe the following mathematical modeling technique in relation to thermal performance of a furnace :

- The Hottel's zone method
- Representation of real furnace gas by :
  - ☐ Mixed grey gases
  - ☐ Carbon dioxide and water vapour
  - ☐ Combination of carbon dioxide, water vapour and soot

  - ☐ Johnson's Soot modeling by weighted sum of grey gases
- Johnson's averaging technique to analyze the variation in species concentration throughout the furnace.

Reacting flow contributes a major factor in the furnace thermal modeling because it affects the convective heat transfer process and heat releasing rate inside the furnace. In 1975, Khalil[15] studied the two-dimensional flow in a cylindrical furnace. In his study, the following aspects had been dealt with :

- Turbulence modeling by applying the k-ε model
- Aerodynamic modeling by using the steady state two-dimensional momentum equations
- Combustion model by using one of the following :
  - ☐ Model 1 : This model is physically well controlled, but oxygen and fuel are not allowed to coexist in the same location.
  - ☐ Model 2 : For this model, the reaction rate is assumed to be infinitely fast, but fuel and oxygen can coexist in certain locations.
  - ☐ Model 3 : This model is more realistic in which the reaction rate is finite and can be expressed as an Arrhenius type in the form of :

$$R_{fu}=m_{fu}\rho^2 m_{ox}A\exp(-E/RT) \qquad \text{.... [2.7]}$$

The system of differential equations obtained from these models could then be solved by finite difference method.

The convective heat transfer coefficient, which is the most important parameter in convection, can be obtained either experimentally or analytically. In the analytical method, the conservation equations can usually be solved, with the aid of suitable velocity and temperature profiles, by numerical method and computation because of the large number of calculations involved. In many cases, experimental approach gives direct and reliable results which can be used immediately or as foundation for numerical simulation. Lebedev[16] studied the convective heat transfer process in a rectangular direct-heating furnace and obtained the criteria equation in the form as presented below :

$$Nu=A_1Re^{0.75} \quad \ldots . [2.8]$$

Where A_1 is equal to :

0.175 for both end of the furnace

0.283 for roof of the furnace

0.142 for side walls of the furnace

0.185 for the whole enclosure

Khalil[17] used finite difference method and the k-ε turbulence model to solve the conservation equations of mass, momentum, chemical species and energy. The emphasis was put on the following two radiation models:

- Four-flux model was suggested to express the angular variation of the radiation intensity in a furnace by the first few terms of a Taylor series expansion. A set of flux equations was obtained by substituting the radiation intensity into the radiation heat transfer equation and integrating over a number of solid angles.
- The model derived from the discrete ordinates approximation, in which the angular distribution of radiation intensity in a furnace is approximated by a finite

number of intensities in discrete directions. Equations for the discrete intensities were obtained by evaluating the exact equation of heat transfer for each discrete direction, and a finite number of coupled partial differential equations in the space variables were developed, which could be solved by standard numerical technique.

For these two methods, they produced almost the same accuracy.

In 1977, Hutchinson[18] measured and calculated the furnace flow properties experimentally by using a 20° flame angle and a swirl number of 0.3 and 0.5 respectively. Particular attention was paid to the influence of the velocity profile in the plane at the burner exit. Furthermore, the calculated results obtained by numerical solution of the conservation equations in differential forms were compared with the experimental results. In 1980, Hutchinson[19] extended the calculation into flow and heat transfer characteristics in the furnace. The k-ε model was adapted as the turbulence model. For the combustion model, both diffusion, premixed and arbitrary fire flame were considered. Radiation model using the flux method led to a system of partial differential equations, which were solved numerically.

In 1986, Song[20] used the conservation equations of mass, momentum and energy with combustion analysis to simulate the flow, combustion and heat transfer in a two-dimensional natural gas-fired furnace. In his analysis, the k-ε model was used to represent the turbulent flow in the furnace. Combustion model was provided in the Arrhenius form. For the radiation model, he also considered the interaction between turbulence and radiation to form the radiation-turbulence interaction equation.

Li[21] investigated the thermal performance of furnace by including the load analysis, and the furnace was a slab type equipped with multi-burners. In his work, Hottel's zone method was applied to sub-divide the furnace into 5 zones. For each zone, he analyzed the radiation exchange by using the exchange areas. For the slab, he took into account the convection and radiation heat transfer and the skidrail had been modeled in order to see the mechanism of skid mark formation. In addition, the effect on temperature distribution both in the furnace and on the slab was studied by varying the skidrail speed.

Chapman[22,23] studied the heat transfer processes of the load inside the furnace. The analysis was extended to the transient heat transfer from the load. For his furnace model, the well-stirred furnace model had been used. Heat from combustion was calculated by assuming the stoichiometric reaction between hydrocarbon fuel and air. In the radiation model, the exchange areas were calculated by using the Monte Carlo statistical method. This approach seems to overcome the major problem in the "total exchange areas" method, i.e. limited information were available in the equations to predict total exchange areas. The combustion gas was modeled as a mixture of four grey gases. The convective heat transfer coefficient was evaluated by applying Lebedev's work[16].

Honney[24] analyzed the flow inside a complex rectangular furnace with four burners installing in the same plane by experimental and computational methods. The k-ε turbulence model had been employed together the conservation equations of mass and momentum, which were numerically solved by finite difference method. The predictions showed that the flow is highly turbulent and swirling with a slightly back flow. Comparison of the predicted and measured results concluded a good agreement in the mean velocity, but the predicted turbulence level was slightly lower than that obtained from experiment.

Stehlik[25] provided a simple description of the modeling procedure of simple heat exchanger type furnace and the applicability of the method. Basically, the furnace was modeled as a well-stirred zone, in which convection and radiation were both considered.

Sun[26] and Liang[27] described the modeling technique, numerical simulation procedure, gas-solid two-phase flow, heat transfer and combustion characteristics in a three-dimensional coal-fired W-shaped flame furnace. The W-shaped flame was formed by four burners locating at four corners of the furnace, and the air/fuel supplies were flowing tangentially with appropriate secondary aeration. Experimental verification had been done with data obtained from a steam power plant.

Reviewing the relevant literatures, Hottel's long furnace model is a very useful tool for the present study to analyze the radiation heat transfer between different zones. However, the equations to predict total exchange areas, which are the most essential parameters to predict radiation, are only available for very simple geometry, such as cube or cylinder[12]. It certainly limits the applicability of this method. A possible approach to overcome this drawback may be the application of the Monte Carlo method to generate the total exchange areas.

For the combustion model, there are two approaches suitable to determine the heat released from combustion, i.e. the stoichiomatric caloric value and reacting flow theory. Lucas's[11] different models, namely, combustion model, convection model, radiation model will be adopted to describe these three important physical criteria in a furnace. Determination of the convective heat transfer coefficient in a furnace encounters difficulty due to the complication of fluid dynamics. Lebedev[16] has provided useful experimental results for the prediction of convective heat transfer coefficient inside a furnace.

Among the previous studies, most of them are concerned with the steady-state operation of a furnace. In Chapman's work[22,23], the transient state of the load has been considered, but the furnace under consideration was still under steady-state condition. In the present work, both the steady-state and transient thermal response of the furnace gas and enclosure will be involved. It is very important in furnace thermal design to cover the transient period in addition to the steady-state condition, because a lot of design specifications of furnace are related to the time required for the furnace to reach its steady-state condition.

Monte Carlo method is a positive method to simplify the calculation of the exchange areas and a lot of multiple numerical integration can be avoided. Indeed, there is certain drawback by using this method. Even though the Monte Carlo method satisfies the conservation condition, its accuracy is normally poor in satisfying the Reciprocity Theorem. In the present investigation, the Monte Carlo Method is adopted with its drawback overcome by using a least square smoothing technique. The method is suggested by Chen et al[28] to calculate the radiation in a direct injection diesel engine.

3. Methodology

In order to determine the thermal performance of an oil-fired open flame furnace, there are two possible approaches, namely, experimental and computational.

As mentioned previously, thermal performance of an oil-fired open flame furnace can be affected by various parameters. It is very difficult to describe its thermal behaviour by a single or a set of non-dimensional equations, which are developed from experimental results.

Therefore, the most positive approach is to predict the thermal performance of a furnace by computational method. In this case, the affecting parameters can be put into the programme to perform all the calculations, and all the thermally dependent properties can be arranged in a database and be available when they are required. Another advantage of using computational method is to reduce human error, which will be encountered frequently because the calculation work is very tedious and complicated.

Unfortunately, software specialised for furnace design is not available in the market. Therefore significant effort has been made in the present study to develop a programme to integrate the mathematical models in determining the thermal performance of a furnace. The Visual Basic has been used, because it enables the development of a user-friendly interface in the Window environment.

4. Smoothing Monte Carlo Method

4.1 Introduction

Radiation is a very complicated problem due to the non-linearity nature of the control equations, problems varied with different geometry, optical properties of media and wave properties dependent of the radiation. The problem is almost certain that cannot be solved until the mature technological development of the computer and numerical methods.

Recently, the methods used to analyze the radiation problems are analytical method, Hottel's zone method, flux method, discrete ordinate method and Monte Carlo method.

Basically, Hottel's zone method is a powerful tool to calculate the radiation heat transfer within an enclosure. Its accuracy can be nearly close to the analytical method if the zone size is sufficiently small. However, the direct exchange areas or the total exchange areas involved in the calculation are very difficult and tedious to be evaluated. Equations to predict the direct exchange areas are only available for simple geometry, such as cubic or cylindrical enclosure. In the solution procedure, several multiple integrals are required to be solved, the problem becomes more complicated when the absorption coefficient is varied in the media.

For a grey enclosure of complicated geometry containing an emitting and absorbing media, Hottel's zone method incorporating the Monte Carlo method is a positive approach to solve the problem. In the past, Monte Carlo method was a statistical method to estimate the value of π. But later Howell[2] and Taniguchi[3] proposed to use this method to solve the radiation problem. Although the computational rate of Monte

Carlo method is slow, it is a good and simple method to deal with the radiation problems for an enclosure of complicated geometry.

However, there is an imperfection by using the conventional Monte Carlo method. The total exchange areas predicted by this method may be accurate only if the following constraints are fulfilled :

$$\sum_j S_i S_j + \sum_j S_i G_j = \varepsilon_i A \qquad \text{.... [4.1]}$$

$$\sum_j G_i S_j + \sum_j G_i G_j = 4K \qquad \text{.... [4.2]}$$

$$S_i S_j = S_j S_i \qquad \text{.... [4.3]}$$

$$S_i G_j = G_j S_i \qquad \text{.... [4.4]}$$

$$G_i G_j = G_j G_i \qquad \text{.... [4.5]}$$

Equations [4.1] and [4.2] are used to satisfy the First Law of Thermodynamics (i.e. completeness) and equations [4.3] to [4.5] are the Second Law of Thermodynamics compliance (i.e. symmetry or reciprocity).

For the conventional Monte Carlo method, although it is good to fulfill the First Law of Thermodynamics, it is poor to comply with the Second Law of Thermodynamics. In the present study, the least square smoothing technique will be introduced to improve its accuracy. In addition, the method provided in the present study enables the evaluation of not only the direct exchange area, but also the total exchange area in an instant. The difference between the direct exchange area and the total exchange area can be expressed as follows :

Direct exchange area – The fraction of radiation leaving a zone which reaches a particular zone without considering reflection.

Total exchange area – The fraction of radiation leaving a zone which is absorbed by a particular zone after numerous reflections are taking place in the enclosure.

In the later analysis, all the exchange areas involved will be specified as the total exchange areas.

4.2 Monte Carlo Method

When radiation is transmitting in an absorbing medium, its intensity will be absorbed by the medium and decreased along the path it travels, and it seems to have the continuum property.

According to the quantum theory, radiation consists of a large amount of pockets of energy, called photon (i.e. discretization of energy). When a photon is absorbed by a medium, its energy will be absorbed totally instead of partially. When a photon is passing through a medium, its energy will pass through the medium totally. However, there is no criteria to know whether the photon is absorbed or not, it is entirely a random process. This property can also be applied to the reflection or absorption of a grey body, which is also a random process.

By using this concept, statistical method can be implemented to handle the radiation heat transfer problem. Since a bundle of radiation ray consists of a large amount of photons, hence the accuracy can be improved by using a large number of photon to simulate the real problem.

In the Monte Carlo method, the radiative energy is discretized into N photons. For each photon, the position of emission, the direction of emission, absorption or transmition of the absorbing medium, reflection or absorption of the grey surface, are considered as random processes. Eventually, the region where the photon has been absorbed will be known after numerous number of random processes.

4.2.1 Discretization of Radiation

For any gaseous zone 'i', the radiative energy is given by :

$$Q_{gi} = 4K_a E_{bgi} V_i = 4K_a \sigma T_{gi}^4 V_{gi} \quad \text{.... [4.6]}$$

If it is discrtized into N photons, the energy of each photon is :

$$Q_i = \frac{Q_{gi}}{N_i} = \frac{4K_a \sigma T_{gi}^4 V_i}{N_i} \quad \text{.... [4.7]}$$

For any surface zone 'i', the radiative energy is given by :

$$Q_{si} = \varepsilon_{si} E_{bsi} A_i = \varepsilon_{si} \sigma T_{si}^4 A_i \quad \text{.... [4.8]}$$

If the surface is divided into N photons, the energy of each photon becomes :

$$Q_i = \frac{\varepsilon_{si} \sigma T_{si}^4 A_i}{N_i} \quad \text{.... [4.9]}$$

The total number of photons in the enclosure is equal to :

$$M = \sum_{i=1}^{N_g} N_i + \sum_{i=1}^{N_s} N_i \quad \text{.... [4.10]}$$

Where :

M = the Total number of photon in the enclosure

N_g = Number of photon from the gas zone

N_s = Number of photon from the surface zone

N_i = The i^th photon

4.2.2 Position of Photon Emission from a Gaseous Zone

The position of photon emission can be described by 3 random numbers R_x ,R_y and R_z as shown in Fig. 4.1such that :

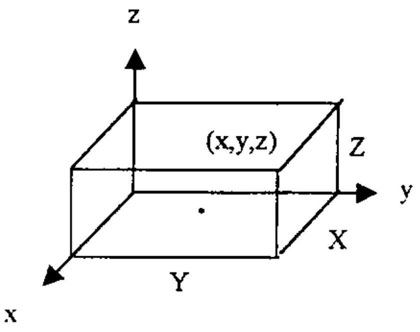


Fig. 4.1 Position Of Photon Emission From Gaseous Zone

$$x = R_x X \qquad \text{.... [4.11]}$$

$$y = R_y Y \qquad \text{.... [4.12]}$$

$$z = R_z Z \qquad \text{.... [4.13]}$$

where x, y and z are the local Cartesian Coordinates.

4.2.3 Direction of Photon Emission from a Gaseous Zone

Radiation will emit in all direction evenly in a spherical space. It can be described by the solid angle as shown in Fig. 4.2, which is defined as :

$$d\omega = \frac{dA}{r^2} \qquad \text{.... [4.14]}$$

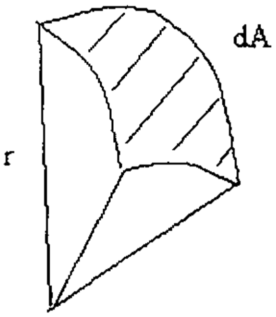


Fig. 4.2 Definition Of Solid Angle

Since radiation is evenly distributed in the spherical space, hence each photon occupies the solid angle of :

$$d\omega = \frac{4\pi}{N_i} \qquad \text{.... [4.15]}$$

From Fig. 4.3, the solid angle can be expressed by spherical co-ordinate as shown below :

$$d\omega = (\sin\eta)(d\eta)(d\theta) \qquad \text{.... [4.16]}$$

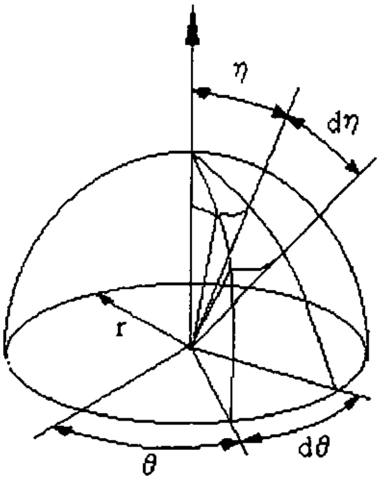


Fig. 4.3 Solid Angle In Spherical Co-ordinates

As a result, the probability density function is equal to :

$$\frac{d\,\omega}{4\,\pi} = \left(\frac{\sin\ \eta\ d\ \eta}{2}\right)\left(\frac{d\ \theta}{2\ \pi}\right) \qquad \text{.... [4.17]}$$

where the domains of θ is in the range of [0, 2π] and that of η is [0, π].

The probability function stated in equation [4.17] can be identified into two independent probability functions, i.e. η and θ :

$$f(\theta) = \frac{1}{2\pi} \qquad \text{.... [4.18]}$$

$$f(\eta) = \frac{\sin\eta}{2} \qquad \text{.... [4.19]}$$

The accumulated probability functions can then be obtained by integrating the equations [4.18] and [4.19] as shown below :

$$\int_0^\theta f(\theta)d\theta = \int_0^\theta \frac{1}{2\pi}d\theta \qquad \text{.... [4.20]}$$

$$F(\theta) = \frac{\theta}{2\pi} \qquad \text{.... [4.21]}$$

$$\int_0^\eta f(\eta)d\eta = \int_0^\eta \frac{\sin\eta}{2}d\eta \qquad \text{.... [4.22]}$$

$$F(\eta) = \frac{1-\cos\eta}{2} \qquad \text{.... [4.23]}$$

Therefore the random direction of a particular photon can be evaluated by :

$\theta = 2\pi R_\theta$ and .... [4.24]

$\eta = \arccos(1-R_\eta)$ .... [4.25]

where R_θ and R_η are the random numbers, ranging from zero to unity, to determine direction of the emitted photon.

4.2.4 Position of Photon Emission from a Surface Zone

Similar to the gaseous zone, random position of photon emission from a surface zone can be determined by 2 random numbers R_x and R_y as shown in Fig. 4.4.

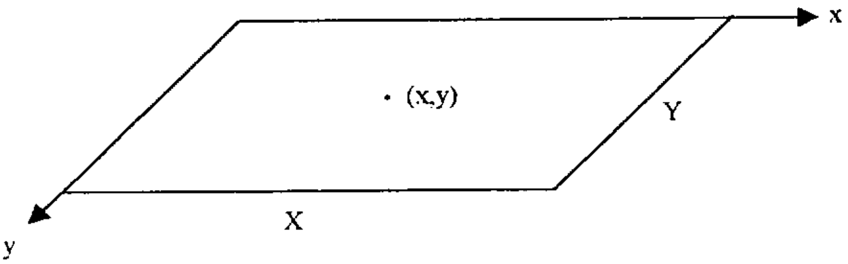


Fig. 4.4 Position Of Photon Emission From Surface Zone

$$x = R_xX \quad \text{.... [4.26]}$$

$$y = R_yY \quad \text{.... [4.27]}$$

4.2.5 Direction of Photon Emission from a Surface Zone

By multiplying $\cos\eta/\pi$ to both sides of equation [4.16], we have the probability density function as follows :

$$\frac{\cos\,\eta d\omega}{\pi} = \left(\frac{\sin\,\eta\,\cos\,\eta d\eta}{1/2}\right)\left(\frac{d\theta}{2\pi}\right) \quad \text{.... [4.28]}$$

For the surface zone, the domain for θ is $[0,2\pi]$ and that for η is $[0,\pi/2]$.

Similar to the gaseous zone, the direction of photon emission can be evaluated as :

For the cirumferential angle :

$$\theta = 2\pi R_\theta \quad \text{.... [4.29]}$$

For conical angle, the probability function is :

$$f(\eta) = 2\,\sin\eta\cos\eta \quad \text{.... [4.30]}$$

Integrate both sides, we have :

$$\int_0^\eta f(\eta)d\eta = \int_0^\eta 2\sin\,\eta\cos\,\eta d\eta \quad \text{.... [4.31]}$$

$$F(\eta) = \sin^2\eta \quad \text{.... [4.32]}$$

Therefore the conical angle will be :

$$\eta = \arcsin\,\sqrt{R_\eta} \quad \text{.... [4.33]}$$

Using these 2 random numbers R_θ and R_η, the direction of photon emission can be determined.

4.2.6 Photon Travelling Distance

Once the position and direction of the photon emission have been determined, the maximum distance for the photon to travel before striking on other surface zones (r_{max}) can be evaluated as shown in Fig. 4.5.

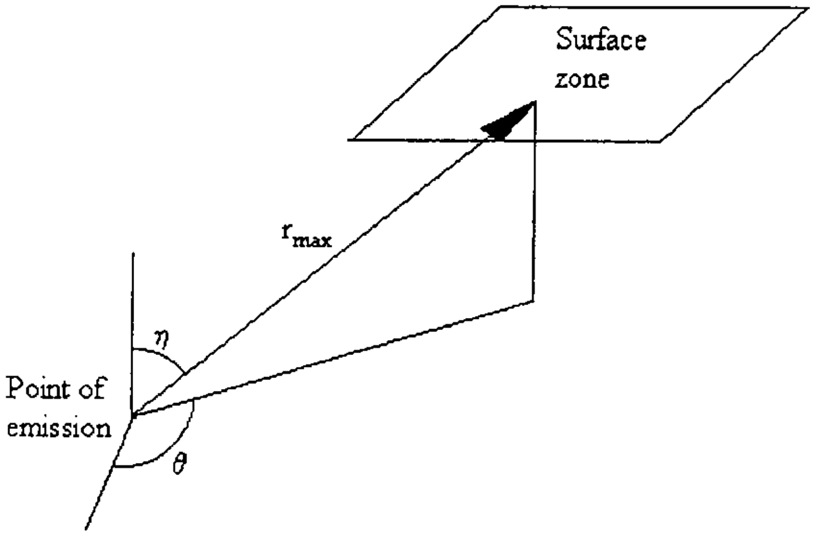


Fig.4.5 Maximum Distance Traveled By A Photon

Due to the fact that the radiation will be absorbed by the gas and follows the decay law, that is :

$$I_r = I_o e^{-K_a r} \qquad \text{.... [4.34]}$$

or

$$\underline{Q}_r = \underline{Q}_o e^{-K_a r} \qquad \text{.... [4.35]}$$

The radiation absorbed by gas which is travelling through a distance dr is given as :

$$-dQ_r = Q_o K_a e^{-K_a r} dr \qquad \text{.... [4.36]}$$

$$-\frac{dQ_r}{Q_o} = K_a e^{-K_a r} dr \qquad \text{.... [4.37]}$$

Therefore, the probability function of the radiation, which is absorbed at the distance r is given by :

$$f(r) = K_a e^{-K_a r} \qquad \text{.... [4.38]}$$

Its accumulated probability function can be determined by :

$$\int_0^r f(r) dr = \int_0^r K_a e^{-K_a r} dr \qquad \text{.... [4.39]}$$

$$F(r) = 1 - e^{-K_a r} \qquad \text{.... [4.40]}$$

Hence, the expected distance traveled by a photon can be determined by a random number R_r.

In term of R_r, the expected distance traveled by the photon is :

$$r = -\frac{1}{K_a} \ln(1 - R_r) \qquad \text{.... [4.41]}$$

According to the Quantum Theory, we have the following 2 possibilities :

$r < r_{max}$ The photon is absorbed by the gas

$r > r_{max}$ The photon is not absorbed by the gas

4.2.7 Reflection or Absorption by a Surface

If the expected distance traveled by a photon is greater than the maximum distance traveled, i.e. $r>r_{max}$, it means that the photon can pass through the gas and reaches the surface zone 'j'. Subsequently, the photon is either absorbed or reflected by the surface, depending on emissivity of the surface. In order to determine the photon is absorbed or reflected, one more random number R_ε is required such that :

If $R_\varepsilon < \varepsilon_j$ The photon is absorbed by the surface 'j'

If $R_\varepsilon > \varepsilon_j$ The photon is reflected by the surface 'j'

If the photon is absorbed by surface 'j', then the tracking of that photon will be terminated and the energy absorbed by 'j' will be stored in a memory unit U_{sj}. If the photon is reflected by surface 'j', then the tracking of that photon will be continued. The whole procedure will be repeated until the photon is absorbed by either the gas zone or the surface zone.

4.3 Integration Of Zone Method And Monte Carlo Method

Basically, Hottel's zone method is a powerful and accuracy method if the zone size is sufficiently small. However, its major drawback is the complicated calculations involved, especially the determination of the exchange areas. Monte Carlo method provides a simple method to calculate the exchange areas even though the geometry is complex. In addition, the Monte Carlo method enables the determination of the total exchange areas directly instead of the direct exchange areas, which will simplify the calculation of the radiation exchange. The integration of zone method and Monte

Carlo method is a perfect couple to handle the radiation problem in an enclosure. The procedure of using this method is listed below :

4.3.1 Zone Division in An Enclosure

The enclosure is divided into different surface and gaseous zones. For each zone, the memory units and their associated parameters are allocated such that :

For gaseous zone g_i : Volume V_i, absorption coefficient K_{ai}, memory unit U_{gi}

where $i = 1, 2, \dots, N_g$ and N_g is the number of gaseous zone

For surface zone s_i : Area A_i, emissivity ε_i, memory unit U_{si}

Where $i = 1, 2, \dots, N_s$ and N_s is the number of surface zone

4.3.2 Discretization of Energy

Assume the gas zone g_i is the unique radiation source in an enclosure. Its volume is V_i, the number of photons is N_{gi} and the energy of each photon is 1W. We have :

$$4K_aV_iE_{bi} = N_{gi} \qquad \dots [4.42]$$

$$E_{bi} = \frac{N_i}{4K_aV_i} \qquad \dots [4.43]$$

4.3.3 Photon Exchange Analysis

Using the method suggested in 4.2, tracking of each photon can be determined by the Monte Carlo method.

4.3.4 Total Exchange Areas of Gaseous Zones

According to the Monte Carlo method, U_{gij} is the radiation absorbed by the gaseous zone g_j which are emitted from gaseous zone g_i, after numerous reflections have been carried out in the enclosure. Since the radiation energy for each photon is assumed to be 1W, therefore the energy absorbed by a gaseous zone Q_{gigj} is :

$$Q_{gigj} = U_{gij} \qquad \text{.... [4.44]}$$

According to definition of exchange area, we have :

$$Q_{gigj} = G_iG_jE_{bi} \qquad \text{.... [4.45]}$$

$$G_iG_j = \frac{Q_{g_ig_j}}{E_{b_i}} \qquad \text{.... [4.46]}$$

Combining equations [4.43] to [4.46], the gas-gas exchange areas can be determined as follows :

$$G_iG_j = \frac{4K_aV_iU_{g_j}}{N_i} \qquad \text{.... [4.47]}$$

where : i = A gaseous zone in the enclosure

j = Another gaseous zone in the enclosure

Similarly, the gas-surface exchange areas are :

$$G_iS_j = \frac{4K_aV_iU_{s_j}}{N_i} \qquad \text{.... [4.48]}$$

where : i = A gaseous zone in the enclosure

j = A surface zone in the enclosure

4.3.5 Total Exchange Areas of Surface Zones

Similarly, the total exchange areas for surface-surface and surface-gas can be evaluated.

Assume the surface 'i' with an area A_i is the unique zone emitting radiation and the radiation energy of each photon is 1W, we have :

$$\varepsilon_i A_i E_{bi} = N_i \qquad \text{.... [4.49]}$$

$$E_{b_i} = \frac{N_i}{\varepsilon_i F_i} \qquad \text{.... [4.50]}$$

The radiation transfer can then be expressed as :

$$Q_{s_i s_j} = U_{s_j} \qquad \text{.... [4.51]}$$

By the definition of exchange area :

$$Q_{s_i s_j} = S_i S_j E_{b_i} \qquad \text{.... [4.52]}$$

Hence we have :

$$S_i S_j = \frac{Q_{s_i s_j}}{E_{b_i}} \qquad \text{.... [4.53]}$$

$$S_i S_j = \frac{\varepsilon_i A_i U_{s_j}}{N_i} \qquad \text{.... [4.54]}$$

where i = A surface zone in the enclosure

j = Another surface zone in the enclosure

Similarly, the exchange area for surface-gas is equal to :

$$S_iS_j = \frac{\varepsilon_i A_i U_{g_j}}{N_i} \qquad \text{.... [4.55]}$$

where i = A surface zone in the enclosure

j = A gaseous zone in the enclosure

After all the surface-surface, surface-gas, gas-surface and gas-gas total exchange areas are evaluated and applied to the Hottel's zone method, the problem becomes relatively simple. This is an advantage to integrate the Hottel's zone method with the Monte Carlo method. Since the path of each photon is tracked and its energy is clearly equated, therefore the Monte Carlo method is good to fulfill the First Law of Thermodynamics, that is the conditions as shown by equations [4.1] and [4.2]. Nevertheless, the method does not comply with the Second Law of Thermodynamics, that is the constraints shown by equations [4.3] to [4.5]. In the next section, the least square smoothing technique is introduced to improve the accuracy of the Monte Carlo method can comply with both the First Law and Second Law of Thermodynamics.

4.4 Least Square Smoothing Monte Carlo Method

As mentioned previously, the exchange areas are said to be accurate if both the First Law and Second Law of Thermodynamics are fulfilled, which are given by the conditions as stated in equations [4.1] to [4.5]. The conventional Monte Carlo method is good to comply with the First Law of Thermodynamics but poor for the Second Law compliance. In this section, a least square smoothing technique will be introduced to :

1. fulfill the Reciprocity Theorem, and hence the Second Law of Thermodynamics in order to improve the accuracy, and
2. yield a symmetrical matrix of the exchange areas to facilitate more compact storage.

It can been shown that the fractional error ($|F_{ij,exact}$-$F_{ij}/F_{ij}|$) in the exchange areas predicted by the Monte Carlo method is given by[4] :

$$C_{ij} = K\sqrt{\frac{1-F_{ij}}{N_i F_{ij}}} \qquad \text{.... [4.56]}$$

where K =1.96 for 95 % confidence.

A new set of the exchange areas can be obtained, which can comply with the Second law of Thermodynamics, as shown :

$$S_i S_j = \left(\frac{C_{ji}^2}{C_{ij}^2 + C_{ji}^2}\right) S_i S_j + \left(1 - \frac{C_{ji}^2}{C_{ij}^2 + C_{ji}^2}\right) S_j S_i \qquad \text{.... [4.57]}$$

However, the exchange areas as predicted by equation [4.57] may increase the error in complying with the First Law of Thermodynamics. In order to minimise the error made in complying with both the First Law and Second Law, a least square technique[5] is employed to yield another set of exchange areas in the following matrix form :

$$[X] = \begin{bmatrix} [SS] & [SG] \\ [SG]^T & [GG] \end{bmatrix} \qquad \text{.... [4.58]}$$

A matrix equation can be formed as follows and λ is evaluated by :

$$[R]\bar{\lambda} = \bar{\delta} \qquad \text{.... [4.59]}$$

Where :

$$\left.\begin{aligned} r_{ij} &= w_{ij} && \text{when } i \neq j \\ r_{ii} &= w_{ii} + \sum_{j=1}^{M} w_{ij} \\ \delta_i &= c_i - \sum_{j=1}^{M} x_{ij} \\ w_{ij} &= x_{ij}^2 \\ c_i &= \varepsilon_{si} A_{si} && \text{for surface zones} \\ c_i &= 4K_a V_{gi} && \text{for gaseous zones} \end{aligned}\right\} \qquad \text{.... [4.60]}$$

Combining equations [4.58], [4.59] and [4.60], the exchange areas are produced by a smoothing Monte Carlo method such that both the First Law and Second Law of Thermodynamics can be fulfilled. They are calculated by the following equation :

$$x_{ij}' = x_{ij} + w_{ij}(\lambda_i + \lambda_j) \qquad \text{.... [4.61]}$$

By using the method suggested above, a new set of total exchange areas, x_{ij}', can be evaluated which are used in the radiation calculation of the present study.

4.5 Application of Smoothing Monte Carlo Method in Present Study

The idea of the Monte Carlo method is to generate the total exchange areas by random nature. The least square smoothing technique is aimed to provide one more constraint in selecting the appropriate total exchange areas in the present purpose, that is to force the total exchange areas to fulfill both the First Law and the Second Law of Thermodynamics.

This technique was proposed by Loehrke[4] and Larsen[5]. Chen[28] applied this technique to calculate the radiation transfer in a diesel combustion engine. In the present study, the method is extended to a much larger system, an oil-fired open flame furnace. The total exchange areas are predicted by both conventional and smoothing Monte Carlo methods and compared as shown in Tables 6.1 and 6.2. Results show that, after using the least square smoothing technique, a more symmetrical matrix has been obtained. That is the total exchange areas fulfill the Reciprocity Theorem or the Second Law of Thermodynamics.

4.6 Flow Chart Showing The Smoothing Monte Carlo Method

The flow chart showing the algorithm to implement the subroutine of the Monte Carlo method is indicated in Fig. 4.6, whereas Fig. 4.7 shows the flow chart to apply the smoothing procedure.

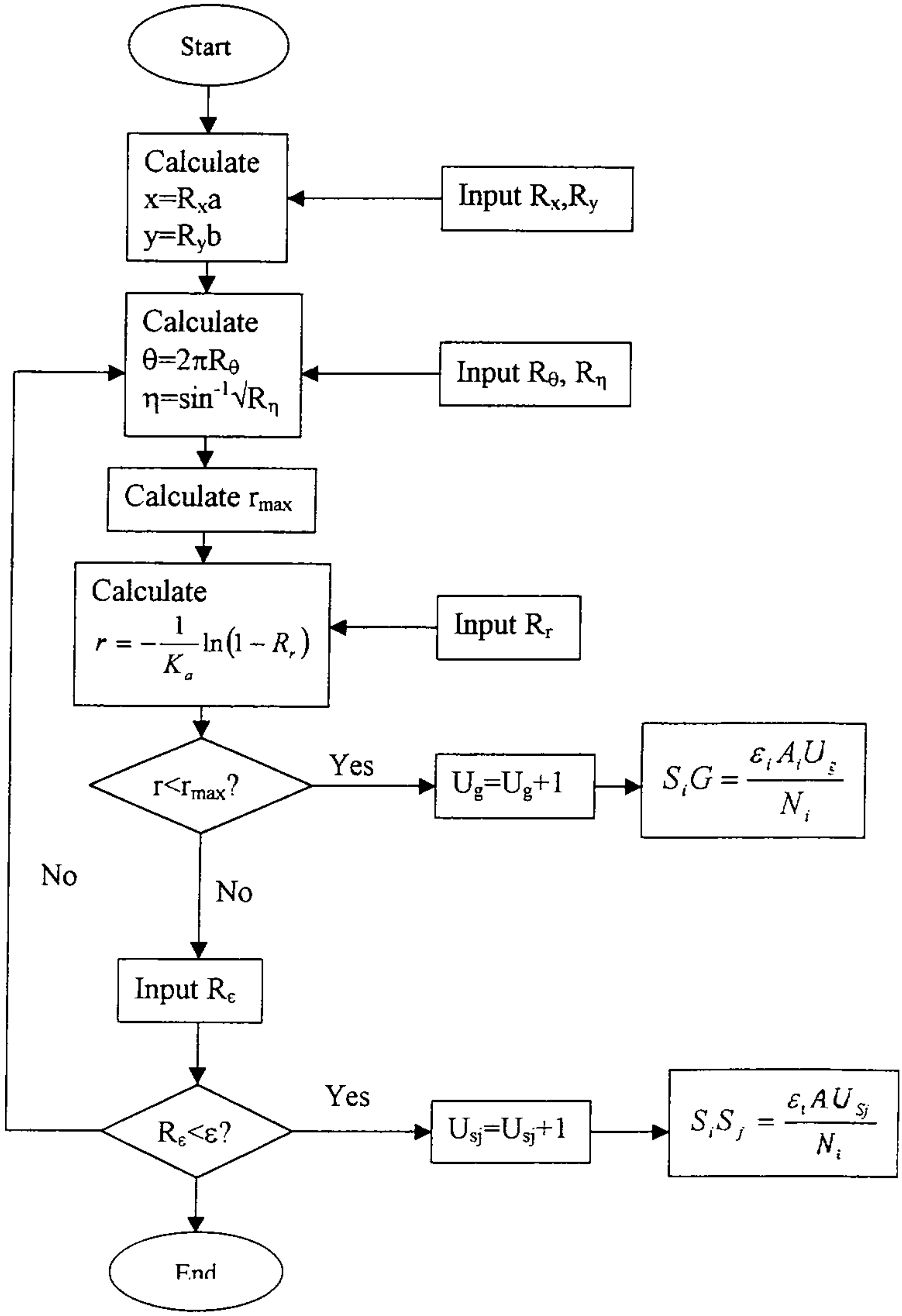


Fig. 4.6 Flow Chart Showing The Monte Carlo Method

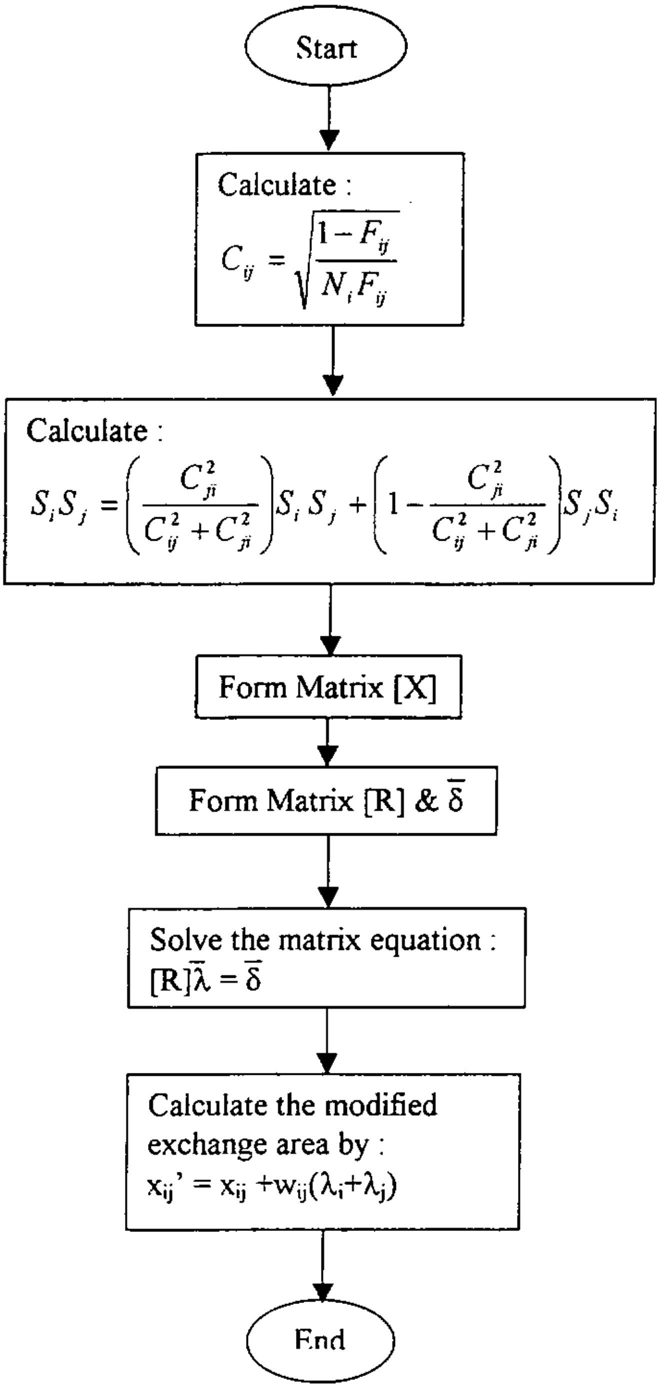


Fig. 4.7 Flow Chart Showing The Smoothing Procedure

5 Furnace Mathematical Models –

Thermal Performance Prediction

5.1 Introduction

Thermal aspect is one of the most important design criteria of a furnace to deal with the temperature and heat flux distributions in the furnace. For an oil-fired open flame furnace, the determination of the heat transfer from the hot combustion gas to the furnace wall and load, and their subsequent temperature distribution is a complicated problem because the thermal performance is affected by many parameters such as the furnace geometry, materials of construction, air/fuel supplies, combustion processes, aerodynamics, heat transfer processes and the heating period etc.

In order to optimize the thermal design and have a clear and full picture of the thermal behaviour of the furnace, a full understanding of these parameters is essentially important. In this chapter, the relevant models will be discussed and integrated together in an energy balance equation such that a complete thermal analysis of an oil-fired open flame furnace can be possible. The present mathematical models will consist of furnace model, combustion model, soot model, convection model, radiation model and conduction model.

5.2 Assumptions

Development of the present mathematical models are based on the following assumptions :

- Heat transfer calculation in the furnace is based on the Hottel's zone method, and the developed model accounts for heat transfer of emission and reflection by the walls, and emission and absorption by the gas. Convection and radiation between the combustion gas, the load and the furnace enclosure are considered
- The gas flow is one-dimensionally along the furnace length.
- The combustion process is complete in the well-stirred zone.
- The combustion gas temperature at burner exit is equal to the adiabatic flame temperature.
- The combustion gas contains carbon dioxide, water vapour and soot. Because the order of quantity of absorption coefficient of soot is around 10 and that of carbon dioxide and water vapour is in order of less than 1 that is much lower than that of soot (i.e. in multiple of 100). Therefore, it is justified to assume that the radiation due to soot is the dominant emitting and absorbing component in the combustion product. This approach has been adopted by many researchers[30,31].
- Convection heat transfer coefficient in the furnace can be calculated by the Lebedev's model[16] (i.e. equation [2.8]).
- Throughout each gas volume, the gas composition is uniform and equal to that of the combustion gas without dissociation[23].
- In each zone, the gas temperature is uniform.
- Temperatures of the combustion gas, the enclosure and the load are allowed for transient variation.

5.3 Furnace Model

Basic assumptions to simplify the complicated furnace are required before calculation of the combustion processes, heat transfer processes and temperature distributions can be proceeded. Therefore it is essential to adopt a suitable furnace model.

Basically, the furnace model can be classified into the following types[31] :

Type "0" model

This model can be used to determine the flow pattern, temperature distribution and thermal properties, which are considered to be constant with respect to position. The whole furnace may be modeled by the Hottel's well-stirred zone[8], in which the gas composition and gas temperature are assumed to be uniform throughout the furnace space.

Type "1" model

This model can be used to evaluate the flow pattern, temperature distribution and thermal properties, which are considered to vary one-dimensionally, in the axial direction of the flame. In this model, Hottel's "long furnace" concept can be applied. The whole furnace is divided into numerous zones. The first zone, where a highly turbulent mixing is taken place and complete combustion is occurred, is called the "well-stirred" zone. The hot combustion product will flow downstream through a number of "plug-flow" zones. Fig. 5.1 shows the long furnace model.

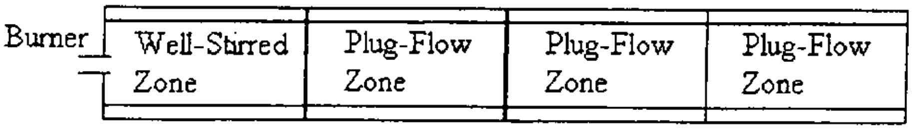


Fig.5.1 Long Furnace Model

Type “2” model

This is a more detail model. The flow pattern, temperature distribution and thermal properties under consideration are varying in two-dimension, normally applied to cylindrical furnace where the thermal properties vary in both radial and axial directions. For this kind of furnace model, system of conservation equations so obtained is very large and usually a lot of computations are required.

5.4 Combustion Model

Combustion gas is the heat source in a furnace. Combustion process is affecting by several aspects such as the fuel type, air/fuel ratio, air/fuel mixture flow rate, burner type, geometry of flame, flame luminosity, flame stability, completeness of combustion, and rate of reaction. Fuel type, air/fuel ratio and air/fuel mixture flow rate affect directly the heat input into the furnace. Burner type will govern the aerodynamic pattern at the burner exit and the subsequent flow pattern throughout the furnace. Since the velocity terms are involved in the energy equation, the furnace flow pattern will greatly affect the convection heat transfer from the combustion gas to the wall and load. Furthermore, burner design also controls the flame geometry. Since heat is transferred from flame locally and volume of the flame will affect the heat transfer at any location. For heavy oil combustion, the flame may be luminous with different absorption coefficients and emissivities depending on the type of fuel used[7], which makes the radiation model very complicated. Combustion in a furnace may be classified as premixed or diffusion, or mostly the combination of them. Such combustion classification will affect the location of combustion and amount of heat released from combustion. For premixed flame, the reaction rate is controlled and can be expressed by an Arrhenius equation. For diffusion flame, the reaction rate is controlled by the diffusion transport process. For simplicity, the reaction rate in the present study is assumed to be completed within the well-stirred zone. The flame is non-luminous and its temperature is equal to the adiabatic flame temperature. As a result, the effective temperature for analysis is assumed to be the adiabatic temperature, whereas the combustion gas volume and the gas temperature are uniform and calculated from the heat balance on a gas volume.

The adiabatic flame temperature is calculated by the total enthalpy balance of the fuel, air and combustion product. The enthalpy of the combustion can be expressed by the following equation :

$$H_{cp} = \sum_i \left(\int_{298}^{Tg} C_{p,i} dT + \Delta h_{fu,i} \right) \dot{N}_i \qquad \text{.... [5.1]}$$

The molar flow rate of the combustion product depends on the air/fuel ratio and the stoichiometry of the reaction, which can be calculated by an atomic balance of the generalized combustion equation for a hydrocarbon fuel. For the present study, C_4H_{10} is used as the fuel for analysis. The stoichiometric equation for the reaction is given by:

$$C_4H_{10} + 6.5(O_2 + 3.76N_2) \longrightarrow 4CO_2 + 5H_2O + 24.44N_2 \qquad \text{.... [5.2]}$$

In practice, the combustion is carried out with either a lean or rich air/fuel mixture. The subsequent combustion equations for these two cases are as shown below :

If AFR > 6.5, then :

$$\begin{aligned}&C_4H_{10} + AFR(O_2 + 3.76N_2) \longrightarrow \\ &4CO_2 + 5H_2O + 3.76AFR \cdot N_2 + (AFR - 6.5)O_2\end{aligned} \quad \text{.... [5.3]}$$

If AFR < 6.5, then :

$$\begin{aligned}&C_4H_{10} + AFR(O_2 + 3.76N_2) \longrightarrow \\ &\left(1 - \frac{AFR}{6.5}\right)C_4H_{10} + 4\left(\frac{AFR}{6.5}\right)CO_2 + 5\left(\frac{AFR}{6.5}\right)H_2O + 3.76AFR \cdot N_2\end{aligned} \quad \text{.... [5.4]}$$

In general, the combustion equation can be written as :

$$\begin{aligned}&C_4H_{10} + AFR(O_2 + 3.27N_2) \longrightarrow \\ &\alpha C_4H_{10} + 4\beta CO_2 + \gamma O_2 + 3.76AFR.N_2\end{aligned} \quad \text{.... [5.5]}$$

where :

If AFR = 6.5, then

$\alpha = 0$; $\beta = 1$; $\gamma = 0$ .... [5.6]

If AFR > 6.5, then

$\alpha = 0$; $\beta = 1$; $\gamma = AFR - 6.5$ .... [5.7]

If AFR < 6.5, then

$\alpha = 1 - AFR/6.5$; $\beta = AFR / 6.5$; $\gamma = 0$ .... [5.8]

Combining equations [5.1] to [5.8] and the First Law of Thermodynamics, we have the enthalpy balance equation[32,33] :

$$H_{react} = H_{prod} \qquad \text{.... [5.9]}$$

$$\sum_{react} N_i h_i = \sum_{prod} N_i h_i \qquad \text{.... [5.10]}$$

$$\sum_{react} N_i h_i = \sum_{prod} N_i \left[h^{\circ}_{fu,i} + c_{p,i} \left(T_{ad} - 298 \right) \right] \qquad \text{.... [5.11]}$$

The adiabatic temperature can be determined by equation [5.11].

5.5 Soot Model

Soot contributes a significant portion of the combustion product especially when heavy fuel is burnt. Its importance is due to the radiation emitted from soot is very high, which can be comparable with convection in a furnace.

Radiation heat transfer in a combustor is mainly due to the soot particles, which may be formed during the combustion process. Radiation is also emitted from many intermediate species, carbon dioxide and water molecules, but since their concentration is low and hence their effect is less important. Unlike soot, whose radiation is broad banded and that from gaseous species is comparably narrow. Therefore, the magnitude of radiation from gaseous species is substantially smaller than that produced by soot particles.

As mention in Section 5.4, there are two different kinds of combustion processes, i.e. the premixed and diffusion combustions. In premixed flame, the soot is almost free from combustion. In that case, the radiation is much lower when compared with convection. However, in the real application, the combustion will be taken place by diffusion or the combination of premixed and diffusion. In this circumstance, the radiation heat transfer can be of the same order of the magnitude as the convection heat transfer.

5.5.1 Absorption Coefficient

In order to understand the radiation produced by soot, its absorption coefficient must be investigated. Radiation from soot depends on its spatial distribution, particle size and their reflective indices[29]. For the soot of small size as encountered in the oil combustion, an approximation known as the Rayleigh limit applies. From Mie theory developed by Van de Hulst[29], the absorption coefficient can be written as :

$$K_{a_\lambda} = \frac{36\pi f_v}{\lambda} \frac{nk}{\left(n^2 - k^2 + 2\right)^2 + (2nk)^2} = \frac{f_v}{\lambda} g(n,k) \qquad \text{.... [5.12]}$$

Where f_v is the volume fraction of soot in the gas and n and k are the refraction and absorption index respectively, both of which are the functions of fuel used and wavelength.

A close approximation to the equation [5.12] can be described as[34] :

$$K_a = 3.6 f_v gT \; / \; C \qquad \text{.... [5.13]}$$

Where the value of g depends on the hydrocarbon fuel used. Experimental data[33] shows that g = 6.3 for oil flame.

From equation [5.13], it shows that in order to calculate the absorption coefficient of soot particles, the value of the volume fraction or so-called the soot concentration is needed. The concentration can be obtained from the soot concentration model which tracks the instantaneous rates of soot formation and oxidation.

5.5.2 Soot Concentration Model

Indeed, soot formation depends on the oil diffusion combustion process and it occurs from combustion in oxygen poor regions surrounding the fuel droplets. The physical processes involved are very complicated, as they depend on :

- Chemistry of precursor reaction
- Coagulation and particle growth processes
- Carbon oxidation chemistry

Which in turn, depend on :

- Fuel composition
- Pressure
- Temperature
- Local fuel and oxygen concentrations

In the soot concentration model, the time development of soot mass is described as a process taking place in two regions :

1. An active burning region
2. A fully burned region

The amount of fuel burnt in any finite time increment is assumed to produce soot, which immediately begins to burn up. Since the mass from the actively burning zone is continuously entrained into the fully burnt zone, the soot formed in the actively burning zone is entrained as well. The actively burning zone is assumed to be a very thin layer separating the burned and unburned zones and therefore it does not require a thermodynamic zone.

The soot formation rate can be described as[29] :

$$\frac{dS_F}{dt} = A_2\, m_d \exp(-A_3 / T) \qquad \text{.... [5.14]}$$

Equation [5.14] represents the soot formation rate in actively burning zone in diffusion combustion. Where A_2 and A_3 are equal to 0.38 and 5000 respectively[35] and m_d is the fuel burning rate.

The subsequent burn up rate in the burnt zone can be expressed as[29] :

$$\frac{dS_C}{dt} = -B_1 \frac{S_{net}}{\rho_s d_s} \exp\left(\frac{-B_2}{T}\right) P_{O_2}^{0.5} \qquad \text{.... [5.15]}$$

In equation [5.15], P_{O2} represents the partial pressure of oxygen in the burnt zone. ρ_s is the soot density which is taking as 900 kg/m^3 and d_s is the soot particle diameter ranging from 0.012 to 0.032 μm. The constants B_1 and B_2 are equal to 0.015 and 5000 respectively[36].

As a result, the net soot production rate is given by :

$$\frac{dS_{net}}{dt} = \frac{dS_F}{dt} + \frac{dS_C}{dt} \qquad \text{.... [5.16]}$$

After the net production rate of soot becomes steady, its derivative of time will approach zero, i.e.

$$\frac{dS_{net}}{dt} = 0 \qquad \text{.... [5.17]}$$

Using combining equations [5.14] to [5.17], the amount of soot at complete combustion can be calculated.

In equation [5.13], the emissivity produced by soot can be described as :

$$\varepsilon_s = 1 - \exp(-3.6 f_v gTL / C_2) \qquad \text{.... [5.18]}$$

Where f_v can be expressed as :

$$f_v = \frac{S_{net}}{\rho_s \times Volume \cdot of \cdot Furnace} \qquad \text{.... [5.19]}$$

5.6 Radiation Model

Integrating the combustion model and the soot model, the absorption coefficient of a particular gas zone at a particular gas temperature can be determined. After the absorption coefficient has been known, all the total exchange areas within the enclosure can be calculated by the smoothing Monte Carlo method suggested in Section 4. Once the total exchange areas have been obtained, the radiation heat transfer between the surface zones and gaseous zones can be evaluated.

Consider a furnace consisting of N_s surface zones and N_g gaseous zones, the radiation heat transfer from a gaseous zone "i" to the other gaseous zones and the surface zones can be described as follows :

$$\dot{Q}_{r,i} = \sigma \left(\sum_{j=1}^{N_s} G_i S_j + \sum_{j=1}^{N_g} G_i G_j \right) T_i^4 \qquad \text{.... [5.20]}$$

And for a surface zone 'i', the radiation heat transfer from it to other surface zones and gaseous zones can be described as :

$$\dot{Q}_{r,i} = \sigma\left(\sum_{j=1}^{N_s} S_i S_j + \sum_{j=1}^{N_g} S_i G_j\right) T_i^4 \qquad \ldots . [5.21]$$

5.7 Convection Model

For convection heat transfer in a furnace, there are two mechanisms involved. One is the forced convection heat transfer from the hot combustion gas to the internal furnace wall and another is the natural convection heat transfer from the external furnace wall to the surrounding.

5.7.1 Forced Convection

In solving the convection heat transfer problems, analytical and experimental approaches are both commonly used. In the analytical approach, the mass, momentum, energy and combustion equations are required to solve. Since the velocity functions are involved in the energy equation and the reacting flow is affecting the rate of energy released in the combustion region, these four equations must be solved simultaneously with appropriate boundary conditions, normally by numerical method. Even this method provides an accurate solution at a local position in the furnace, it relies on a lot of complicated computation.

Another possible solution of convection problems is by empirical equations coupling with experimental technique. These methods provide a more convenient solution but are subject to the availability in the literature. In the present study, Lebedev's[16] work has been employed to determine the convection heat transfer coefficient in the furnace as shown in equation [2.8]. i.e.

$$Nu = A_1 Re^{0.75} \qquad \text{.... [5.22]}$$

Where A_1 is equal to

0.175 for both end of the furnace

0.283 for roof of the furnace

0.142 for side walls of the furnace

0.185 for the entire furnace

After the heat transfer coefficient has been determined, the convection heat transfer rate from the gaseous zone 'i' to a surface zone 'j' can be calculated by the Newton's Law of Cooling :

$$\dot{Q}_{f,ij} = h_{F,i} A_j \left(T_i - T_j\right) \qquad \text{.... [5.23]}$$

5.7.2 Natural Convection

Natural convection takes place between the external furnace wall to the surrounding. It can be divided into three components :

1. Vertical wall of the furnace ;
2. Horizontal plane with heated plate facing upward, i.e. the top wall of the furnace ;
3. Horizontal plane with heated plate facing downward, i.e. the bottom wall of the furnace (this component can be neglected if the furnace is built on an adiabatic foundation).

Convection heat transfer coefficients for these three components to air at atmospheric pressure and moderate temperature can be calculated by the following dimensional equations[37] :

Vertical wall :

$$h_N = 1.42\left(\frac{\Delta T}{L}\right)^{\frac{1}{4}} \qquad \text{.... [5.24]}$$

Horizontal wall with heated plate facing upward :

$$h_N = 1.32\left(\frac{\Delta T}{L}\right)^{\frac{1}{4}} \qquad \text{.... [5.25]}$$

Horizontal wall with heated plate facing downward :

$$h_N = 0.59\left(\frac{\Delta T}{L}\right)^{\frac{1}{4}} \qquad \text{.... [5.26]}$$

Equations [5.24] to [5.26] are valid when :

$$10^4 < GrPr < 10^9 \qquad \text{.... [5.27]}$$

As a result, the convection heat transfer rate from the external furnace wall 'i' to the surrounding can be determined by :

$$\dot{Q}_{\infty,i} = h_{N,i} A_i \left(T_{w,i} - T_\infty\right) \qquad \text{.... [5.28]}$$

5.8 Conduction Model

Assuming transient, one-dimensional heat conduction in the furnace wall and the load, the energy equation can be written as :

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial n}\left(k \frac{\partial T}{\partial n} \right) \qquad \text{.... [5.29]}$$

Where n is a coordinate measured normal to each furnace wall or load.

Heat balance at the internal furnace wall 'i', which is exposed to the combustion gas, is given as :

$$- k_i A_i \frac{\partial T_i}{\partial n} = A_i h_i \left(T_g - T_{s,i}\right) + \sum_{j=1}^{N_g} \sigma \left(G_j S_i T_{g,j}^4 - S_i G_j T_{s,i}^4\right)$$
$$+ \sum_{j=1}^{N_s} \sigma \left(S_j S_i T_{s,j}^4 - S_i S_j T_{s,i}^4\right) \qquad \text{.... [5.30]}$$

Heat balance at the external wall which is in contact with the surrounding is given by :

$$- k_i \frac{\partial T_i}{\partial n} = h_{N,i} \left(T_i - T_\infty\right) \qquad \text{.... [5.31]}$$

5.9 Energy Balance Equation

By integrating the furnace model, combustion model, soot model, radiation model, convection model and conduction model, an energy balance equation applied to a particular gaseous zone 'i' can be written as follows :

$$H_{fu,i} + H_{a,i} + H_{cp,i-1} - H_{cp,i} - \sum_{k=1}^{L}\left[A_k h_k \left(T_{g,i} - T_{s,k}\right)\right]$$
$$- \sum_{j=1}^{N_g} \sigma \left(G_i G_j T_i^4 - G_j G_i T_j^4\right) - \sum_{j=1}^{N_s} \sigma \cdot \left(G_i S_j T_{g,i}^4 - S_j G_i T_{s,j}^4\right) = Q_{acc} \qquad \text{.... [5.32]}$$

Where L represents the number of surface zones adjacent to the gaseous zone 'i' as illustrated in Fig. 5.2 :

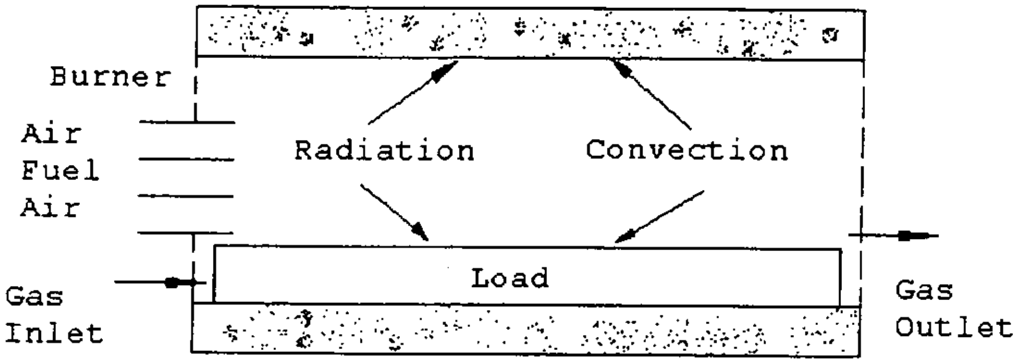


Fig. 5.2 Energy Transfer In Gaseous Zone

In the above equation [5.32] :

a) First term represents heat of the fuel entering into the zone, which will be zero for the plug flow zone because combustion is complete in the well-stirred zone.

b) Second term represents heat of the air entering into the zone, which will be zero for the plug flow zone because only combustion gas can enter this zone.

The first two terms can be calculated by equation [5.1]

c) Third term represents heat of the combustion gas entering into the zone from the previous zone, which will be zero for the well-stirred zone.

d) Fourth term represents heat of the combustion gas leaving the zone.

Third and forth terms can be calculated by :

$$H = \dot{m} C_{p,g} T \qquad \text{.... [5.33]}$$

e) Fifth term represents convection heat transfer from the combustion gas to the load and the enclosure.

f) Sixth term represents radiation heat transfer between the gaseous zones.

g) Seventh term represents radiation heat transfer between the combustion gas and the load and enclosure.

h) Eighth term represents heat absorbed by the furnace gas during the transient operation which can be expressed as :

$$Q_{acc} = \rho C_{p,g} \frac{LWH}{No.of.Zone} \frac{T_{g,i}^{k+1} - T_{g,i}^{k}}{\Delta t} \qquad \text{.... [5.34]}$$

5.10 Characteristics of the Developed Thermal Model

- Apply the smoothing Monte Carlo method to solve the radiation. The method is originally used in the cylinder of a diesel engine, which is much smaller in size and containing only very few zones. The method can provide better accuracy in prediction by complying with both the First and Second Laws of Thermodynamics.
- Integrate several models in an energy balance equation and apply to calculate the thermal performance of a furnace. All models are presented in numerical form, which enables the analysis to be performed computationally.
- The developed thermal model is able to predict the temperature and heat flux distributions of the furnace under both steady-state and transient operation, the later is particularly important during the start-up period which can be several minutes for large furnace.

6. Numerical Prediction

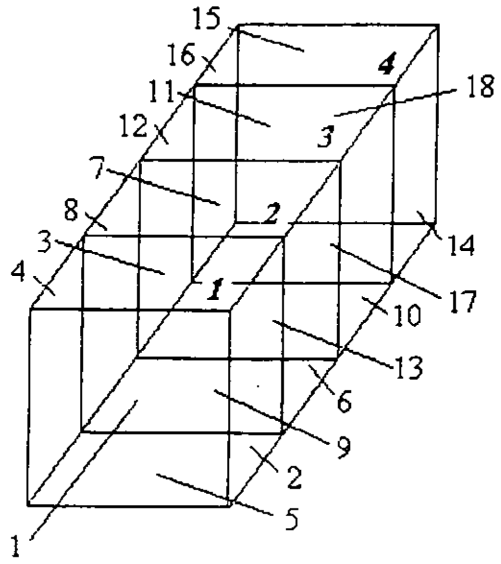
6.1 Introduction

The mathematical models for the prediction of the temperature distribution and the heat transfer rate within an oil-fired open flame furnace have been developed in the last section. In this section, the computational method of each of the mathematical models will be discussed and the parameters of an industrial oil-fired furnace are used as the inputs to test the practicability of the computer program. In this example, C_4H_{10} is used as the fuel for the prediction.

The predicted solution will be calculated by a computer program written in Microsoft Visual Basic, which is attached in Section 14.

6.2 Furnace Model

The Hottel's long furnace model will be adopted as the foundation. The whole furnace is divided into 18 surface zones and 4 gas zones as shown in Fig. 6.1



Note : The gas zones are indicated by bold letters

Fig.6.1 Zone Configuration in furnace

6.3 Adiabatic Flame Temperature

The adiabatic flame temperature can be calculated by equation [5.11]. The specific heat of each substance Cp(T) is the function of temperature and they can be expressed as follows[33] :

$$Cp_{C4H10} = 3.954 + 37.12\theta - 1.833\theta^2 + 0.03498\theta^3 \quad \text{.... [6.1]}$$

$$Cp_{O2} = 37.432 + 0.020102\,\theta^{1.5} - 178.57\theta^{-1.5} + 236.88\theta^{-2} \quad \text{.... [6.2]}$$

$$Cp_{N2} = 39.060 - 512.79\theta^{-1.5} + 1072.7\theta^{-2} - 820.40\theta^{-3} \quad \text{... [6.3]}$$

$$Cp_{CO2} = -3.7357 + 30.529\theta^{0.5} - 4.1034\theta + 0.024198\theta^2 \quad \text{.... [6.4]}$$

$$Cp_{H2O} = 143.05 - 183.54\theta^{0.25} + 82.751\theta^{0.5} - 3.6989\theta \quad \text{.... [6.5]}$$

Where :

$$\theta = \text{Temperature(Kelvin)} / 100 \quad \text{.... [6.6]}$$

Temperature of the combustion product is exactly equal to the adiabatic flame temperature, which is required to solve. As iterative scheme is implemented with an initial guess of $T_{ad}^{(0)} = 1000$ K.

The iterative equation to determine the adiabatic flame temperature becomes :

$$T_{ad}^{(k+1)} = \frac{\sum\limits_{react} N_i h_i - \sum\limits_{prod} N_i h^{\circ}_{f,i}}{\sum\limits_{prod} N_i c_{p,i}(T^{(k)})} + 298 \quad \text{.... [6.7]}$$

6.4 Soot Absorption Coefficient

Determination of the absorption coefficient of soot has been described in Section 5.5. As mentioned in this section, the absorption coefficient of soot depends on the soot volume fraction, temperature and type of fuel used. Soot mass can be calculated in term of volume fraction by combining equations [5.14] to [5.17].

6.5 Radiation Heat Transfer

By applying the conventional Monte Carlo method, the exchange areas of various zones, i.e. S_1S_1, S_1S_2, ... , S_1S_{Ns}, S_1G_1, ... , S_1G_{Ng}, can be calculated as shown in the following section :

Fig. 6.2 shows the co-ordinate system of a furnace with length (L), width (W) and height (H). Suppose a photon is emitting from the location (0,y,z) with an emitting angle of (θ,η), the zone and the point where the photon will arrive at can be determined by the circumferential angle θ and η under the following conditions :

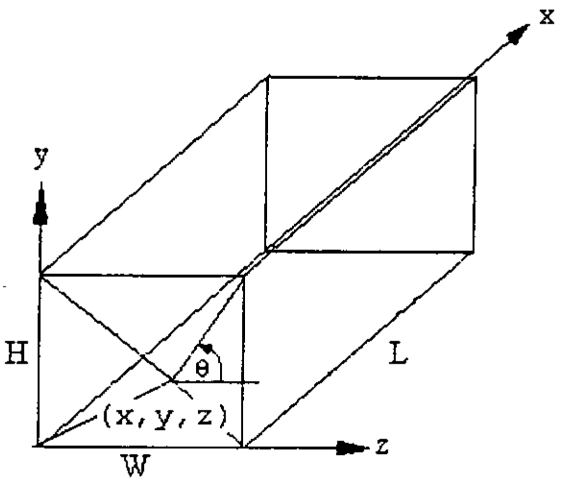


Fig. 6.2 Furnace Co-ordinate System

When :

$$2\pi - \tan^{-1}\frac{y}{W-z} < \theta < \tan^{-1}\frac{H-y}{W-z} \quad \ldots [6.8]$$

Then the photon will reach zones 2, 6, 10 or 14 at the point (x',y',z'), where :

(Note that the numbering of each zone can be referred to Fig. 6.1)

$$x' = \left|\frac{W-z}{cas\theta\tan\eta}\right| \qquad \text{.... [6.9]}$$

$$y' = y + (W-z)\tan\theta \qquad \text{.... [6.10]}$$

$$z' = W \qquad \text{.... [6.11]}$$

When

$$\tan^{-1}\frac{H-y}{W-z} < \theta < \pi + \tan^{-1}\frac{z}{H-y} \qquad \text{.... [6.12]}$$

Then the photon will reach zones 3, 7, 11 or 15 at the point

$$x' = \left|\frac{H-y}{\sin\theta\tan\eta}\right| \qquad \text{.... [6.13]}$$

$$y' = H \qquad \text{.... [6.14]}$$

$$z' = z + \frac{H-y}{\tan\theta} \qquad \text{.... [6.15]}$$

When :

$$\pi + \tan^{-1}\frac{z}{H-y} < \theta < 2\pi + \tan^{-1}\frac{y}{z} \qquad \text{.... [6.16]}$$

Then the photon will reach zones 4, 8, 12 or 16 at the point :

$$x' = \left|\frac{z}{\cos\theta\tan\eta}\right| \qquad \text{.... [6.17]}$$

$$y' = y - z\tan\theta \qquad \text{.... [6.18]}$$

$$z' = 0 \qquad \text{.... [6.19]}$$

When :

$$\pi + \tan^{-1}\frac{y}{z} < \theta < 2\pi - \tan^{-1}\frac{y}{W-z} \qquad \text{.... [6.20]}$$

Then the photon will reach 5, 9, 13 or 17 at the point :

$$x' = \left|\frac{y}{\sin\theta\tan\eta}\right| \qquad \text{.... [6.21]}$$

$$y' = 0 \qquad \text{.... [6.22]}$$

$$z' = z - \frac{y}{\tan\theta} \qquad \text{.... [6.23]}$$

In any case mentioned before, the photon will reach zone 18 when x'>L and the intersection point will be :

$$x' = L \qquad \text{.... [6.24]}$$

$$y' = y + L\tan\eta\sin\theta \qquad \text{.... [6.25]}$$

$$z' = z + L\tan\eta\cos\theta \qquad \text{.... [6.26]}$$

Similarly, this approach can be applied to all other zones. With the aid of these data, we can determine the maximum distance that the photon has traveled in each gas zone by using the following method.

Fig. 6.3 shows a photon which is emitting from the location (x,y,z) with an emitting angle of (θ,η) and the interface between zones, i.e. A. The intersection between the photon path and the plane A is given by :

x' = L/4, L/2 or 3L/4 .... [6.27]

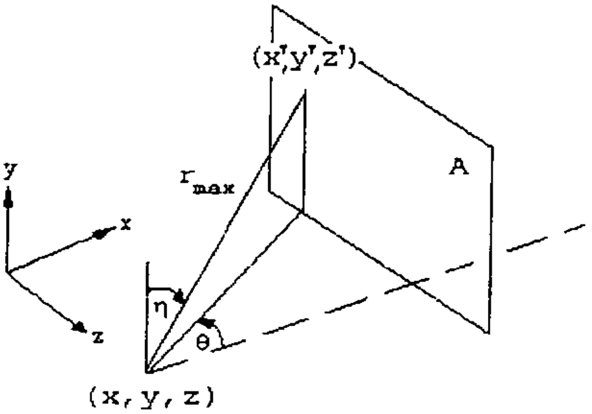


Fig. 6.3 Maximum Distance for A Photon to Travel in Gas Zone

The other values can also be obtained depends on the exact interface between zones

$$y' = y + \frac{x' - x}{\cos\theta \tan\eta} \quad \text{.... [6.28]}$$

$$z' = z - (x' - x)\tan\theta \quad \text{.... [6.29]}$$

$$r_{max} = \frac{x' - x}{\cos\theta \sin\eta} \quad \text{.... [6.30]}$$

After substituting the absorption coefficient corresponding to the temperature in that particular zone, the expected distance traveled by a photon can be evaluated and compared with r_{max} to determine whether the photon is absorbed by the gas or not. If the photon has not been absorbed by this gas zone, then the same procedure will be repeated in the next gas zone.

Following the procedures as shown in the flowchart on Fig. 4.6, we can evaluate the total exchange areas by using the conventional Monte Carlo method. In the present study, 5000 photons have been used. In the flowchart as shown in Fig. 4.7, we can modify the total exchange areas by using the smoothing technique to comply with both the conservation and reciprocity constraints. The possible methods in solving the matrix equation [4.59] are Gauss elimination, Gauss-Seidel iterative scheme and method of residual. In the present study, the Gauss-Seidel iterative scheme is employed because it is easier in programming. The initial input of the scheme is $\lambda_i^{(0)}=1$.

As a result, the net radiation transfer from a surface zone or gas zone can be expressed as :

$$\dot{Q}_{s,i} = \sigma\left\{\sum_{j=1}^{N_s}\left(S_iS_jT_{s,i}^4 - S_jS_iT_{s,j}^4\right) + \sum_{j=1}^{N_g}\left(S_iG_jT_{s,i}^4 - G_jS_iT_{g,j}^4\right)\right\} \qquad \ldots [6.31]$$

$$\dot{Q}_{g,i} = \sigma\left\{\sum_{j=1}^{N_s}\left(G_iS_jT_{g,i}^4 - S_jG_iT_{s,j}^4\right) + \sum_{j=1}^{N_g}\left(G_iG_jT_{g,i}^4 - G_jG_iT_{g,j}^4\right)\right\} \qquad \ldots [6.32]$$

6.6 Convection Heat Transfer

In convection model, Lebedev's model has been employed to determine the convection heat transfer coefficient, i.e. equation [5.22]. In this equation, Nusselt Number and Reynolds Number are temperature dependent. A thermal property table has been facilitated in form of a database in the program with interpolation feature. Therefore, each time when the convection is calculated, the convective heat transfer coefficient can be determined more conveniently.

6.7 Conduction Heat Transfer

Finite difference method is commonly used in solving the transient conduction problems. For finite difference method, explicit scheme, implicit scheme or explicit-implicit scheme are the possible methods. In order to calculate the conduction heat transfer in the furnace enclosure and load, equation [5.29] can be employed and solved numerically by using the finite difference method. The explicit scheme is chosen because it can be programmed easily and less memory is used. The parameters with initial-boundary conditions are as shown belows :

Grid size $\Delta x = t/2$ .... [6.33]

Time step Δt = Length of each zone / velocity .... [6.34]

where velocity :

$$v = \frac{m_d}{MW_{C_4H_{10}} HW} (\alpha MW_{C_4H_{10}} + 4\beta MW_{CO_2} + 5\beta MW_{H_2O} + \gamma MW_{O_2} + 3.76 AFR MW_{N_2}) \qquad \text{.... [6.35]}$$

Initial conditions :

$$T_{s,i}^{(0)} = T_{g,i}^{(0)} = T_{w,i}^{(0)} = T_\infty \qquad \text{.... [6.36]}$$

Boundary conditions :

$$-k_i A_i \frac{T_{w,2}^{(k)} - T_{w,1}^{(k)}}{\Delta x} = A_i h_i \left(T_g^{(k)} - T_{s,i}^{(k)}\right) + \sum_{j=1}^{N_g} \sigma \left(G_j S_i T_{g,j}^{(k)^4} - S_i G_j T_{s,i}^{(k)^4}\right) + \sum_{j=1}^{N_s} \sigma \left(S_j S_i T_{s,j}^{(k)^4} - S_i S_j T_{s,i}^{(k)^4}\right) \qquad \text{.... [6.37]}$$

6.8 Energy Balance Equation

The explicit numerical scheme is employed in solving the transient temperature response by using the energy balance equation [5.32] and the accumulated energy term can be written as :

$$Q_{acc,i}^{(k)} = \rho V C_{p,i}(T) \frac{T_i^{(k+1)} - T_i^{(k)}}{\Delta t} \qquad \text{.... [6.38]}$$

Where $C_{p,i}(T)$ is the specific heat capacity in the gas zone 'i', and T and V are the temperature and volume of the gas zone.

6.9 Predicted Results

6.9.1 Hardware Specification

The specification of the computer platform used for simulation is described as follows :

CPU : Pentium III 650 MHz

Memory : 128 MB SDRAM (PC100)

Hard Disk Capacity : 10 GB Ultra DMA

6.9.2 Programme Input Information

The transient temperatures predicted by the mathematical models and the numerical method as discussed in Chapter 5 and 6 respectively have been computed by a computer programme written in Visual Basic, which is attached in Chapter 14. The whole furnace is divided into 18 surface zones and 4 gas zones as shown in Fig. 6.1. The parameters of an industrial oil-fired furnace are used as the inputs to test the practicability of the developed computer programme :

Length = 8000 mm

Width = 2000 mm

Height = 2000 mm

Thickness of enclosure = 50 mm

Material of the enclosure = Mild steel

The thickness of the load is negligible

Fuel used = C_4H_{10}

Fuel consumption rate = 0.05 kg/s

Molar air/fuel ratio = 7

Pre-heat temperature = 25 °C

Room temperature = 25 °C

The furnace has an insulated foundation

The furnace is heating up from room temperature

In this particular case, the following information has been obtained from the programme :

1. Time step = 1.5 sec
2. Adiabatic flame temperature = 2137.87 K
3. Velocity of combustion product = 1.33 m/s
4. Soot mass formed in the combustion product = 2.12×10^{-4} kg
5. Volume fraction of soot = 7.37×10^{-9}
6. The Reynolds Number is ranging from 6442 to 171103 for different gas temperatures

6.9.3 Predicted total exchange areas

In particular, take the steady state as an example, the total exchange areas predicted by conventional Monte Carlo method and smoothing Monte Carlo method are shown in Table 6.1 and 6.2 in the following page respectively.

As notice that for the total exchange areas predicted by smoothing Monte Carlo method, it yields a more symmetrical matrix which fulfills the Second Law of Thermodynamics.

Table 6.1 Total Exchange Areas Predicted by Conventional Monte Carlo Method

i	SiS1	SiS2	SiS3	SiS4	SiS5	SiS6	SiS7	SiS8	SiS9	SiS10	SiS11
1	8.10E-02	1.13E-01	1.18E-01	1.17E-01	1.22E-01	3.66E-02	4.10E-02	3.94E-02	3.66E-02	1.68E-02	1.64E-02
2	1.14E-01	8.28E-02	1.16E-01	1.08E-01	1.15E-01	3.88E-02	4.96E-02	6.00E-02	4.88E-02	1.82E-02	1.62E-02
3	1.17E-01	1.13E-01	7.56E-02	1.10E-01	1.10E-01	4.86E-02	3.72E-02	5.38E-02	5.88E-02	1.90E-02	1.84E-02
4	1.20E-01	1.05E-01	1.15E-01	8.62E-02	1.21E-01	5.92E-02	4.38E-02	3.84E-02	4.52E-02	1.58E-02	2.02E-02
5	1.10E-01	1.15E-01	1.13E-01	1.19E-01	7.64E-02	5.10E-02	5.56E-02	4.66E-02	4.14E-02	1.46E-02	2.00E-02
6	4.44E-02	3.98E-02	5.18E-02	5.68E-02	4.82E-02	6.58E-02	1.08E-01	1.03E-01	1.05E-01	2.90E-02	4.38E-02
7	4.32E-02	4.74E-02	4.30E-02	4.98E-02	6.30E-02	9.78E-02	5.80E-02	1.06E-01	9.18E-02	4.34E-02	3.28E-02
8	4.70E-02	6.00E-02	4.64E-02	4.06E-02	5.46E-02	9.22E-02	1.00E-01	6.18E-02	1.00E-01	4.68E-02	4.18E-02
9	4.48E-02	5.28E-02	6.14E-02	5.44E-02	3.50E-02	9.62E-02	1.01E-01	9.84E-02	5.92E-02	3.80E-02	4.98E-02
10	2.42E-02	1.68E-02	2.50E-02	1.68E-02	1.66E-02	3.64E-02	4.54E-02	5.28E-02	4.60E-02	6.28E-02	9.86E-02
11	2.14E-02	1.94E-02	1.70E-02	1.86E-02	1.72E-02	3.70E-02	3.84E-02	4.94E-02	5.34E-02	1.03E-01	6.74E-02
12	1.78E-02	1.98E-02	2.18E-02	1.76E-02	1.72E-02	5.44E-02	4.28E-02	3.54E-02	4.50E-02	9.98E-02	9.64E-02
13	2.24E-02	1.84E-02	1.76E-02	1.80E-02	1.88E-02	4.28E-02	5.60E-02	4.62E-02	4.22E-02	8.82E-02	9.80E-02
14	1.24E-02	1.00E-02	1.20E-02	7.00E-03	9.80E-03	1.64E-02	1.80E-02	2.12E-02	1.68E-02	3.96E-02	4.82E-02
15	1.18E-02	9.60E-03	8.40E-03	1.02E-02	1.06E-02	2.00E-02	1.84E-02	1.84E-02	2.10E-02	4.60E-02	4.24E-02
16	1.28E-02	9.60E-03	8.60E-03	1.14E-02	8.80E-03	2.00E-02	1.92E-02	1.72E-02	1.96E-02	5.78E-02	4.64E-02
17	1.14E-02	1.10E-02	1.08E-02	1.04E-02	7.40E-03	1.88E-02	1.90E-02	2.10E-02	1.66E-02	4.56E-02	6.24E-02
18	1.56E-02	1.10E-02	1.16E-02	1.06E-02	1.42E-02	1.86E-02	2.04E-02	2.14E-02	1.88E-02	4.52E-02	4.08E-02
	GiS1	GiS2	GiS3	GiS4	GiS5	GiS6	GiS7	GiS8	GiS9	GiS10	GiS11
1	9.40E-02	9.30E-02	1.28E-01	8.98E-02	5.29E-02	3.53E-02	3.80E-02	3.18E-02	3.05E-02	1.34E-02	1.22E-02
2	2.17E-02	2.22E-02	2.33E-02	2.38E-02	1.88E-02	4.04E-02	5.76E-02	4.21E-02	2.71E-02	1.84E-02	2.18E-02
3	7.85E-03	6.52E-03	4.99E-03	5.52E-03	5.85E-03	1.44E-02	1.74E-02	1.38E-02	1.24E-02	2.95E-02	4.38E-02
4	3.04E-03	3.36E-03	3.68E-03	2.67E-03	2.24E-03	4.16E-03	4.74E-03	4.00E-03	4.10E-03	1.28E-02	1.46E-02

i	SiS12	SiS13	SiS14	SiS15	SiS16	SiS17	SiS18	SiG1	SiG2	SiG3	SiG4
1	2.14E-02	1.82E-02	1.18E-02	1.28E-02	1.20E-02	9.00E-03	1.20E-02	7.10E-02	4.84E-02	3.96E-02	6.40E-03
2	1.52E-02	1.84E-02	9.60E-03	7.40E-03	7.00E-03	7.60E-03	1.06E-02	6.84E-02	4.16E-02	3.60E-02	1.00E-02
3	1.42E-02	1.96E-02	7.80E-03	8.80E-03	8.00E-03	7.60E-03	9.20E-03	6.94E-02	4.94E-02	3.14E-02	1.32E-02
4	1.44E-02	1.70E-02	8.60E-03	1.12E-02	1.04E-02	8.00E-03	1.10E-02	6.18E-02	4.60E-02	3.56E-02	7.00E-03
5	1.92E-02	1.40E-02	6.80E-03	4.40E-03	9.00E-03	1.14E-02	1.08E-02	6.80E-02	4.34E-02	4.08E-02	9.60E-03
6	4.96E-02	4.22E-02	1.30E-02	1.64E-02	1.70E-02	1.72E-02	1.82E-02	7.56E-02	1.64E-02	2.82E-02	1.08E-02
7	4.80E-02	5.12E-02	1.98E-02	1.72E-02	1.58E-02	1.82E-02	1.92E-02	7.80E-02	1.92E-02	2.56E-02	1.16E-02
8	3.14E-02	4.50E-02	2.16E-02	1.94E-02	1.88E-02	1.36E-02	1.70E-02	8.22E-02	2.02E-02	2.90E-02	1.06E-02
9	4.20E-02	3.82E-02	1.70E-02	1.82E-02	1.76E-02	1.76E-02	1.78E-02	7.58E-02	2.16E-02	3.14E-02	1.14E-02
10	8.92E-02	1.01E-01	3.68E-02	4.30E-02	5.12E-02	5.34E-02	3.90E-02	9.64E-02	2.38E-02	1.36E-02	1.12E-02
11	9.22E-02	8.60E-02	4.54E-02	4.06E-02	5.50E-02	5.86E-02	4.12E-02	9.10E-02	2.64E-02	1.36E-02	8.00E-03
12	6.84E-02	9.44E-02	5.76E-02	4.70E-02	4.34E-02	4.54E-02	4.06E-02	8.28E-02	3.04E-02	1.34E-02	8.60E-03
13	1.05E-01	5.84E-02	4.64E-02	6.02E-02	4.90E-02	3.68E-02	3.82E-02	8.50E-02	3.00E-02	1.24E-02	9.80E-03
14	5.48E-02	4.98E-02	8.02E-02	1.12E-01	1.06E-01	1.23E-01	1.02E-01	9.84E-02	4.10E-02	1.74E-02	4.20E-03
15	4.76E-02	5.22E-02	1.18E-01	8.56E-02	1.18E-01	1.08E-01	1.07E-01	8.86E-02	4.16E-02	1.34E-02	2.40E-03
16	3.68E-02	4.94E-02	1.05E-01	1.09E-01	8.52E-02	1.15E-01	1.09E-01	9.60E-02	4.32E-02	1.86E-02	1.80E-03
17	4.54E-02	3.80E-02	1.13E-01	1.03E-01	1.10E-01	8.30E-02	1.13E-01	9.52E-02	4.16E-02	1.86E-02	4.80E-03
18	4.42E-02	4.30E-02	1.10E-01	1.14E-01	1.20E-01	1.15E-01	8.92E-02	7.40E-02	4.10E-02	1.78E-02	3.20E-03
	GiS12	GiS13	GiS14	GiS15	GiS16	GiS17	GiS18	GiG1	GiG2	GiG3	GiG4
1	1.22E-02	1.62E-02	6.99E-03	7.95E-03	6.36E-03	6.36E-03	9.70E-03	4.61E-02	3.83E-02	2.59E-02	0.00E+00
2	1.67E-02	1.51E-02	6.60E-03	7.84E-03	7.66E-03	7.92E-03	6.96E-03	3.35E-02	7.04E-03	1.37E-02	0.00E+00
3	3.05E-02	1.93E-02	1.36E-02	1.79E-02	1.64E-02	1.27E-02	1.44E-02	3.34E-02	9.11E-03	3.39E-03	0.00E+00
4	1.28E-02	1.02E-02	2.89E-02	3.95E-02	2.91E-02	1.83E-02	2.79E-02	2.66E-02	9.97E-03	3.78E-03	0.00E+00

Table 6.2 Total Exchange Areas Predicted by Smoothing Monte Carlo Method

i	SiS1	SiS2	SiS3	SiS4	SiS5	SiS6	SiS7	SiS8	SiS9	SiS10	SiS11
1	8.10E-02	1.14E-01	1.18E-01	1.18E-01	1.16E-01	4.09E-02	4.22E-02	4.35E-02	4.11E-02	2.07E-02	1.90E-02
2	1.14E-01	8.28E-02	1.15E-01	1.07E-01	1.15E-01	3.93E-02	4.85E-02	6.00E-02	5.09E-02	1.75E-02	1.78E-02
3	1.18E-01	1.15E-01	7.56E-02	1.13E-01	1.11E-01	5.02E-02	4.03E-02	5.02E-02	6.01E-02	2.20E-02	1.77E-02
4	1.18E-01	1.07E-01	1.13E-01	8.62E-02	1.20E-01	5.80E-02	4.71E-02	3.95E-02	5.00E-02	1.64E-02	1.94E-02
5	1.17E-01	1.15E-01	1.11E-01	1.20E-01	7.64E-02	4.96E-02	5.93E-02	5.10E-02	3.82E-02	1.58E-02	1.86E-02
6	4.09E-02	3.93E-02	5.03E-02	5.80E-02	4.96E-02	6.58E-02	1.03E-01	9.78E-02	1.01E-01	3.29E-02	4.04E-02
7	4.21E-02	4.85E-02	4.03E-02	4.70E-02	5.95E-02	1.03E-01	5.80E-02	1.03E-01	9.68E-02	4.44E-02	3.58E-02
8	4.35E-02	6.00E-02	5.04E-02	3.95E-02	5.09E-02	9.78E-02	1.03E-01	6.18E-02	9.92E-02	4.99E-02	4.56E-02
9	4.11E-02	5.09E-02	6.01E-02	5.02E-02	3.85E-02	1.01E-01	9.69E-02	9.92E-02	5.92E-02	4.23E-02	5.17E-02
10	2.12E-02	1.75E-02	2.24E-02	1.63E-02	1.57E-02	3.31E-02	4.44E-02	5.00E-02	4.24E-02	6.28E-02	1.01E-01
11	1.92E-02	1.79E-02	1.77E-02	1.94E-02	1.87E-02	4.07E-02	3.58E-02	4.59E-02	5.17E-02	1.01E-01	6.74E-02
12	1.98E-02	1.78E-02	1.88E-02	1.62E-02	1.83E-02	5.21E-02	4.56E-02	3.35E-02	4.36E-02	9.48E-02	9.44E-02
13	2.05E-02	1.84E-02	1.87E-02	1.75E-02	1.68E-02	4.25E-02	5.37E-02	4.56E-02	4.03E-02	9.51E-02	9.24E-02
14	1.21E-02	9.80E-03	1.03E-02	7.88E-03	8.57E-03	1.49E-02	1.89E-02	2.14E-02	1.69E-02	3.83E-02	4.68E-02
15	1.23E-02	8.64E-03	8.60E-03	1.07E-02	8.79E-03	1.84E-02	1.78E-02	1.89E-02	1.97E-02	4.46E-02	4.15E-02
16	1.24E-02	8.51E-03	8.31E-03	1.09E-02	8.90E-03	1.86E-02	1.77E-02	1.80E-02	1.87E-02	5.47E-02	5.11E-02
17	1.03E-02	9.61E-03	9.48E-03	9.36E-03	9.83E-03	1.80E-02	1.86E-02	1.81E-02	1.71E-02	4.98E-02	6.06E-02
18	1.40E-02	1.08E-02	1.05E-02	1.08E-02	1.27E-02	1.84E-02	1.98E-02	1.95E-02	1.83E-02	4.23E-02	4.10E-02
	GiS1	GiS2	GiS3	GiS4	GiS5	GiS6	GiS7	GiS8	GiS9	GiS10	GiS11
1	7.16E-02	1.47E-01	1.77E-01	1.92E-01	1.10E-01	4.44E-02	4.32E-02	4.70E-02	4.48E-02	2.42E-02	2.14E-02
2	1.12E-01	9.25E-02	1.70E-01	1.70E-01	1.15E-01	3.98E-02	4.74E-02	6.00E-02	5.28E-02	1.68E-02	1.94E-02
3	1.15E-01	1.26E-01	9.71E-02	1.66E-01	1.13E-01	5.18E-02	4.30E-02	4.64E-02	6.14E-02	2.50E-02	1.70E-02
4	1.17E-01	1.14E-01	1.44E-01	1.15E-01	1.19E-01	5.68E-02	4.98E-02	4.06E-02	5.44E-02	1.68E-02	1.86E-02

i	SiS12	SiS13	SiS14	SiS15	SiS16	SiS17	SiS18	SiG1	SiG2	SiG3	SiG4
1	1.97E-02	2.05E-02	1.21E-02	1.23E-02	1.24E-02	1.03E-02	1.40E-02	8.10E-02	1.14E-01	1.17E-01	1.19E-01
2	1.78E-02	1.84E-02	9.78E-03	8.54E-03	8.45E-03	9.63E-03	1.08E-02	1.14E-01	8.28E-02	1.15E-01	1.06E-01
3	1.88E-02	1.86E-02	1.00E-02	8.58E-03	8.35E-03	9.30E-03	1.04E-02	1.17E-01	1.14E-01	7.56E-02	1.14E-01
4	1.61E-02	1.75E-02	7.76E-03	1.07E-02	1.08E-02	9.21E-03	1.08E-02	1.19E-01	1.06E-01	1.14E-01	8.62E-02
5	1.82E-02	1.68E-02	8.38E-03	8.33E-03	8.89E-03	9.62E-03	1.25E-02	1.22E-01	1.15E-01	1.10E-01	1.21E-01
6	5.20E-02	4.25E-02	1.50E-02	1.84E-02	1.86E-02	1.80E-02	1.84E-02	3.66E-02	3.88E-02	4.86E-02	5.92E-02
7	4.55E-02	5.37E-02	1.89E-02	1.78E-02	1.75E-02	1.86E-02	1.98E-02	4.10E-02	4.96E-02	3.72E-02	4.38E-02
8	3.36E-02	4.56E-02	2.14E-02	1.90E-02	1.80E-02	1.76E-02	1.92E-02	3.94E-02	6.00E-02	5.38E-02	3.84E-02
9	4.35E-02	4.01E-02	1.69E-02	1.96E-02	1.85E-02	1.71E-02	1.83E-02	3.66E-02	4.88E-02	5.88E-02	4.52E-02
10	9.45E-02	9.50E-02	3.83E-02	4.46E-02	5.46E-02	4.95E-02	4.22E-02	1.68E-02	1.82E-02	1.90E-02	1.58E-02
11	9.44E-02	9.23E-02	4.69E-02	4.15E-02	5.10E-02	6.04E-02	4.10E-02	1.64E-02	1.62E-02	1.84E-02	2.02E-02
12	6.84E-02	9.99E-02	5.62E-02	4.73E-02	4.03E-02	4.54E-02	4.25E-02	2.14E-02	1.52E-02	1.42E-02	1.44E-02
13	1.00E-01	5.84E-02	4.81E-02	5.63E-02	4.92E-02	3.74E-02	4.08E-02	1.82E-02	1.84E-02	1.96E-02	1.70E-02
14	5.62E-02	4.82E-02	8.02E-02	1.15E-01	1.06E-01	1.18E-01	1.06E-01	1.18E-02	9.60E-03	7.80E-03	8.60E-03
15	4.73E-02	5.65E-02	1.15E-01	8.56E-02	1.13E-01	1.06E-01	1.11E-01	1.28E-02	7.40E-03	8.80E-03	1.12E-02
16	4.04E-02	4.92E-02	1.06E-01	1.14E-01	8.52E-02	1.13E-01	1.15E-01	1.20E-02	7.00E-03	8.00E-03	1.04E-02
17	4.54E-02	3.74E-02	1.18E-01	1.06E-01	1.13E-01	8.30E-02	1.14E-01	9.00E-03	7.60E-03	7.60E-03	8.00E-03
18	4.25E-02	4.07E-02	1.06E-01	1.11E-01	1.15E-01	1.14E-01	8.92E-02	1.20E-02	1.06E-02	9.20E-03	1.10E-02
	GiS12	GiS13	GiS14	GiS15	GiS16	GiS17	GiS18	GiG1	GiG2	GiG3	GiG4
1	1.78E-02	2.24E-02	1.24E-02	1.18E-02	1.28E-02	1.14E-02	1.56E-02	8.10E-02	1.14E-01	1.17E-01	1.20E-01
2	1.98E-02	1.84E-02	1.00E-02	9.60E-03	9.60E-03	1.10E-02	1.10E-02	1.14E-01	8.28E-02	1.15E-01	1.05E-01
3	2.18E-02	1.76E-02	1.20E-02	8.40E-03	8.60E-03	1.08E-02	1.16E-02	1.17E-01	1.15E-01	7.56E-02	1.15E-01
4	1.76E-02	1.80E-02	7.00E-03	1.02E-02	1.14E-02	1.04E-02	1.06E-02	1.20E-01	1.05E-01	1.15E-01	8.62E-02

6.9.4 Predicted transient temperatures

The transient gas temperature and enclosure temperatures are predicted and shown from fig. 6.4 to fig. 6.7.

Reasonably accurate results are obtained. The gaseous temperatures of the gas zones 1 to 4, as shown in Fig. 6.4, are not changing significantly with time. However, the temperatures of the furnace walls and loads are increasing almost exponentially until they reach to the steady-state values.

At the steady-state condition, the gas temperatures are ranging from 716K to 2137K (i.e. the average gas temperature is about 1426.5K), whereas the load temperature (i.e. temperature of the bottom furnace enclosure) are ranging from 333K to 445K (i.e. the average load temperature is about 389K). The results agree well with those predicted by Viskanta[23]. The accuracy, stability and validation of the mathematical model will be discussed in the Section 7.

Fig. 6.4 Transient Response of Gas Zones

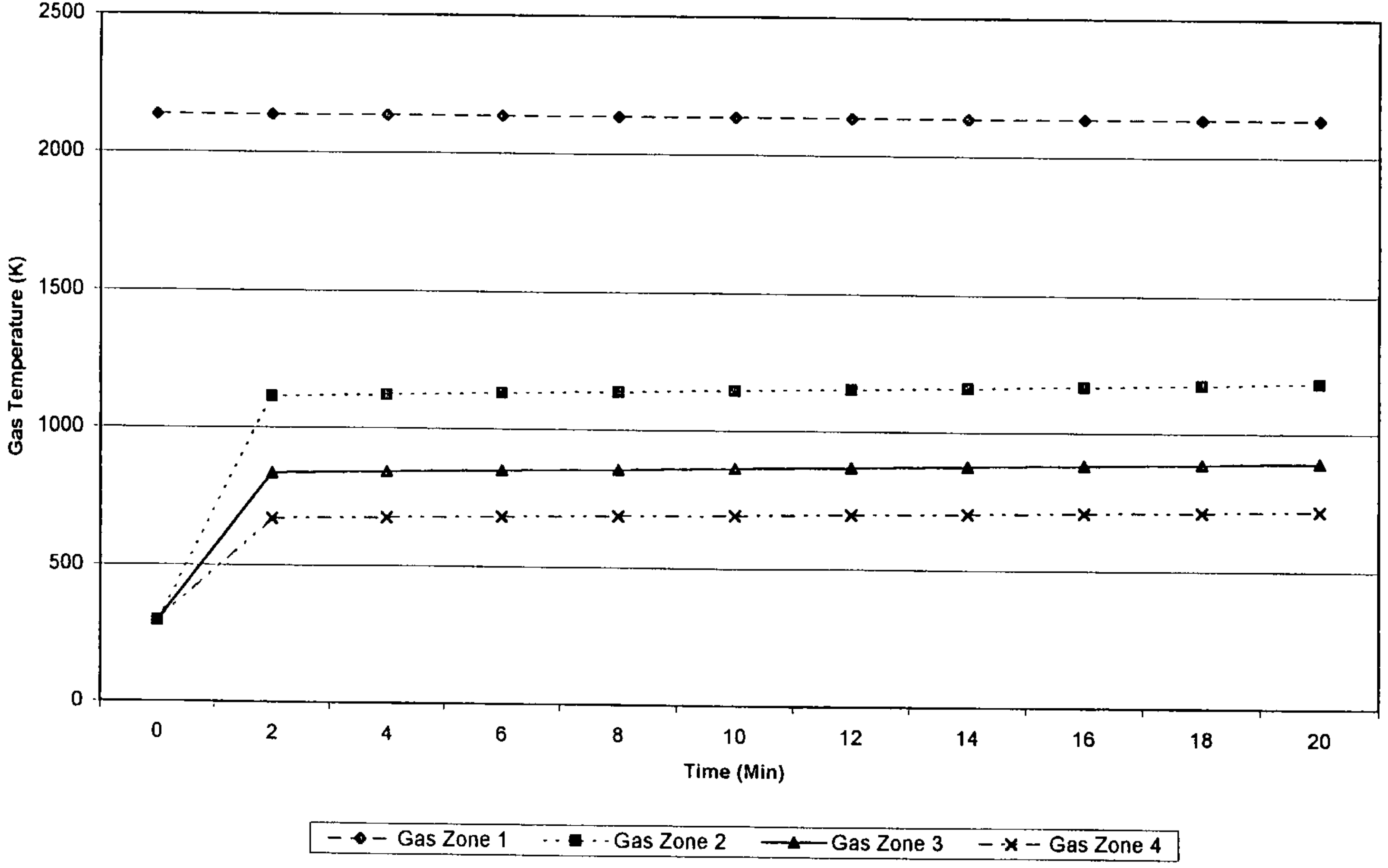


Fig. 6.5 Transient Response of Side Enclosure

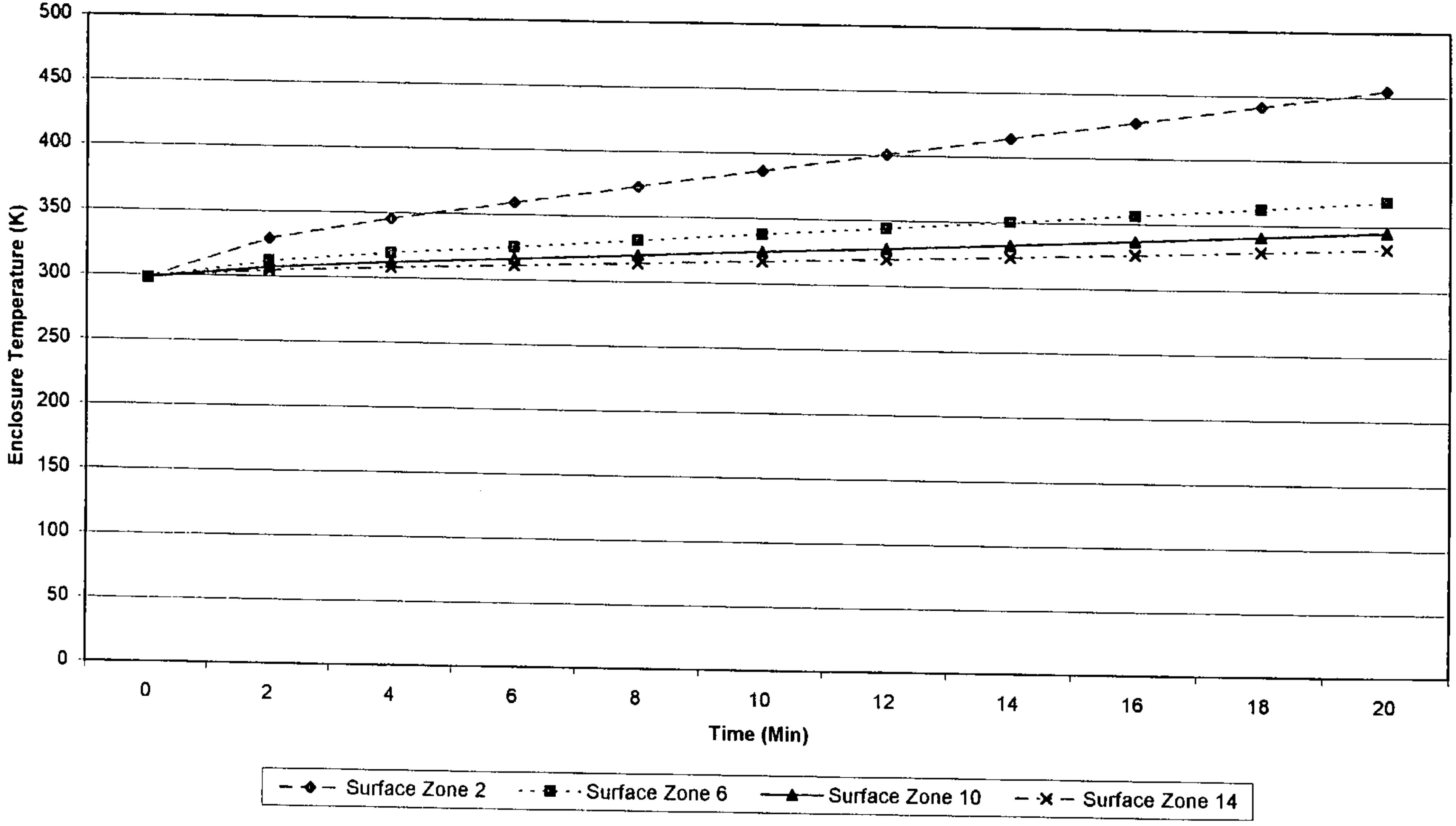


Fig. 6.6 Transient Response of Top Enclosure

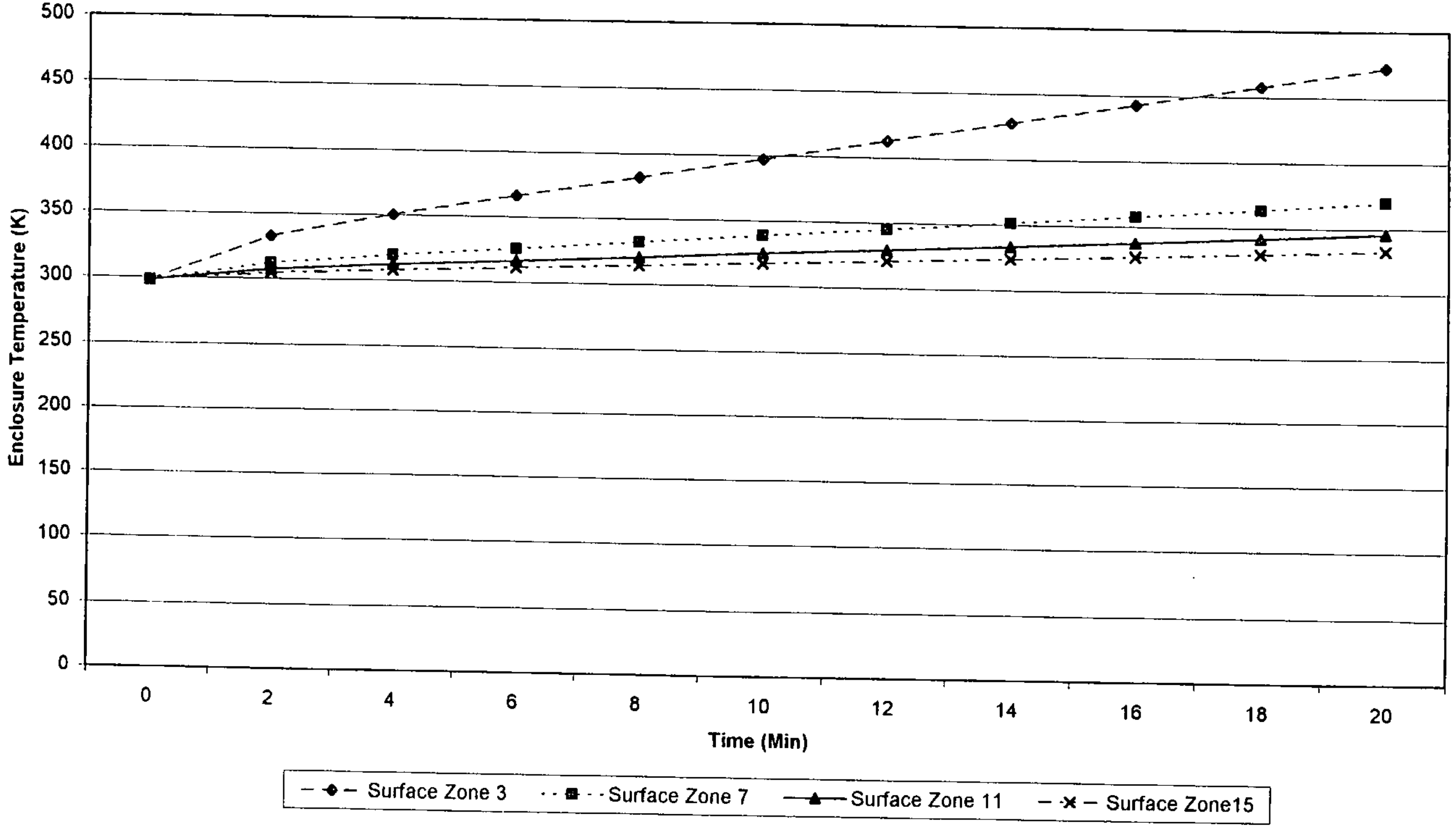
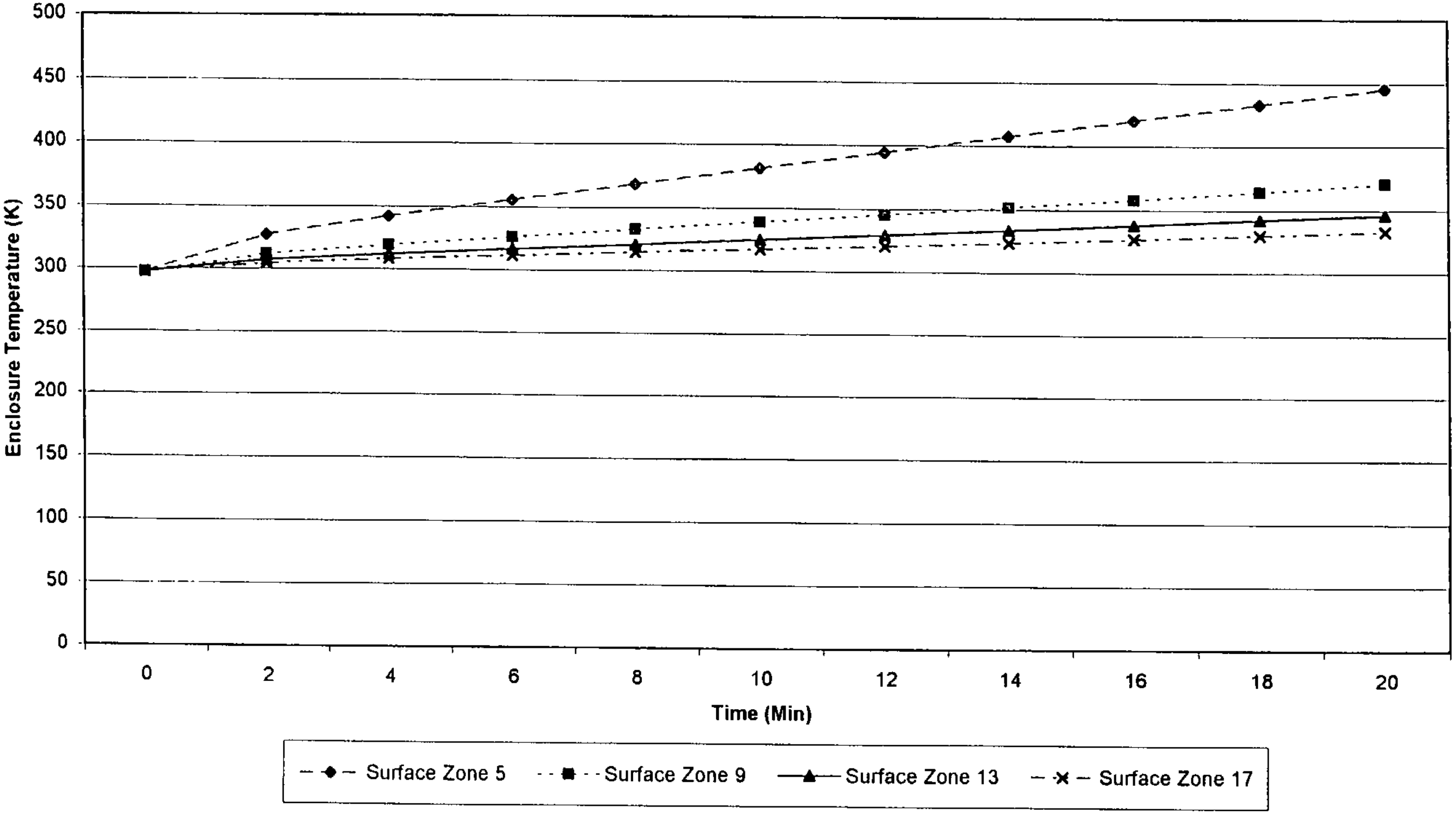


Fig. 6.7 Transient Response of Bottom Enclosure



7. Reliability and Stability of Numerical Predictions

7.1 Introduction

Accuracy of the predictions and stability of the solution procedure are the most important considerations for computational study. In this chapter, they will be discussed accordingly.

7.2 Error Analysis

The present furnace model developed in the present work had considered most of the factors affecting its thermal performance including combustion, soot concentration, conduction, convection, radiation, furnace geometry and material of construction. It is very confident that accurate and reliable predictions can be obtained, however, two categories of possible errors be alerted. Firstly, error will arise from the deviation between the assumptions made and the actual situation. The second group of errors comes from the numerical/computational method itself.

7.2.1 Error Due to Assumption Made

- The conditions inside a well-stirred zone are assumed to be complete combustion with uniform thermophysical and flow properties. However, in practical cases, especially for large industrial furnace or boiler, such assumptions may not be totally valid. Normally, the flame length may be approximately equal to the length and the further combustion is continued to take place along the combustion gas flow direction. In this case, the energy equation [5.32] will be modified such that the air/fuel energy term is not zero in a plug-flow zone. The rate of energy released by combustion will be calculated by Arrhenius equation and the problem becomes more complicated.

- In this study, energy released during the combustion process and the furnace's combustion efficiency are assumed to be at the maximum. Also, the flame temperature is assumed to be adiabatic, which is an ideal situation that maximum flame temperature occurs. In practice, the efficiency of combustion depends on the design of burner, primary and secondary ventilation air and the stabilizer. In addition, after serving for a certain period of time, some nozzle of the burner may be blocked which will reduce its efficiency.
- In the present study, emission and absorption of the combustion product in calculating the radiation is assumed to be dependent on the soot only. However, carbon dioxide and water vapour will also contribute to the gaseous radiation even though their effect on the total radiation heat transfer is insignificant[29,30].
- In the calculation of convection, Lebedev's work should directly be applied to the flow of Reynold's Number ranging from 17000 to 40000. However, the Reynold's number in some applications as suggested by the present study is out of this range, and may contribute error in the computation.
- For high gas temperature, water vapour molecule will be dissolved. Then a set of chemical equations will be involved in the energy analysis. Therefore the radiation properties and adiabatic flame temperature are required to modify for highly accurate computation.

7.2.2 Computational Error

- In Hottel's zone method, a continuous domain is transformed into a discrete domain when a system is divided into a number of zones, which will introduce error. This error can be reduced by decreasing the zone size. However, it will reduce the computational speed and occupy much more memory. Take the calculation of total exchange areas by Monte Carlo method as an example, for each zone, individual paths of 5000 photons are required to track. It implies that the calculation will be increased by 5000 in each time loop by increasing 1 more zone. It is clearly shown that the accuracy of the present mathematical model can be improved by increasing the number of zones, but it is certainly limited by the computer speed and memory.
- Monte Carlo method is a numerical method using the random nature of photons. Accuracy can be improved by using more photons to represent the radiation field. Once again, the numbers of photons can be adopted is limited by the computational ability.
- Finite difference method has been used to predict the conduction in the furnace wall. For the finite difference method, there are choice of explicit scheme (forward difference), implicit scheme (backward difference) and Crank-Nicolcon method (central difference). The error produced by explicit and implicit schemes are the same and is in the order of the following :

  $$[\Delta t, (\Delta x)^2] \quad .... [7.1]$$

  The error produced by Crank-Nicolson method is shown below :

  $$[(\Delta t)^2, (\Delta x)^2] \quad .... [7.2]$$

The advantage in using explicit scheme is direct calculation of the nodal temperature at next time step by the temperatures at present time step. However, the time step must be restricted by the relationship between Δx and Δt in order to fulfill the stability criteria, which will be discussed in the next section. For implicit scheme, the nodal temperatures in each time step can be written as a system of linear equations that are solved simultaneously, which requires a large number of calculations. However, this method is unconditionally stable. Therefore, a large time step can be used in order to speed up the caculation. In the example as mentioned in the previous chapter, the order of error will be 1.5.

- The round off error of computation is very small because 14 decimal place has been used in the calculation. Hence this minor error can be neglected.

7.3 Stability Analysis

For explicit scheme in finite difference method, there is a constraint in selecting the time step and the grid size. If the time step is inappropriately selected, the solution will be unstable. In the present model, the conduction within the enclosure and the load is assumed to be one-dimensional. The conditions for stability are shown below :

For interior nodes : $Fo \leq \frac{1}{2}$ .... [7.3]

For exterior nodes : $Fo \leq 1/[2(Bi + 1)]$ .... [7.4]

Condition can be determined with the knowledge of Fo and Bi.

Where $Fo = \alpha\Delta t/(\Delta x)^2$, is called the Fourier Number.

and $Bi = h\Delta x/k$, is called the Biot Number.

In the present computational example, k = 43, $\alpha = 1.17\times10^{-5}$ m^2/s, Δx =0.0125 m and Δt = 1.5 s. Hence Fo = 0.11, which is less than ½. Therefore the solution is stable for interior nodes.

For exterior nodes, Fo must be less than the minimum value of 1/[2(Bi + 1)] in order to have a stable solution. It implies that "h_F" must be at its maximum value. It is achieved when the gas temperature is at its minimum value, (i.e. the room temperature). In this case, room temperature is 298 K and h is 78.44 W/m^{2}K. Since 1/[2(Bi + 1)] = 0.49, which is larger than Fo. As a result, the solution is stable both for the interior and exterior nodes.

7.4 Validation of The Developed Model

The predictions obtained from the computer program were compared with Viskanta's work[23] as shown in Fig 7.1. At 20 minutes after the furnace has been started up, the mean temperature of the bottom surface (i.e. the load) is estimated to be 100°C for an emissivity of 0.3 as predicted by Viskanta's model, whereas the result obtained by the present mathematical model is ranging from 55°C to 165°C (i.e. a mean temperature of 110°C). Difference between the predicted mean temperature is only 10°C (i.e. 10%), and the two predictions are found to well agree with each others. Fig. 7.2 shows the comparison among the temperatures of the bottom surface zones in the present model (i.e. Surface zone number 5, 9, 13, 17) and that of the Viskanta's model. The deviation may be due to the following factors :

a. In Viskanta's model, the entire bottom surface is assumed at the same temperature, whereas it is divided into four different zones in the present study.

b. In Viskanta's model, the type of fuel used, air/fuel ratio, fuel flow rate and the pre-heat temperature have not been considered, which will certainly affect the furnace temperature.

c. In the determination of the total exchange areas, the conventional Monte Carlo method is used by Viskanta, whereas an improved technique has been adopted in the present study which gives better accuracy.

Fig.7.1 Comparison of Load Temperature Between Present Model & Viskanta's Model

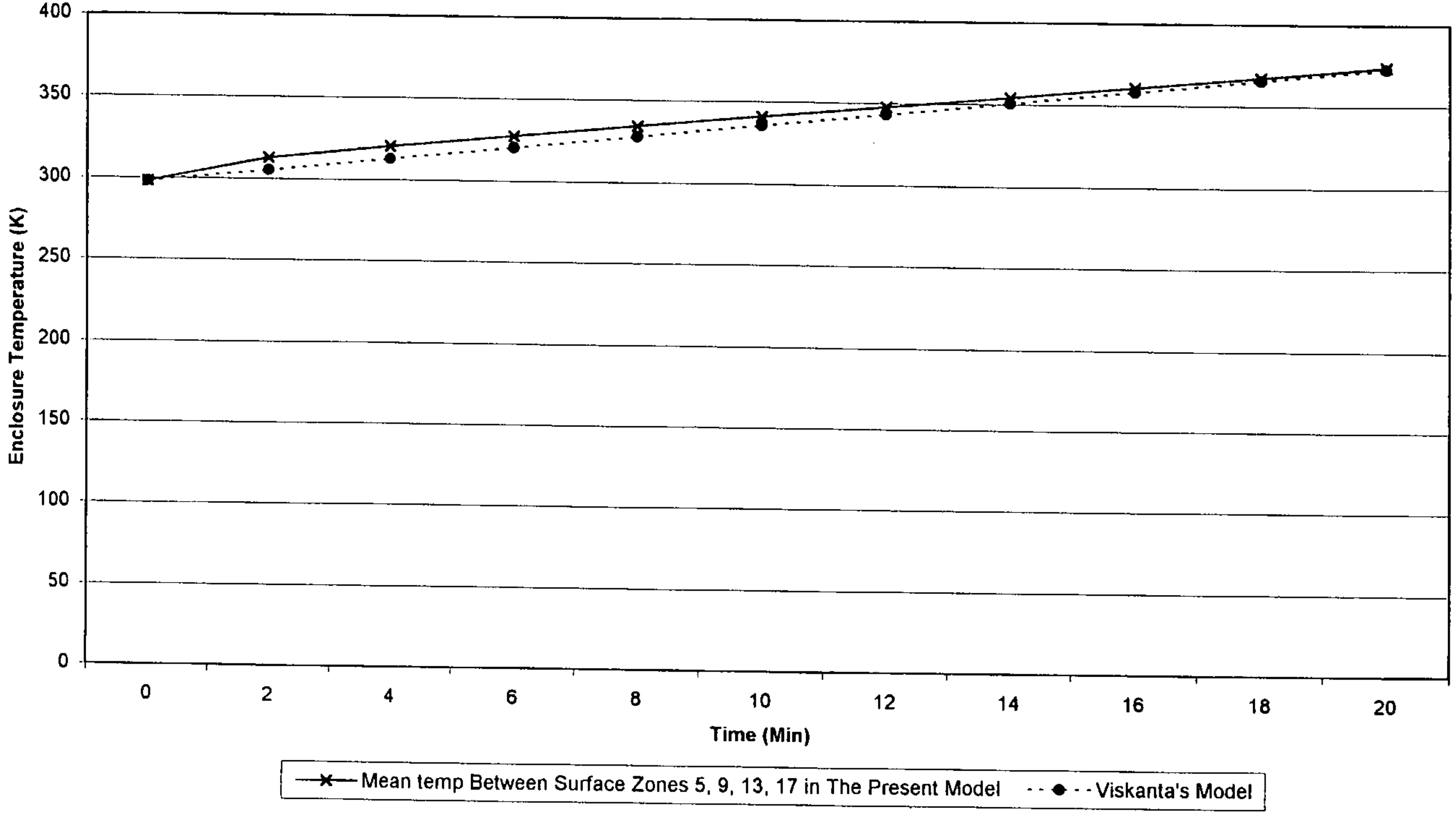
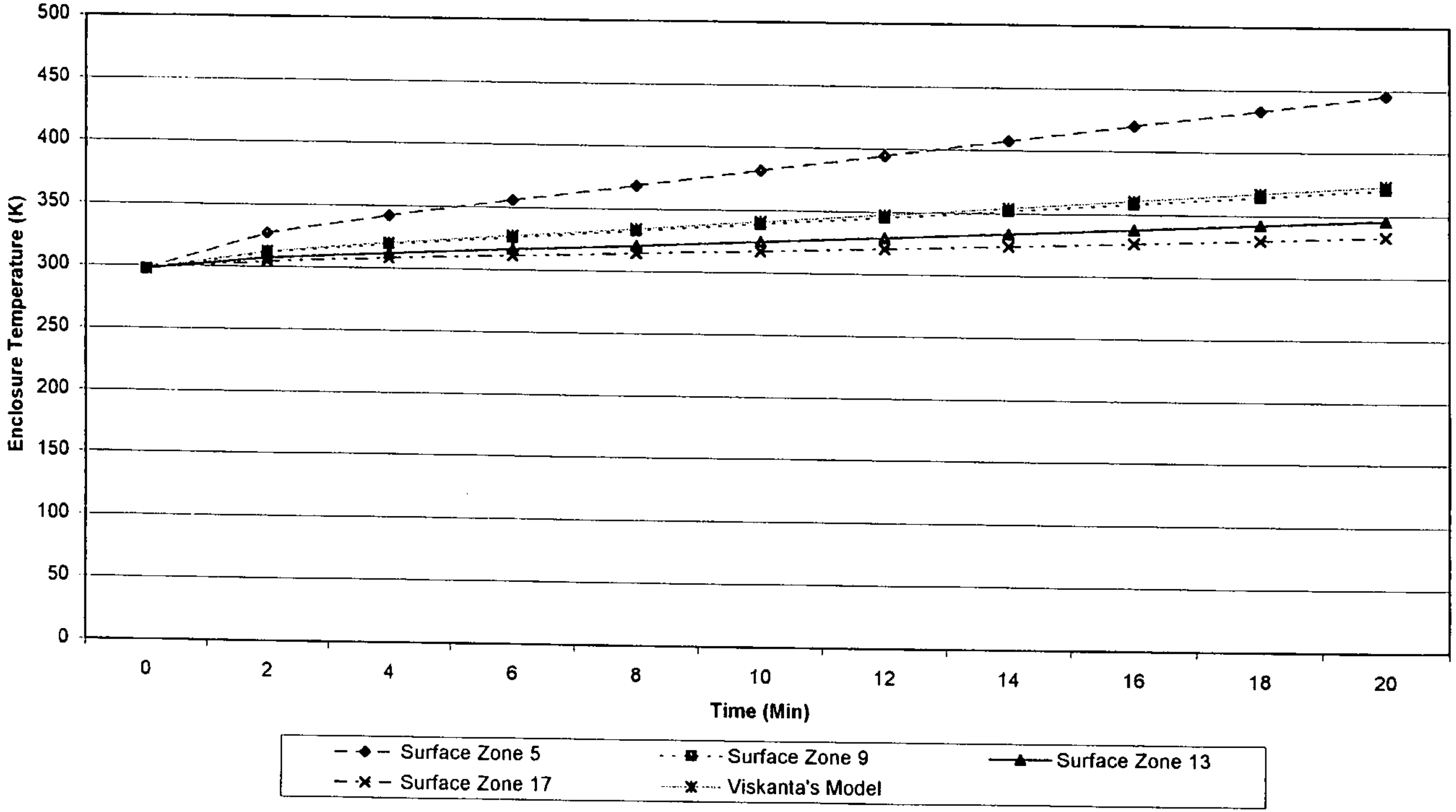


Fig. 7.2 Comparison Among Bottom Surface Zones in the Present Model And Viskanta's Model



8. Discussions

8.1 Discussions on Mathematical Model

- The furnace is modeled as the Hottel's long furnace model which has been adopted by a lot of researchers[11,13,14,21,22,23,25]. Indeed, this method enables an accurate and precise solution to handle the radiation problem. Nevertheless, due to the limitation of the computer speed and memory, the present model can only be discretised into quite small number of zones, therefore its accuracy is reduced. However, accuracy can be improved by increasing the computer capability.
- The combustion model offers a comprehensive approach to handle the combustion problem. In the model, the fuel type, air/fuel ratio, air/fuel mixture flow rate, pre-heat temperature are both considered, which is rare in the existing literatures.
- In soot model, both formation and burning rate have been considered and assumed to become steady. It is justified, because the furnace size is considerably large and there is sufficient time for the soot to become steady.
- Radiation heat transfer is calculated by the Hottel's zone method. The difficulty of using zone method is the tedious procedure to determine the total exchange areas. The present model provides an easier method, Monte Carlo method, to evaluate the total exchange areas. Furthermore, the accuracy of the convectional Monte Carlo method is improved by using a least square smoothing technique to comply with both the First Law and Second Law of Thermodynamics.

- The complication of solving the convection problem is to obtain the solution of the complex thermofluid equations. Non-dimensional equation is employed in the present study which is proposed by Lebedev. It offers a simple approach to solve the convection problem in an algebraic form.
- One-dimensional transient conduction equation is used to calculate the conduction rate through the furnace wall. It is justified, because area of the furnace wall is very large compared with the wall thickness. Therefore it can be treated as a semi-infinite wall.
- The energy equation is good to be applied in the first three gas zones, but may have some error when it is applied in the last gas zone. In the present study, all the combustion gas is assumed to be fully exhausted. However, reflection of combustion gas may occur in real life furnace, hence introduces error into the prediction.

8.2 Discussions on Results

- As shown from the results (i.e. Fig. 4.4 to 4.7), more calculations are required to calculate the steady-state temperature, especially for the furnace enclosures which needs a large computer memory. The present mathematical model integrates most of the factors affecting the thermal performance of a furnace and eventually, involves a large amount of calculations and hence computer memory, which should be alerted in applying the developed software. In addition, if the memory and the processor speed are high enough, the zone size can be reduced to obtain a better solution.

- In the real life example used to evaluate the software, steel is used as the enclosure material which may not be a good choice in industrial furnace since the heat loss to surrounding is very high, such that efficiency of the furnace is much reduced. The reason to use a steel furnace as an example is to shorten the transient state of the furnace, such that both transient and steady-state operations can be observed.
- As shown in the Section 7.4, the results are satisfactory and its accuracy is validated by comparing with Viskanta's model which shows that only 10% of deviation between the present model and Viskanta's model

8.3 Discussions on Programme

8.3.1 User Interface

When the program is executed, a user graphic interface will appear as shown in Fig. 8.1

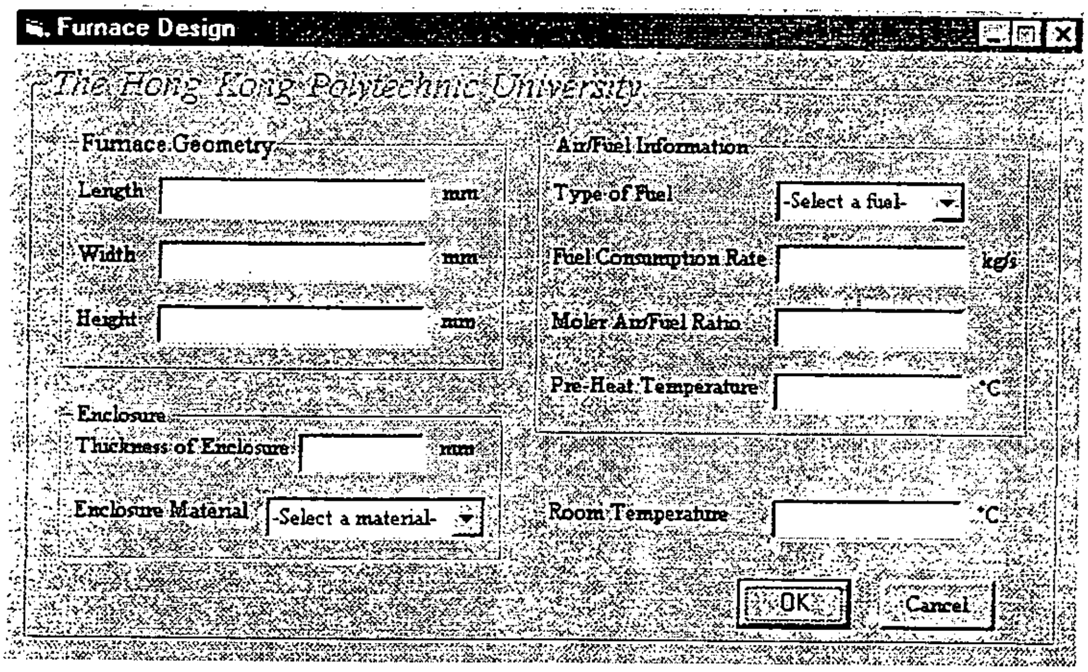


Fig. 8.1 User Interface

In the interface, the user is required to input the fundamental information in each field. After inputting all the necessary information, the program will start to execute. Separate blank Excel spreadsheets will appear and show the predicted gas and enclosure temperatures, convection and radiation heat transfer in the spreadsheets.

8.3.2 Applicability of The Programme

In industry, there are different types of furnaces being used currently. Examples are :

- Open-fired furnaces for heat treatment, ceramic sintering or shell boilers.
- In some process control furnaces, heat will be transferred from the hot combustion product to air through a heat exchanger. It is an indirect heating process. Examples are furnaces used for paint or powder curing, or thermal forming processes.

- Radiant tube furnaces.

For open-fired furnaces, the programme can be applied directly without modification. However, for heat exchanger type furnace, the hot fluid temperature can firstly be evaluated by the programme and heat exchanger analysis is then used to find out the temperature of cold fluid. Furnace aerodynamics is more dominant in this type of furnace because the requirement of a specific temperature distribution is very rigid.

For the radiant tube furnaces, the present program can be applied with little modification. For the radiation analysis in the enclosure with radiant tube installed, apart from radiation emitted from the enclosure surface, the emissive power from the radiant tubes should be added together. The calculations involved in this kind of furnace are relatively simple. On the one hand, convection heat transfer can be neglected because air flow is not significant. On the other hand, since there is no combustion process taken place inside the furnace, the stock air is neither a non-absorbed nor a non-emitting medium. This will simplify the radiation calculation.

8.3.3 Special Features of The Programme

- The programme consists of a furnace mathematical model which integrates most of the factors affecting the thermal performance of the furnace, and accuracy in calculating the radiation heat transfer is improved by using the smoothing Monte Carlo method.
- The programme interface is user-friendly. The furnace design engineer is only required to input several parameters into the fields, then the solution can then be

obtained. Once the solutions are displayed in Excel, they can be saved and printed graphically.

8.3.4 Recommendation

- It is recommended to add part of heat exchanger analysis to make the program more complete. Furthermore, the aerodynamic theory can be applied to investigate the effect of air jet size and direction to the temperature distribution within the furnace stock.
- It is more user-friendly to use the data obtained in this programme to develop a graphical tool, which is easier to show the results in a graph rather than numbers.
- To add more fuel types and enclosure materials in the programme database, in order the programme can be more robust.

8.4 Application of The Developed Software

Since this research project is engaged by a Teaching Company Scheme, its practical value is important. The programme is planed to help the furnace design engineers to predict the thermal performance of a furnace in the preliminary stage while in the project development. Before they work out their detail design, the programme enables to provide the operation details (e.g. transient temperature distribution, transient heat flux distribution etc) of a particular furnace (e.g. different sizes, different burners etc). It can avoid any major design change or modification work due to the prior rough estimation.

Furthermore, any local hot spot or overheating at any location at any time can foresee before the furnace is actually operated.

9. Conclusions

The factors affecting the furnace thermal performance have been studied intensively. They are selected and integrated to form a comprehensive mathematical model to determine the thermal performance of an oil-fired open flame furnace from startup, through transient to steady-state operation, which is missing in the existing literature. The following models have been developed to predict the furnace thermal performance :

- Furnace model

  Hottel's zone method has been employed together with the long furnace modeled in the present studied. The whole furnace has been divided into a 'well-stirred' zone near the burner and a number of 'plug-flow' zone for the rest of the furnace. Furthermore, the size and the materials of enclosure have also been included in the analysis.

- Combustion model

  Combustion is the process to determine the amount of energy supply to the furnace. In the present study, the following parameters have been considered in the combustion model :

  - ☐ Type of fuel
  - ☐ Molar air/fuel ratio
  - ☐ Air/fuel mixture flow rate
  - ☐ Air/fuel mixture pre-heat temperature

- Soot model

  Soot will be formed in the diffusion combustion of heavy fuel. The importance of the soot is its radiation effect which enables the radiation to be comparable with the convection heat transfer. In the present study, soot formation model and soot burning model are used to determine the amount of the soot, volume fraction, emissivity and absorption coefficient, which are important inputs to evaluate the radiation exchange inside the furnace.

- Radiation model

  Hottel's zone method has been applied to determine the radiation exchange inside the furnace. Total exchange areas have been calculated by a smoothing Monte Carlo method, where the accuracy havs been improved by the least square smoothing technique. The adopted method produces results which are able to comply with the First Law and Second Law of Thermodynamics. The medium has been treated as a grey gas and its absorption and emission are mainly due to soot.

- Convection model

  A non-dimensional equation proposed by Lebedev for furnace has been implemented to handle the convection problem. All the temperature dependent properties involved in the model have been obtained from a database inside the programme developed in the present study. Eventually, the convective heat transfer coefficient in each gas-enclosure surface has been determined individually, in calculating the convection heat transfer rate.

On the other hand, natural convection between the external furnace enclosure and the surrounding has been also considered.

- Conduction model

  Conduction takes place within the enclosure and the load. One-dimensional conduction model, with the aid of finite difference technique, has been used to determine the conduction rate.

After integrating all the parameters mentioned above, an energy balance equation has been developed to calculate both the transient and steady-state responses of the furnace. A programme written by Visual Basic has been employed to obtain the temperature distribution, convection heat transfer rate and radiation exchange rate.

The developed programme has been used to predict the transient operation of a real life oil-fired open flame furnace. The results are validated by comparing with the prediction of Viskanta's model[23], and a good agreement is obtained.

The present study has integrated the various parameters affecting the thermal performance of an oil-fired furnace. The developed programme enables the tedious and complicated thermal design and analysis processes of an oil-fired furnace to be performed more easier and accurate. A significant feature of the developed programme is the ability to predict the transient operation of the furnace, which may be very important for some industrial heating processes.

9. List of Symbols

$a_{g,n}(T)$	Weighted function in calculating the emissivity of gas at Temperature T in equation [2.6]
A	Constant in equation [2.7]
A	Area, m^2
A_1	Constant in equation [2.8] or [5.22]
B	Constant in equation [2.4] or [2.5], m^2/kgK
A_2,A_3	Constant in equation [5.14]
B_1,B_2	Constant in equation [5.15]
c	Soot Concentration, kg/m^3
C	Plank’s constant
C_{ij}	Fractional error in equation [4.56]
C_p	Specific heat, kJ/kgK
d_s	Soot particle diameter, m
E	Activation energy, kJ
E_b	Black body emissive power, kW/m^2
$f(r),f(\theta),f(\eta)$	Probability function
$F(r),F(\theta),F(\eta)$	Accumulated probability function
F_{ij}	View factor
f_v	Volume fraction of soot
g	Constant in equation [5.13]
G_iG_j	Exchange area from gaseous zone ‘i’ to gaseous zone ‘j’, m^2
G_iS_j	Exchange area fromo gaseous zone ‘i’ to surface zone ‘j’, m^2
H	Total enthalpy, kJ/kmol
H	Height of furnace, m
h_F	Heat transfer coefficient for forced convection, kW/m^2K
h_N	Heat transfer coefficient for natural coefficient, kW/m^2K
h	Enthalpy, kJ/kmol
h^o	Enthalpy of formation @298K, kJ/kmol
I	Intensity of radiation
K	Confidence measure in equation [4.56]
K_a	Absorption coefficient, 1/m
k	Absorption index
k	Thermal conductivity, kW/mK
L	Length or length of furnace, m
L	Number of surface zones adjacent to the gaseous zone
M	Total number of photon in an enclosure
m_d	Rate of fuel burnt, kg/s
N	Number of photon emitted from surface or gaseous zone
N	Number of mole
N_g	Number of gaseous zone
N_s	Number of surface zone
n	Refraction index
Q	Heat transfer rate, kJ/s
Q_{acc}	Rate of heat absorbed by a gaseous zone, kJ/s
r	Radius,m
r	Distance traveled by a photon, m
R	Random number, universal gas constant or reaction rate
[R]	Exchange area matrix in equation [4.59]
S_C	Amount of soot burnt, kg
P_{O2}	Partial pressure of oxygen, bar
S_F	Amount of soot formation, kg
S_{net}	Net amount of soot, kg
S_iG_j	Exchange area from surface zone ‘i’ to gaseous zone ‘j’, m^2

S_iS_j	Exchange area from surface zone 'i' to surface zone 'j', m^2
T	Temperature, K
T_{ad}	Adiabatic flame temperature, K
t	Time, s
t	Thickness, m
V	Gas volume, m^3
U_{gj}	Number of photon absorbed by gaseous zone 'j'
Usj	Number of photon absorbed by surface zone 'j'
W	Width of furnace, m
x_{ij}	Element in matrix in equation [4.58]
x_{ij}'	Modified exchange areas in equation [4.61]
x,y,z	Cartesian co-ordinates

Greek Letter

Δx	Grid size in equation [6.33]
α	Thermal diffusivity, m^2/s or parameters in combustion equation [5.5]
β,γ	Parameters in combustion equation [5.5]
δ	Constraint vector in equation [4.59]
ε	Emissivity
η	Conical angle, rad
θ	Circumferential angle, rad
θ	Temperature(Kelvin)/100, K
Λ	Mean wave length, μm
ρ	Density of furnace enclosure, kg/m^3
ρ_s	Soot particle density, kg/m^3
σ	Stefan-Boltzmann constant, W/m^{2}K^4

Subscript

a	Air
F	
fu	Fuel
g	Gas
i	Substance or zone 'i'
j	Zone 'j'
k	Surface zone adjacent to the gaseous zone
N	Natural convection
ox	Oxygen
prod	Product
r	Radiation
react	Reactant
s	Surface or soot
w	Furnace wall or load
∞	Natural convection or ambient
λ	Wavelength

Superscript

k	Iterative scheme index or time step

Non-Dimensional Number

Bi = Biot Number
Fo = Fourier Number
Gr = Grashof Number

Nu = Nusselt Number
Pr = Prandtl Number
Re = Reynolds Number

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Module1

```
 Public Const Pi = 3.14159265, hC4H10 = -126148, hN2 = 0, hO2 = 0, hH2O = -241827, hCO2 = -393522,
 Rho_C4H10 = 228.2057
 Public Const MW_Air = 28.97, MW_C4H10 = 58.124, MW_CO2 = 44.01, MW_H2O = 18.015, MW_N2
 = 28.013, MW_O2 = 31.999
 Public Const Sigma = 0.00000005669
 Public Msg, Style, Title As String
 Public Flag, L, W, H, Time, Troom
 Public Mass_AFR, Mole_AFR, Alpha, Beta, DeltaT1, Gamma, md, Hproduct, Hq, Hreact, s, T1, Tad(), Tf
 Public Hyd_Dia, Vel, Heat_Coeff, T
 Public epsilon, Eta, Gas_Number, K, m, n, R_epsilon, Surface_Number, Theta, Trial_No, x, V,
 Volume_Number, XX, XXX, XXXX, y, YY, YYY, YYYY, z, ZZ, ZZZ, ZZZZ, Zone_Length,
 Zone_Number As Variant
 Public Density, k_Enc, N_Heat_Coeff, SHC, Th, Time_Interval
 Public C1(18, 18), C2(18, 18), C3(18, 18), C4(4, 4), Delta(22), F1(18, 18), F2(18, 4), F3(4, 18), F4(4, 4),
 GG(4, 4), GG1(22, 22), GS(4, 18), GS1(22, 22), Lamda(), MatrixR(22, 22), MatrixX(22, 22), MatrixX1(22,
 22), rg(12), SG(18, 4), SG1(18, 4), Smin(4), SS(18, 18), SS1(18, 18), SumX(22), SumW(22),
 Total_Distance(4), Ugg(4, 4), Ugs(4, 18), Usg(18, 4), Uss(18, 18), wij(22, 22) As Variant
 Public Alpha_Air(34), Cp_Air(34), k_Air(34), Nu(34), Rho(34), Vol_Fraction
 Public Qn(), QTw(), Te(), Tm(), Ts(), Tw()
 Public QLr(), QLv(), Qr(), Qv(), Tg()

Function arcsin(x)
   If x <> 1 Then
      arcsin = Atn(Sqr(x * x / (1 - x * x)))
   Else
      arcsin = 1.5708
   End If
End Function

Function arccos(x)
   If x <> 0 Then
      arccos = Atn(Sqr(1 / (x * x) - 1))
   Else
      arccos = 1.5708
   End If
End Function

Function A(Surface_Number)  'Calculate surface area
   If Surface_Number = 1 Or Surface_Number = 18 Then
      A = H * W
   ElseIf Surface_Number Mod 2 = 0 Then
      A = H * Zone_Length
   ElseIf Surface_Number Mod 2 = 1 Then
      A = W * Zone_Length
   End If

End Function

Function CpC4H10(T1)
   CpC4H10 = 3.954 + 37.12 * T1 / 100 - 1.833 * (T1 / 100) * (T1 / 100) + 0.03498 * (T1 / 100) * (T1 /
100) * (T1 / 100)
```

```
End Function

Function CpO2(T1)
   CpO2 = 37.432 + 0.02 * (T1 / 100) ^ 1.5 - 178.57 * (T1 / 100) ^ -1.5 + 236.88 * (T1 / 100) ^ -2

End Function

Function CpN2(T1)
   CpN2 = 39.06 - 512.79 * (T1 / 100) ^ -1.5 + 1072.7 * (T1 / 100) ^ -2 - 820.4 * (T1 / 100) ^ -3

End Function

Function CpCO2(T1)
   CpCO2 = -3.7357 + 30.529 * (T1 / 100) ^ 0.5 - 4.1034 * (T1 / 100) + 0.024 * (T1 / 100) ^ 2

End Function

Function CpH2O(T1)
   CpH2O = 143.05 - 183.54 * (T1 / 100) ^ 0.25 + 82.751 * (T1 / 100) ^ 0.5 - 3.6989 * (T1 / 100)

End Function

Function Rho_Air(T)

   If T < 2500 Then
      If T <= 1000 Then
         i15 = (T - 100) / 50 + 1
      Else
         i15 = (T - 1000) / 100 + 19
      End If

      Rho_Air = (Rho(Int(i15) + 1) - Rho(Int(i15))) * (i15 - Int(i15)) + Rho(Int(i15))
   Else
      Rho_Air = ((Rho(34) - Rho(33)) * (T - 2400)) / 100 + Rho(33)
   End If

End Function

Function Kin_Vis(T)

   If T < 2500 Then
      If T <= 1000 Then
         i15 = (T - 100) / 50 + 1
      Else
         i15 = (T - 1000) / 100 + 19
      End If

      Kin_Vis = (Nu(Int(i15) + 1) - Nu(Int(i15))) * (i15 - Int(i15)) + Nu(Int(i15))
   Else
      Kin_Vis = ((Nu(34) - Nu(33)) * (T - 2400)) / 100 + Nu(33)
   End If
```

```
End Function

Function Cond(T)

  If T < 2500 Then
    If T <= 1000 Then
      i15 = (T - 100) / 50 + 1
    Else
      i15 = (T - 1000) / 100 + 19
    End If

    Cond = (k_Air(Int(i15) + 1) - k_Air(Int(i15))) * (i15 - Int(i15)) + k_Air(Int(i15))
  Else
    Cond = ((k_Air(34) - k_Air(33)) * (T - 2400)) / 100 + k_Air(33)
  End If


End Function

Function Cp(T)

  If T < 2500 Then
    If T <= 1000 Then
      i15 = (T - 100) / 50 + 1
    Else
      i15 = (T - 1000) / 100 + 19
    End If

    Cp = ((Cp_Air(Int(i15) + 1) - Cp_Air(Int(i15))) * (i15 - Int(i15)) + Cp_Air(Int(i15))) * 1000
  Else
    Cp = (((Cp_Air(34) - Cp_Air(33)) * (T - 2400)) / 100 + Cp_Air(33)) * 1000
  End If

End Function

Sub Air_Properties()

Rho(1) = 3.601: Cp_Air(1) = 1.0266: Nu(1) = 0.000001923: k_Air(1) = 0.009246: Alpha_Air(1) =
0.000002501
Rho(2) = 2.3675: Cp_Air(2) = 1.0099: Nu(2) = 0.000004343: k_Air(2) = 0.13735: Alpha_Air(2) =
0.00005745
Rho(3) = 1.7684: Cp_Air(3) = 1.0061: Nu(3) = 0.00000749: k_Air(3) = 0.1809: Alpha_Air(3) =
0.000010165
Rho(4) = 1.4128: Cp_Air(4) = 1.0053: Nu(4) = 0.00001131: k_Air(4) = 0.02227: Alpha_Air(4) =
0.000015675
Rho(5) = 1.1774: Cp_Air(5) = 1.0057: Nu(5) = 0.00001569: k_Air(5) = 0.02624: Alpha_Air(5) =
0.00002216
Rho(6) = 0.998: Cp_Air(6) = 1.009: Nu(6) = 0.00002076: k_Air(6) = 0.03003: Alpha_Air(6) = 0.00002983
Rho(7) = 0.8826: Cp_Air(7) = 1.014: Nu(7) = 0.0000259: k_Air(7) = 0.03365: Alpha_Air(7) = 0.0000376
Rho(8) = 0.7833: Cp_Air(8) = 1.0207: Nu(8) = 0.00003171: k_Air(8) = 0.03707: Alpha_Air(8) = 0.4222
Rho(25) = 0.7048: Cp_Air(25) = 1.0295: Nu(25) = 0.0000379: k_Air(25) = 0.04038: Alpha_Air(25) =
0.00005564
```

```
Rho(10) = 0.6423: Cp_Air(10) = 1.0392: Nu(10) = 0.00004434: k_Air(10) = 0.0436: Alpha_Air(10) =
0.00006532
Rho(11) = 0.5879: Cp_Air(11) = 1.0551: Nu(11) = 0.00005134: k_Air(11) = 0.04659: Alpha_Air(11) =
0.00007512
Rho(12) = 0.543: Cp_Air(12) = 1.0635: Nu(12) = 0.00005851: k_Air(12) = 0.04953: Alpha_Air(12) =
0.00008578
Rho(13) = 0.503: Cp_Air(13) = 1.0752: Nu(13) = 0.00006625: k_Air(13) = 0.0523: Alpha_Air(13) =
0.00009672
Rho(14) = 0.4709: Cp_Air(14) = 1.0856: Nu(14) = 0.00007391: k_Air(14) = 0.05509: Alpha_Air(14) =
0.00010774
Rho(15) = 0.4405: Cp_Air(15) = 1.0978: Nu(15) = 0.00008229: k_Air(15) = 0.05779: Alpha_Air(15) =
0.00011951
Rho(16) = 0.4149: Cp_Air(16) = 1.1095: Nu(16) = 0.00009075: k_Air(16) = 0.06028: Alpha_Air(16) =
0.00013097
Rho(17) = 0.3925: Cp_Air(17) = 1.1212: Nu(17) = 0.0000993: k_Air(17) = 0.06279: Alpha_Air(17) =
0.00014271
Rho(18) = 0.3716: Cp_Air(18) = 1.1321: Nu(18) = 0.0001082: k_Air(18) = 0.06525: Alpha_Air(18) =
0.0001551
Rho(19) = 0.3524: Cp_Air(19) = 1.1417: Nu(19) = 0.0001178: k_Air(19) = 0.06752: Alpha_Air(19) =
0.00016779
Rho(20) = 0.3204: Cp_Air(20) = 1.16: Nu(20) = 0.0001386: k_Air(20) = 0.0732: Alpha_Air(20) =
0.0001969
Rho(21) = 0.2947: Cp_Air(21) = 1.179: Nu(21) = 0.0001591: k_Air(21) = 0.0782: Alpha_Air(21) =
0.0002251
Rho(22) = 0.2707: Cp_Air(22) = 1.197: Nu(22) = 0.0001821: k_Air(22) = 0.0837: Alpha_Air(22) =
0.0002583
Rho(23) = 0.2515: Cp_Air(23) = 1.214: Nu(23) = 0.0002055: k_Air(23) = 0.0891: Alpha_Air(23) =
0.000292
Rho(24) = 0.2355: Cp_Air(24) = 1.23: Nu(24) = 0.0002291: k_Air(24) = 0.0946: Alpha_Air(24) =
0.0003262
Rho(25) = 0.2211: Cp_Air(25) = 1.248: Nu(25) = 0.0002545: k_Air(25) = 0.1: Alpha_Air(25) = 0.0003609
Rho(26) = 0.2082: Cp_Air(26) = 1.267: Nu(26) = 0.0002805: k_Air(26) = 0.105: Alpha_Air(26) =
0.0003977
Rho(27) = 0.197: Cp_Air(27) = 1.287: Nu(27) = 0.0003081: k_Air(27) = 0.111: Alpha_Air(27) =
0.0004379
Rho(28) = 0.1858: Cp_Air(28) = 1.309: Nu(28) = 0.0003385: k_Air(28) = 0.117: Alpha_Air(28) =
0.0004811
Rho(29) = 0.1762: Cp_Air(29) = 1.338: Nu(29) = 0.000369: k_Air(29) = 0.124: Alpha_Air(29) = 0.000526
Rho(30) = 0.1682: Cp_Air(30) = 1.372: Nu(30) = 0.0003996: k_Air(30) = 0.131: Alpha_Air(30) =
0.0005715
Rho(31) = 0.1602: Cp_Air(31) = 1.419: Nu(31) = 0.0004326: k_Air(31) = 0.139: Alpha_Air(31) =
0.000612
Rho(32) = 0.1538: Cp_Air(32) = 1.482: Nu(32) = 0.000464: k_Air(32) = 0.149: Alpha_Air(32) = 0.000654
Rho(33) = 0.1458: Cp_Air(33) = 1.574: Nu(33) = 0.000504: k_Air(33) = 0.161: Alpha_Air(33) = 0.000702
Rho(34) = 0.1394: Cp_Air(34) = 1.688: Nu(34) = 0.054305: k_Air(34) = 0.175: Alpha_Air(34) =
0.0007441

End Sub
```

```
Form1

Private Sub Command1_Click()

    L = Text1.Text / 1000
    W = Text2.Text / 1000
    H = Text3.Text / 1000
    Th = Text4.Text / 2000
    md = Text5.Text * 1
    Mole_AFR = Text6.Text * 1
    T1 = Text7.Text + 273
    Troom = Text8.Text + 273

    If Combo1.Text = "Brick" Then
        Density = 1600
        epsilon = 0.87
        SHC = 8400
        k_Enc = 0.69
    ElseIf Combo1.Text = "Mild Steel" Then
        Density = 7800
        epsilon = 0.25
        SHC = 4700
        k_Enc = 43
    End If

    Trial_No = 5000
    K = 1.96
    Zone_Length = L / 4
    V = H * W * Zone_Length

    Load_Excel
    Air_Properties
    Flame_Temp
    Velocity (T1)
    Enegry_Balance

    End

End Sub
Sub Enegry_Balance()

    Time = 0
    ReDim Preserve Tg(4, Time + 1)
    ReDim Preserve Tw(18, Time + 1)
    ReDim Preserve Tm(18, Time + 1)
    ReDim Preserve Ts(18, Time + 1)
    ReDim Preserve Qv(4, 18, Time + 1)
    ReDim Preserve Qr(22, 22, Time + 1)
    ReDim Preserve QTw(18, Time + 1)
    ReDim Preserve Qn(18, Time + 1)
    ReDim Preserve QLv(4, Time + 1)
    ReDim Preserve QLr(4, Time + 1)
    ReDim Preserve Te(4, Time + 1)
```

```
 For i38 = 1 To 18
   Tw(i38, Time) = Troom
   Tm(i38, Time) = Troom
   Ts(i38, Time) = Troom
 Next i38

 For i37 = 1 To 4
   Tg(i37, Time) = Troom
 Next i37

   Tg(1, Time) = Tf
   Flag = 1

 Do

 Time = Time + 1
 Finish = 0

 ReDim Preserve Tg(4, Time + 1)
 ReDim Preserve Tw(18, Time + 1)
 ReDim Preserve Tm(18, Time + 1)
 ReDim Preserve Ts(18, Time + 1)
 ReDim Preserve Qv(4, 18, Time + 1)
 ReDim Preserve Qr(22, 22, Time + 1)
 ReDim Preserve QTw(18, Time + 1)
 ReDim Preserve Qn(18, Time + 1)
 ReDim Preserve QLv(4, Time + 1)
 ReDim Preserve QLr(4, Time + 1)
 ReDim Preserve Te(4, Time + 1)

   Soot
   Radiation
   Heat_Flux

   Time_Interval = Zone_Length / Vel

   Conduction_1 1, Time - 1

For Zone_Number = 2 To 16 Step 2
  Conduction_2 Zone_Number, Time - 1
Next Zone_Number

For Zone_Number = 3 To 17 Step 2
  Conduction_3 Zone_Number, Time - 1
Next Zone_Number

  Conduction_1 18, Time - 1

For Gas_Number = 1 To 4
  If Gas_Number = 1 Then
    For i39 = 1 To 5
      QLv(Gas_Number, Time - 1) = QLv(Gas_Number, Time - 1) + Qv(Gas_Number, i39, Time - 1)
```

```
      Next i39
      For i40 = 1 To 22
        QLr(Gas_Number, Time - 1) = QLr(Gas_Number, Time - 1) + Qr(Gas_Number, i40, Time - 1)
      Next i40
    ElseIf Gas_Number = 2 Then
      For i39 = 6 To 9
        QLv(Gas_Number, Time - 1) = QLv(Gas_Number, Time - 1) + Qv(Gas_Number, i39, Time - 1)
      Next i39
      For i40 = 1 To 22
        QLr(Gas_Number, Time - 1) = QLr(Gas_Number, Time - 1) + Qr(Gas_Number, i40, Time - 1)
      Next i40
    ElseIf Gas_Number = 3 Then
      For i39 = 10 To 13
        QLv(Gas_Number, Time - 1) = QLv(Gas_Number, Time - 1) + Qv(Gas_Number, i39, Time - 1)
      Next i39
      For i40 = 1 To 22
        QLr(Gas_Number, Time - 1) = QLr(Gas_Number, Time - 1) + Qr(Gas_Number, i40, Time - 1)
      Next i40
    ElseIf Gas_Number = 4 Then
      For i39 = 14 To 18
        QLv(Gas_Number, Time - 1) = QLv(Gas_Number, Time - 1) + Qv(Gas_Number, i39, Time - 1)
      Next i39
      For i40 = 1 To 22
        QLr(Gas_Number, Time - 1) = QLr(Gas_Number, Time - 1) + Qr(Gas_Number, i40, Time - 1)
      Next i40
    End If

      Tg(1, Time) = Tf
      Te(Gas_Number, Time - 1) = Tg(Gas_Number, Time - 1) - (QLv(Gas_Number, Time - 1) +
QLr(Gas_Number, Time - 1)) * Time_Interval / ((Rho_Air(Tg(Gas_Number, Time - 1)) * V *
Cp(Tg(Gas_Number, Time - 1))))
    If Gas_Number <> 1 Then
      Tg(Gas_Number, Time) = Te(Gas_Number - 1, Time - 1)
    End If

    If Abs(Tg(Gas_Number, Time) - Tg(Gas_Number, Time - 1)) < 0.01 Then
      Control = 1
    Else
      Control = 0
    End If

  Finish = Finish + Control

  Next Gas_Number

  'If (Time * Time_Interval) > Flag * 60 Then
    'Display
    'Flag = Flag + 1
  'End If

  Display

  Display1
```

```
    Loop Until Finish = 4

End Sub
Sub Flame_Temp()

    DeltaT1 = T1 - 298

    Hreact = (hC4H10 + CpC4H10(T1) * DeltaT1) + Mole_AFR * (hO2 + CpO2(T1) * DeltaT1) + 3.76 *
Mole_AFR * (hN2 + CpN2(T1) * DeltaT1)

    If Mole_AFR = 6.5 Then
        Alpha = 0
        Beta = 1
        Gamma = 0
    ElseIf Mole_AFR > 6.5 Then
        Alpha = 0
        Beta = 1
        Gamma = Mole_AFR - 6.5
    Else
        Alpha = 1 - Mole_AFR / 6.5
        Beta = Mole_AFR / 6.5
        Gamma = 0
    End If

    Hproduct = Alpha * hC4H10 + 4 * Beta * hCO2 + 5 * Beta * hH2O + Gamma * hO2 + 3.76 *
Mole_AFR * hN2

    i = 1
    Do
        ReDim Preserve Tad(i + 1)
        Tad(1) = 1000
        Hq = Alpha * CpC4H10(Tad(i)) + 4 * Beta * CpCO2(Tad(i)) + 5 * Beta * CpH2O(Tad(i)) + Gamma
* CpO2(Tad(i)) + 3.76 * Mole_AFR * CpN2(Tad(i))
        i = i + 1
        Tad(i) = (Hreact - Hproduct) / Hq

    Loop Until Abs(Tad(i) - Tad(i - 1)) < 0.01

    Tf = Tad(i) + 298

End Sub

Sub Velocity(T)

    Vel = (Alpha * MW_C4H10 + 4 * Beta * MW_CO2 + 5 * Beta * MW_H2O + Gamma * MW_O2 +
3.76 * Mole_AFR * MW_N2) * md / (MW_C4H10 * Rho_Air(Tf) * H * W)

End Sub
Function F_Heat_Coeff(Tg)

    Hyd_Dia = 2 * H * W / (H + W)
    Re = Vel * Hyd_Dia / Kin_Vis(Tg)
```

```
    F_Heat_Coeff = 0.715 * Cond(Tg) * Re ^ 0.75 / Hyd_Dia

End Function
Sub Radiation()

    Randomize
    Surface
    gas
    Smooth

End Sub
Sub Soot()

    A1 = 0.38: A2 = 5000
    B1 = 0.015: B2 = 5000
    Rho_s = 900: ds = 0.000000022
    PO2 = Gamma / (Alpha + 9 * Beta + Gamma + 3.76 * Mole_AFR) * 1

    s = A1 * md * Exp(-A2 / Tf) * Rho_s * ds / (B1 * Exp(-B2 / Tf) * PO2 ^ 0.5)

    Vol_Fraction = s / (Rho_s * (L * H * W))

End Sub
Function Ka(Ty)

    g = 6.3: C = 0.014388

    Ka = 3.6 * Vol_Fraction * g * Ty / C

End Function
Sub Surface()  'Calculate exchange area from surface zone

For i37 = 1 To 18
    For i38 = 1 To 4
        Usg(i37, i38) = 0
    Next i38
Next i37

For i39 = 1 To 18
    For i40 = 1 To 18
        Uss(i39, i40) = 0
    Next i40
Next i39

For Surface_Number = 1 To 18

    For i1 = 1 To Trial_No
        If Surface_Number = 1 Then
            x = 0
            Do
            y = H * Rnd
            Loop Until y <> 0
            Do
```

```
        z = W * Rnd
        Loop Until z <> 0
        zone1 x, y, z
      ElseIf Surface_Number = 18 Then
        x = L
        Do
        y = H * Rnd
        Loop Until y <> 0
        Do
        z = W * Rnd
        Loop Until z <> 0
        zone6 x, y, z
      ElseIf Surface_Number Mod 4 = 2 Then
        Do
        x = Zone_Length * (Int(Surface_Number / 4) + Rnd)
        Loop Until x <> 0
        Do
        y = H * Rnd
        Loop Until y <> 0
        z = W
        zone2 x, y, z
      ElseIf Surface_Number Mod 4 = 3 Then
        Do
        x = Zone_Length * (Int(Surface_Number / 4) + Rnd)
        Loop Until x <> 0
        y = H
        Do
        z = W * Rnd
        Loop Until z <> 0
        zone3 x, y, z
      ElseIf Surface_Number Mod 4 = 0 Then
        Do
        x = Zone_Length * (Int(Surface_Number / 4) - Rnd)
        Loop Until x <> 0
        Do
        y = H * Rnd
        Loop Until y <> 0
        z = 0
        zone4 x, y, z
      ElseIf Surface_Number Mod 4 = 1 Then
        Do
        x = Zone_Length * (Int(Surface_Number / 4) - Rnd)
        Loop Until x <> 0
        y = 0
        Do
        z = W * Rnd
        Loop Until z <> 0
        zone5 x, y, z
      End If


Line30:
  Distance x, y, z, XXX, YYY, ZZZ
```

```
    If x < XXX Then
    Gas_Number = 0
    Do
      Gas_Number = Gas_Number + 1
      rg(Gas_Number) = -Log(1 - Rnd) / Ka(Tg(Gas_Number, Time - 1))
      If Gas_Number = 4 Then GoTo Line10
    Loop Until rg(Gas_Number) <= Smin(Gas_Number)
    Else
    Gas_Number = 5
    Do
      Gas_Number = Gas_Number - 1
      rg(Gas_Number) = -Log(1 - Rnd) / Ka(Tg(Gas_Number, Time - 1))
      If Gas_Number = 1 Then GoTo Line10
    Loop Until rg(Gas_Number) <= Smin(Gas_Number)
    End If
      Usg(Surface_Number, Gas_Number) = Usg(Surface_Number, Gas_Number) + 1
      GoTo Line20
 Line10:
      R_epsilon = Rnd
      If epsilon >= R_epsilon Then
        Zone_Location XXX, YYY, ZZZ
        Uss(Surface_Number, Zone_Number) = Uss(Surface_Number, Zone_Number) + 1
        GoTo Line20
      Else
        x = XXX
        y = YYY
        z = ZZZ
        If XXX = 0 Then
          zone1 0, y, z
        ElseIf ZZZ = W Then
          zone2 x, y, W
        ElseIf YYY = H Then
          zone3 x, H, z
        ElseIf ZZZ = 0 Then
          zone4 XXX, YYY, 0
        ElseIf YYY = 0 Then
          zone5 XXX, 0, ZZZ
        ElseIf XXX = L Then
          zone6 L, YYY, ZZZ
        End If
        GoTo Line30
      End If
Line20:
  Next i1

     For Gas_Number = 1 To 4
       SG(Surface_Number, Gas_Number) = epsilon * A(Surface_Number) * Usg(Surface_Number,
Gas_Number) / Trial_No
     Next Gas_Number
     For Zone_Number = 1 To 18
       SS(Surface_Number, Zone_Number) = epsilon * A(Surface_Number) * Uss(Surface_Number,
Zone_Number) / Trial_No
     Next Zone_Number
```

```
 Next Surface_Number


 End Sub

 Sub gas()   'Calculate Exchange area from gas zone

 For i41 = 1 To 4
    For i42 = 1 To 4
       Ugg(i41, i42) = 0
    Next i42
 Next i41

 For i43 = 1 To 4
    For i44 = 1 To 18
       Ugs(i43, i44) = 0
    Next i44
 Next i43

 For Volume_Number = 1 To 4
       For i2 = 1 To Trial_No
          Do
          x = Zone_Length * (Volume_Number - Rnd)
          Loop Until x <> 0
          Do
          y = H * Rnd
          Loop Until y <> 0
          Do
          z = W * Rnd
          Loop Until z <> 0
          Gas_zone x, y, z
Line30:
   Distance x, y, z, XXX, YYY, ZZZ
   If x < XXX Then
   Gas_Number = 0
   Do
      Gas_Number = Gas_Number + 1
      rg(Gas_Number) = -Log(1 - Rnd) / Ka(Tg(Gas_Number, Time - 1))
      If Gas_Number = 4 Then GoTo Line10
   Loop Until rg(Gas_Number) <= Smin(Gas_Number)
   Else
   Gas_Number = 4
   Do
      Gas_Number = Gas_Number - 1
      rg(Gas_Number) = -Log(1 - Rnd) / Ka(Tg(Gas_Number, Time - 1))
      If Gas_Number = 1 Then GoTo Line10
   Loop Until rg(Gas_Number) <= Smin(Gas_Number)
   End If
      Ugg(Volume_Number, Gas_Number) = Ugg(Volume_Number, Gas_Number) + 1
      GoTo Line20
Line10:
      R_epsilon = Rnd
```

```
        If epsilon >= R_epsilon Then
           Zone_Location XXX, YYY, ZZZ
           Ugs(Volume_Number, Zone_Number) = Ugs(Volume_Number, Zone_Number) + 1
           GoTo Line20
        Else
           x = XXX
           y = YYY
           z = ZZZ
           If XXX = 0 Then
              zone1 0, y, z
           ElseIf ZZZ = W Then
              zone2 x, y, W
           ElseIf YYY = H Then
              zone3 x, H, z
           ElseIf ZZZ = 0 Then
              zone4 XXX, YYY, 0
           ElseIf YYY = 0 Then
              zone5 XXX, 0, ZZZ
           ElseIf XXX = L Then
              zone6 L, YYY, ZZZ
           End If
           GoTo Line30
       End If
Line20:
   Next i2
      For Gas_Number = 1 To 4
         GG(Volume_Number, Gas_Number) = 4 * Ka(Tg(Volume_Number, Time - 1)) * V *
Ugg(Volume_Number, Gas_Number) / Trial_No
      Next Gas_Number
      For Zone_Number = 1 To 18
         GS(Volume_Number, Zone_Number) = 4 * Ka(Tg(Volume_Number, Time - 1)) * V *
Ugs(Volume_Number, Zone_Number) / Trial_No
      Next Zone_Number

Next Volume_Number
End Sub

Sub zone1(x, y, z)  'Calculate Intersection from zone 1

Do
  Theta = 2 * Pi * Rnd
Loop While Theta = 0

Do
  Eta = arccos(Sqr(Rnd))
Loop While Eta = 0

  Select Case Theta

  Case 0 To Atn((H - y) / (W - z))
    XX = Abs((W - z) / (Cos(Theta) * Tan(Eta)))

    If XX < L Then
```

```
      XXX = XX
      YYY = y + (W - z) * Tan(Theta)
      ZZZ = W
    Else
      XXX = L
      YYY = y + L * Tan(Eta) * Sin(Theta)
      ZZZ = z + L * Tan(Eta) * Cos(Theta)
    End If

  Case (Atn((H - y) / (W - z))) To (Pi / 2 + Atn(z / (H - y)))
    XX = Abs((H - y) / (Sin(Theta) * Tan(Eta)))

    If XX < L Then
      XXX = XX
      YYY = H
      ZZZ = z + (H - y) / Tan(Theta)
    Else
      XXX = L
      YYY = y + L * Tan(Eta) * Sin(Theta)
      ZZZ = z + L * Tan(Eta) * Cos(Theta)
    End If

  Case (Pi / 2 + Atn(z / (H - y))) To (Pi + Atn(y / z))
    XX = Abs(z / (Cos(Theta) * Tan(Eta)))

    If XX < L Then
      XXX = XX
      YYY = y - z * Tan(Theta)
      ZZZ = 0
    Else
      XXX = L
      YYY = y + L * Tan(Eta) * Sin(Theta)
      ZZZ = z + L * Tan(Eta) * Cos(Theta)
    End If

  Case (Pi + Atn(y / z)) To (2 * Pi - Atn(y / (W - z)))
    XX = Abs(y / (Sin(Theta) * Tan(Eta)))

    If XX < L Then
      XXX = XX
      YYY = 0
      ZZZ = z - y / Tan(Theta)
    Else
      XXX = L
      YYY = y + L * Tan(Eta) * Sin(Theta)
      ZZZ = z + L * Tan(Eta) * Cos(Theta)
    End If

  Case Else
    XX = Abs((W - z) / (Cos(Theta) * Tan(Eta)))

    If XX < L Then
      XXX = XX
```

```
        YYY = y + (W - z) * Tan(Theta)
        ZZZ = W
      Else
        XXX = L
        YYY = y + L * Tan(Eta) * Sin(Theta)
        ZZZ = z + L * Tan(Eta) * Cos(Theta)
      End If

  End Select

End Sub

Sub zone2(x, y, z)  'Calculate intersection from zone 2


Do
  Theta = 2 * Pi * Rnd
Loop While Theta = 0

Do
  Eta = arccos(Sqr(Rnd))
Loop While Eta = 0

  Select Case Theta

    Case 0 To Atn((H - y) / (L - x))
      ZZ = W - Abs((L - x) / (Cos(Theta) * Tan(Eta)))

      If ZZ > 0 Then
        XXX = L
        YYY = y + (L - x) * Tan(Theta)
        ZZZ = ZZ
      Else
        XXX = x + W * Cos(Theta) * Tan(Eta)
        YYY = y + W * Sin(Theta) * Tan(Eta)
        ZZZ = 0
      End If

    Case Atn((H - y) / (L - x)) To Pi / 2 + Atn(x / (H - y))
      ZZ = W - Abs((H - y) / (Sin(Theta) * Tan(Eta)))

      If ZZ > 0 Then
        XXX = x + (H - y) / Tan(Theta)
        YYY = H
        ZZZ = ZZ
      Else
        XXX = x + W * Cos(Theta) * Tan(Eta)
        YYY = y + W * Sin(Theta) * Tan(Eta)
        ZZZ = 0
      End If

    Case Pi / 2 + Atn(x / (H - y)) To Pi + Atn(y / x)
      ZZ = W - Abs(x / (Cos(Theta) * Tan(Eta)))
```

```
        If ZZ > 0 Then
            XXX = 0
            YYY = y - x * Tan(Theta)
            ZZZ = ZZ
        Else
            XXX = x + W * Cos(Theta) * Tan(Eta)
            YYY = y + W * Sin(Theta) * Tan(Eta)
            ZZZ = 0
        End If

    Case Pi + Atn(y / x) To 2 * Pi - Atn(y / (L - x))
        ZZ = W - Abs(y / (Sin(Theta) * Tan(Eta)))

        If ZZ > 0 Then
            XXX = x - y / Tan(Theta)
            YYY = 0
            ZZZ = ZZ
        Else
            XXX = x + W * Cos(Theta) * Tan(Eta)
            YYY = y + W * Sin(Theta) * Tan(Eta)
            ZZZ = 0
        End If

    Case Else
        ZZ = W - Abs((L - x) / (Cos(Theta) * Tan(Eta)))

        If ZZ > 0 Then
            XXX = L
            YYY = y + (L - x) * Tan(Theta)
            ZZZ = ZZ
        Else
            XXX = x + W * Cos(Theta) * Tan(Eta)
            YYY = y + W * Sin(Theta) * Tan(Eta)
            ZZZ = 0
        End If

    End Select


End Sub

Sub zone3(x, y, z)  'Calculate intersection from zone3


Do
    Theta = 2 * Pi * Rnd
Loop While Theta = 0

Do
    Eta = arccos(Sqr(Rnd))
Loop While Eta = 0
```

```
Select Case Theta

  Case 0 To Atn(x / z)
    YY = H - Abs(z / (Cos(Theta) * Tan(Eta)))

    If YY > 0 Then
      XXX = x - z * Tan(Theta)
      YYY = YY
      ZZZ = 0
    Else
      XXX = x - H * Sin(Theta) * Tan(Eta)
      YYY = 0
      ZZZ = z - H * Cos(Theta) * Tan(Eta)
    End If

  Case Atn(x / z) To Pi - Atn(x / (W - z))
    YY = H - Abs(x / (Sin(Theta) * Tan(Eta)))

    If YY > 0 Then
      XXX = 0
      YYY = YY
      ZZZ = z - x / Tan(Theta)
    Else
      XXX = x - H * Sin(Theta) * Tan(Eta)
      YYY = 0
      ZZZ = z - H * Cos(Theta) * Tan(Eta)
    End If

  Case Pi - Atn(x / (W - z)) To Pi + Atn((L - x) / (W - z))
    YY = H - Abs((W - z) / (Cos(Theta) * Tan(Eta)))

    If YY > 0 Then
      XXX = x + (W - z) * Tan(Theta)
      YYY = YY
      ZZZ = W
    Else
      XXX = x - H * Sin(Theta) * Tan(Eta)
      YYY = 0
      ZZZ = z - H * Cos(Theta) * Tan(Eta)
    End If

  Case Pi + Atn((L - x) / (W - z)) To 2 * Pi - Atn((L - x) / z)
    YY = H - Abs((L - x) / (Sin(Theta) * Tan(Eta)))

    If YY > 0 Then
      XXX = L
      YYY = YY
      ZZZ = z + (L - x) / Tan(Theta)
    Else
      XXX = x - H * Sin(Theta) * Tan(Eta)
      YYY = 0
      ZZZ = z - H * Cos(Theta) * Tan(Eta)
    End If
```

```
      Case Else
        YY = H - Abs(z / (Cos(Theta) * Tan(Eta)))

        If YY > 0 Then
          XXX = x - z * Tan(Theta)
          YYY = YY
          ZZZ = 0
        Else
          XXX = x - H * Sin(Theta) * Tan(Eta)
          YYY = 0
          ZZZ = z - H * Cos(Theta) * Tan(Eta)
        End If

      End Select


End Sub

Sub zone4(x, y, z)  'Calculate intersection from zone 4

Do
  Theta = 2 * Pi * Rnd
Loop While Theta = 0

Do
  Eta = arccos(Sqr(Rnd))
Loop While Eta = 0

  Select Case Theta

  Case 0 To Atn((H - y) / (L - x))
    ZZ = Abs((L - x) / (Cos(Theta) * Tan(Eta)))

    If ZZ < W Then
      XXX = L
      YYY = y + (L - x) * Tan(Theta)
      ZZZ = ZZ
    Else
      XXX = x + W * Cos(Theta) * Tan(Eta)
      YYY = y + W * Sin(Theta) * Tan(Eta)
      ZZZ = W
    End If

  Case Atn((H - y) / (L - x)) To Pi - Atn((H - y) / x)
    ZZ = Abs((H - y) / (Sin(Theta) * Tan(Eta)))

    If ZZ < W Then
      XXX = x + (H - y) / Tan(Theta)
      YYY = H
      ZZZ = ZZ
    Else
      XXX = x + W * Cos(Theta) * Tan(Eta)
```

```
            YYY = y + W * Sin(Theta) * Tan(Eta)
            ZZZ = W
          End If

        Case Pi - Atn((H - y) / x) To Pi + Atn(y / x)
          ZZ = Abs(x / (Cos(Theta) * Tan(Eta)))

          If ZZ < W Then
            XXX = 0
            YYY = y - x * Tan(Theta)
            ZZZ = ZZ
          Else
            XXX = x + W * Cos(Theta) * Tan(Eta)
            YYY = y + W * Sin(Theta) * Tan(Eta)
            ZZZ = W
          End If

        Case Pi + Atn(y / x) To 2 * Pi - Atn(y / (L - x))
          ZZ = Abs(y / (Sin(Theta) * Tan(Eta)))

          If ZZ < W Then
            XXX = x - y / Tan(Theta)
            YYY = 0
            ZZZ = ZZ
          Else
            XXX = x + W * Cos(Theta) * Tan(Eta)
            YYY = y + W * Sin(Theta) * Tan(Eta)
            ZZZ = W
          End If

        Case Else
          ZZ = Abs((L - x) / (Cos(Theta) * Tan(Eta)))

          If ZZ < W Then
            XXX = L
            YYY = y + (L - x) * Tan(Theta)
            ZZZ = ZZ
          Else
            XXX = x + W * Cos(Theta) * Tan(Eta)
            YYY = y + W * Sin(Theta) * Tan(Eta)
            ZZZ = W
          End If

    End Select


End Sub

Sub zone5(x, y, z)  'Calculate intersection from zone 5


Do
  Theta = 2 * Pi * Rnd
```

```
Loop While Theta = 0

Do
  Eta = arccos(Sqr(Rnd))
Loop While Eta = 0

  Select Case Theta

    Case 0 To Atn(z / (L - x))
      YY = Abs((L - x) / (Cos(Theta) * Tan(Eta)))

      If YY < H Then
        XXX = L
        YYY = YY
        ZZZ = z - (L - x) * Tan(Theta)
      Else
        XXX = x + H * Cos(Theta) * Tan(Eta)
        YYY = H
        ZZZ = z - H * Sin(Theta) * Tan(Eta)
      End If

    Case Atn(z / (L - x)) To Pi - Atn(z / x)
      YY = Abs(z / (Sin(Theta) * Tan(Eta)))

      If YY < H Then
        XXX = x + z / Tan(Theta)
        YYY = YY
        ZZZ = 0
      Else
        XXX = x + H * Cos(Theta) * Tan(Eta)
        YYY = H
        ZZZ = z - H * Sin(Theta) * Tan(Eta)
      End If

    Case Pi - Atn(z / x) To Pi + Atn((W - z) / x)
      YY = Abs(x / (Cos(Theta) * Tan(Eta)))

      If YY < H Then
        XXX = 0
        YYY = YY
        ZZZ = z + x * Tan(Theta)
      Else
        XXX = x + H * Cos(Theta) * Tan(Eta)
        YYY = H
        ZZZ = z - H * Sin(Theta) * Tan(Eta)
      End If

    Case Pi + Atn((W - z) / x) To 2 * Pi - Atn((W - z) / (L - x))
      YY = Abs((W - z) / (Sin(Theta) * Tan(Eta)))

      If YY < H Then
        XXX = x - (W - z) / Tan(Theta)
        YYY = YY
```

```
          ZZZ = W
        Else
          XXX = x + H * Cos(Theta) * Tan(Eta)
          YYY = H
          ZZZ = z - H * Sin(Theta) * Tan(Eta)
        End If

      Case Else
        YY = Abs((L - x) / (Cos(Theta) * Tan(Eta)))

        If YY < H Then
          XXX = L
          YYY = YY
          ZZZ = z - (L - x) * Tan(Theta)
        Else
          XXX = x + H * Cos(Theta) * Tan(Eta)
          YYY = H
          ZZZ = z - H * Sin(Theta) * Tan(Eta)
        End If

      End Select

 End Sub

Sub zone6(x, y, z)  'Calculate intersection from zone 6

Do
  Theta = 2 * Pi * Rnd
Loop While Theta = 0

Do
  Eta = arccos(Sqr(Rnd))
Loop While Eta = 0

  Select Case Theta

  Case 0 To Atn((H - y) / (W - z))
    XX = L - Abs((W - z) / (Cos(Theta) * Tan(Eta)))

    If XX > 0 Then
      XXX = XX
      YYY = y + (W - z) * Sin(Theta)
      ZZZ = W
    Else
      XXX = 0
      YYY = y + L * Sin(Theta) * Tan(Eta)
      ZZZ = z + L * Cos(Theta) * Tan(Eta)
    End If

  Case Atn((H - y) / (W - z)) To Pi - Atn((H - y) / z)
    XX = L - Abs((H - y) / (Sin(Theta) * Tan(Eta)))

    If XX > 0 Then
```

```
      XXX = XX
      YYY = H
      ZZZ = z + (H - y) / Tan(Theta)
    Else
      XXX = 0
      YYY = y + L * Sin(Theta) * Tan(Eta)
      ZZZ = z + L * Cos(Theta) * Tan(Eta)
    End If

  Case Pi - Atn((H - y) / z) To Pi + Atn(y / z)
    XX = L - Abs(z / (Cos(Theta) * Tan(Eta)))

    If XX > 0 Then
      XXX = XX
      YYY = y - z * Tan(Theta)
      ZZZ = 0
    Else
      XXX = 0
      YYY = y + L * Sin(Theta) * Tan(Eta)
      ZZZ = z + L * Cos(Theta) * Tan(Eta)
    End If

  Case Pi + Atn(y / z) To 2 * Pi - Atn(y / (W - z))
    XX = L - Abs(y / (Sin(Theta) * Tan(Eta)))

    If XX > 0 Then
      XXX = XX
      YYY = 0
      ZZZ = z - y / Tan(Theta)
    Else
      XXX = 0
      YYY = y + L * Sin(Theta) * Tan(Eta)
      ZZZ = z + L * Cos(Theta) * Tan(Eta)
    End If

  Case Else
    XX = L - Abs((W - z) / (Cos(Theta) * Tan(Eta)))

    If XX > 0 Then
      XXX = XX
      YYY = y + (W - z) * Sin(Theta)
      ZZZ = W
    Else
      XXX = 0
      YYY = y + L * Sin(Theta) * Tan(Eta)
      ZZZ = z + L * Cos(Theta) * Tan(Eta)
    End If

  End Select

End Sub
Sub Gas_zone(x, y, z)
```

```
Do
   Theta = 2 * Pi * Rnd
Loop While Theta = 0

Do
   Eta = arccos(1 - 2 * Rnd)
Loop While Eta = 0

   Select Case Theta

   Case 0 To Atn(z / (L - x))
      YY = y + Abs((L - x) / Cos(Theta)) / Tan(Eta)

      If YY > 0 And YY < H Then
         XXX = L
         YYY = YY
         ZZZ = z - (L - x) * Tan(Theta)
      ElseIf YY < 0 Then
         XXX = x + (H - y) * Cos(Theta) * Abs(Tan(Eta))
         YYY = 0
         ZZZ = z - (H - y) * Sin(Theta) * Abs(Tan(Eta))
      ElseIf YY > H Then
         XXX = x + (H - y) * Cos(Theta) * Abs(Tan(Eta))
         YYY = H
         ZZZ = z - (H - y) * Sin(Theta) * Abs(Tan(Eta))
      End If

   Case Atn(z / (L - x)) To Pi - Atn(z / x)
      YY = y + Abs(z / Sin(Theta)) / Tan(Eta)

      If YY > 0 And YY < H Then
         XXX = x + z / Tan(Theta)
         YYY = YY
         ZZZ = 0
      ElseIf YY < 0 Then
         XXX = x + (H - y) * Cos(Theta) * Abs(Tan(Eta))
         YYY = 0
         ZZZ = z - (H - y) * Sin(Theta) * Abs(Tan(Eta))
      ElseIf YY > H Then
         XXX = x + (H - y) * Cos(Theta) * Abs(Tan(Eta))
         YYY = H
         ZZZ = z - (H - y) * Sin(Theta) * Abs(Tan(Eta))
      End If

   Case Pi - Atn(z / x) To Pi + Atn((W - z) / x)
      YY = y + Abs(x / Cos(Theta)) / Tan(Eta)

      If YY > 0 And YY < H Then
         XXX = 0
         YYY = YY
         ZZZ = z + x * Tan(Theta)
      ElseIf YY < 0 Then
```

```
            XXX = x + (H - y) * Cos(Theta) * Abs(Tan(Eta))
            YYY = 0
            ZZZ = z - (H - y) * Sin(Theta) * Abs(Tan(Eta))
         ElseIf YY > H Then
            XXX = x + (H - y) * Cos(Theta) * Abs(Tan(Eta))
            YYY = H
            ZZZ = z - (H - y) * Sin(Theta) * Abs(Tan(Eta))
         End If

      Case Pi + Atn((W - z) / x) To 2 * Pi - Atn((W - z) / (L - x))
         YY = y + Abs((W - z) / Sin(Theta)) / Tan(Eta)

         If YY > 0 And YY < H Then
            XXX = x - (W - z) / Tan(Theta)
            YYY = YY
            ZZZ = W
         ElseIf YY < 0 Then
            XXX = x + (H - y) * Cos(Theta) * Abs(Tan(Eta))
            YYY = 0
            ZZZ = z - (H - y) * Sin(Theta) * Abs(Tan(Eta))
         ElseIf YY > H Then
            XXX = x + (H - y) * Cos(Theta) * Abs(Tan(Eta))
            YYY = H
            ZZZ = z - (H - y) * Sin(Theta) * Abs(Tan(Eta))
         End If

      Case 2 * Pi - Atn((W - z) / (L - x)) To 2 * Pi
         YY = y + Abs((L - x) / Cos(Theta)) / Tan(Eta)

         If YY > 0 And YY < H Then
            XXX = L
            YYY = YY
            ZZZ = z - (L - x) * Tan(Theta)
         ElseIf YY < 0 Then
            XXX = x + (H - y) * Cos(Theta) * Abs(Tan(Eta))
            YYY = 0
            ZZZ = z - (H - y) * Sin(Theta) * Abs(Tan(Eta))
         ElseIf YY > H Then
            XXX = x + (H - y) * Cos(Theta) * Abs(Tan(Eta))
            YYY = H
            ZZZ = z - (H - y) * Sin(Theta) * Abs(Tan(Eta))
         End If

   End Select


End Sub

Sub Zone_Location(x, y, z)  'Identify gas zone location

   Zone_Number = 0
   If x = 0 Then
      Zone_Number = 1
```

```
  ElseIf x = L Then
    Zone_Number = 18
  ElseIf z = W Then
    i3 = 1
    Do
      If x < i3 * Zone_Length Then
        Zone_Number = 2 + (i3 - 1) * 4
      Else
        i3 = i3 + 1
      End If
    Loop Until Zone_Number <> 0
  ElseIf y = H Then
    i3 = 1
    Do
      If x < i3 * Zone_Length Then
        Zone_Number = 3 + (i3 - 1) * 4
      Else
        i3 = i3 + 1
      End If
    Loop Until Zone_Number <> 0
  ElseIf z = 0 Then
    i3 = 1
    Do
      If x < i3 * Zone_Length Then
        Zone_Number = 4 + (i3 - 1) * 4
      Else
        i3 = i3 + 1
      End If
    Loop Until Zone_Number <> 0
  ElseIf y = 0 Then
    i3 = 1
    Do
      If x < i3 * Zone_Length Then
        Zone_Number = 5 + (i3 - 1) * 4
      Else
        i3 = i3 + 1
      End If
    Loop Until Zone_Number <> 0
  End If

End Sub

Sub Distance(X1, Y1, Z1, X2, Y2, Z2)    'Calculate photon travel distance
  m = Int(X1 / Zone_Length)
  n = Int(X2 / Zone_Length)

  For i3 = m + 1 To n - 1
    XXXX = (i3) * Zone_Length
    ZZZZ = Z2 + (Z1 - Z2) * (X2 - XXXX) / (X2 - X1)
    YYYY = Y1 + (Y2 - Y1) * (Sqr((X1 - X2) * (X1 - X2) + (Z1 - Z2) * (Z1 - Z2)) - Sqr((XXXX - X2) *
(XXXX - X2) + (ZZZZ - Z2) * (ZZZZ - Z2))) / (Sqr((X1 - X2) * (X1 - X2) + (Z1 - Z2) * (Z1 - Z2)))
    Total_Distance(i3) = Sqr((XXXX - X1) * (XXXX - X1) + (YYYY - Y1) * (YYYY - Y1) + (ZZZZ -
Z1) * (ZZZZ - Z1))
```

```
    Smin(i3) = Total_Distance(i3) - Total_Distance(i3 - 1)
  Next i3
    If n < 4 Then
    Total_Distance(n + 1) = Sqr((X1 - X2) * (X1 - X2) + (Y1 - Y2) * (Y1 - Y2) + (Z1 - Z2) * (Z1 - Z2))
    Smin(n + 1) = Total_Distance(n + 1) - Total_Distance(n)
    End If
End Sub

Sub Smooth()   'Smoothing Procedure
For Surface_Number = 1 To 18
  For Zone_Number = 1 To 18
    F1(Surface_Number, Zone_Number) = Uss(Surface_Number, Zone_Number) / Trial_No
      If F1(Surface_Number, Zone_Number) = 0 Then
        F1(Surface_Number, Zone_Number) = 0.001
      End If
    C1(Surface_Number, Zone_Number) = K * Sqr((1 - F1(Surface_Number, Zone_Number)) / (Trial_No
* F1(Surface_Number, Zone_Number)))
    SS1(Surface_Number, Zone_Number) = (C1(Zone_Number, Surface_Number) * C1(Zone_Number,
Surface_Number) / (C1(Surface_Number, Zone_Number) * C1(Surface_Number, Zone_Number) +
C1(Zone_Number, Surface_Number) * C1(Zone_Number, Surface_Number))) * SS(Surface_Number,
Zone_Number) + (1 - (C1(Zone_Number, Surface_Number) * C1(Zone_Number, Surface_Number) /
(C1(Surface_Number, Zone_Number) * C1(Surface_Number, Zone_Number) + C1(Zone_Number,
Surface_Number) * C1(Zone_Number, Surface_Number)))) * SS(Zone_Number, Surface_Number)
  Next Zone_Number
  For Gas_Number = 1 To 4
    F2(Surface_Number, Gas_Number) = Usg(Surface_Number, Gas_Number) / Trial_No
      If F2(Surface_Number, Gas_Number) = 0 Then
        F2(Surface_Number, Gas_Number) = 0.001
      End If
    C2(Surface_Number, Gas_Number) = K * Sqr((1 - F2(Surface_Number, Gas_Number)) / (Trial_No *
F2(Surface_Number, Gas_Number)))
    SG1(Surface_Number, Gas_Number) = (C2(Gas_Number, Surface_Number) * C2(Gas_Number,
Surface_Number) / (C2(Surface_Number, Gas_Number) * C2(Surface_Number, Gas_Number) +
C2(Gas_Number, Surface_Number) * C2(Gas_Number, Surface_Number))) * SS(Surface_Number,
Gas_Number) + (1 - (C2(Gas_Number, Surface_Number) * C2(Gas_Number, Surface_Number) /
(C2(Surface_Number, Gas_Number) * C2(Surface_Number, Gas_Number) + C2(Gas_Number,
Surface_Number) * C2(Gas_Number, Surface_Number)))) * SS(Gas_Number, Surface_Number)
  Next Gas_Number
Next Surface_Number

For Volume_Number = 1 To 4
  For Zone_Number = 1 To 18
    F3(Volume_Number, Zone_Number) = Ugs(Volume_Number, Zone_Number) / Trial_No
      If F3(Volume_Number, Zone_Number) = 0 Then
        F3(Volume_Number, Zone_Number) = 0.001
      End If
    C3(Volume_Number, Zone_Number) = K * Sqr((1 - F3(Volume_Number, Zone_Number)) /
(Trial_No * F3(Volume_Number, Zone_Number)))
    GS1(Volume_Number, Zone_Number) = (C3(Zone_Number, Volume_Number) * C3(Zone_Number,
Volume_Number) / (C3(Volume_Number, Zone_Number) * C3(Volume_Number, Zone_Number) +
C3(Zone_Number, Volume_Number) * C3(Zone_Number, Volume_Number))) * SS(Volume_Number,
Zone_Number) + (1 - (C1(Zone_Number, Volume_Number) * C3(Zone_Number, Volume_Number) /
```

```
(C3(Volume_Number, Zone_Number) * C3(Volume_Number, Zone_Number) + C3(Zone_Number,
Volume_Number) * C3(Zone_Number, Volume_Number)))) * SS(Zone_Number, Volume_Number)
    Next Zone_Number
    For Gas_Number = 1 To 4
        F4(Volume_Number, Gas_Number) = Ugg(Volume_Number, Gas_Number) / Trial_No
        If F4(Volume_Number, Gas_Number) = 0 Then
            F4(Volume_Number, Gas_Number) = 0.001
        End If
        C4(Volume_Number, Gas_Number) = K * Sqr((1 - F4(Volume_Number, Gas_Number)) / (Trial_No
* F4(Volume_Number, Gas_Number)))
        GG1(Volume_Number, Gas_Number) = (C4(Gas_Number, Volume_Number) * C4(Gas_Number,
Volume_Number) / (C4(Volume_Number, Gas_Number) * C4(Volume_Number, Gas_Number) +
C4(Gas_Number, Volume_Number) * C4(Gas_Number, Volume_Number))) * SS(Volume_Number,
Gas_Number) + (1 - (C4(Gas_Number, Volume_Number) * C4(Gas_Number, Volume_Number) /
(C4(Volume_Number, Gas_Number) * C4(Volume_Number, Gas_Number) + C4(Gas_Number,
Volume_Number) * C4(Gas_Number, Volume_Number)))) * SS(Gas_Number, Volume_Number)
    Next Gas_Number
Next Volume_Number

For i4 = 1 To 18
    For j4 = 1 To 18
        MatrixX(i4, j4) = SS1(i4, j4)
    Next j4
    For j4 = 19 To 22
        MatrixX(i4, j4) = SG1(i4, j4 - 18)
    Next j4
Next i4

For i5 = 19 To 22
    For j5 = 1 To 18
        MatrixX(i5, j5) = GS1(i5 - 18, j5)
    Next j5
    For j5 = 19 To 22
        MatrixX(i5, j5) = GG1(i5 - 18, j5 - 18)
    Next j5
Next i5

For i6 = 1 To 22
    For j6 = 1 To 22
        wij(i6, j6) = MatrixX(i6, j6) * MatrixX(i6, j6)
        SumW(i6) = SumW(i6) + wij(i6, j6)
        SumX(i6) = SumX(i6) + MatrixX(i6, j6)
    Next j6
Next i6

For i7 = 1 To 22
    For j7 = 1 To 22
        If i7 <> j7 Then
            MatrixR(i7, j7) = wij(i7, j7)
        ElseIf i7 = j7 Then
            MatrixR(i7, j7) = wij(i7, j7) + SumW(i7)
        End If
    Next j7
```

```
   Next i7

   For i8 = 1 To 18
       Delta(i8) = epsilon * A(i8) - SumX(i8)
   Next i8
   For i8 = 19 To 22
       Delta(i8) = 4 * Ka(Tg(i8 - 18, Time - 1)) * V - SumX(i8)
   Next i8

   i9 = 1            'Solve matrix equation by iteration method
   For i10 = 1 To 22
       ReDim Preserve Lamda(23, i9)
       Lamda(i10, i9) = 1
   Next i10

   Do
       Temp2 = 0

      ReDim Preserve Lamda(23, i9 + 1)
      For i11 = 1 To 22
          Temp1 = 0

          For i12 = 1 To 22

              If i11 <> i12 Then
                  Temp1 = Temp1 + Lamda(i12, i9) * MatrixR(i11, i12)
              End If
          Next i12
              If MatrixR(i11, i11) = 0 Then
                  MatrixR(i11, i11) = 0.001
              End If
              Lamda(i11, i9 + 1) = (Delta(i11) - Temp1) / MatrixR(i11, i11)

         If Abs(Lamda(i11, i9 + 1) - Lamda(i11, i9)) < 0.01 Then
             Temp2 = Temp2 + 1
         End If
     Next i11
     i9 = i9 + 1
 Loop While Temp2 <> 22

         For i13 = 1 To 22
             For i14 = 1 To 22
                MatrixX1(i13, i14) = MatrixX(i13, i14) + wij(i13, i14) * (Lamda(i13, i9 - 1) + Lamda(i14, i9 - 1))
             Next i14
         Next i13


End Sub

Sub Heat_Flux()

    For i30 = 1 To 18
        For i31 = 1 To 18
```

```
            Qr(i30, i31, Time - 1) = Sigma * MatrixX1(i30, i31) * Tw(i30, Time - 1) ^ 4
         Next i31
         For i31 = 19 To 22
            Qr(i30, i31, Time - 1) = Sigma * MatrixX1(i30, i31) * Tw(i30, Time - 1) ^ 4
         Next i31
      Next i30
      For i30 = 19 To 22
         For i31 = 1 To 18
            Qr(i30, i31, Time - 1) = Sigma * MatrixX1(i30, i31) * Tg(i30 - 18, Time - 1) ^ 4
         Next i31
         For i31 = 19 To 22
            Qr(i30, i31, Time - 1) = Sigma * MatrixX1(i30, i31) * Tg(i30 - 18, Time - 1) ^ 4
         Next i31
      Next i30

      For i32 = 1 To 4

         If i32 = 1 Then
            For i33 = 1 To 5
               Qv(i32, i33, Time - 1) = F_Heat_Coeff(Tg(i32, Time - 1)) * A(Zone_Number) * (Tg(i32, Time -
1) - Tw(i33, Time - 1))
            Next i33
         ElseIf i32 = 2 Then
            For i33 = 6 To 9
               Qv(i32, i33, Time - 1) = F_Heat_Coeff(Tg(i32, Time - 1)) * A(Zone_Number) * (Tg(i32, Time -
1) - Tw(i33, Time - 1))
            Next i33
         ElseIf i32 = 3 Then
            For i33 = 10 To 13
               Qv(i32, i33, Time - 1) = F_Heat_Coeff(Tg(i32, Time - 1)) * A(Zone_Number) * (Tg(i32, Time -
1) - Tw(i33, Time - 1))
            Next i33
         ElseIf i32 = 4 Then
            For i33 = 14 To 18
               Qv(i32, i33, Time - 1) = F_Heat_Coeff(Tg(i32, Time - 1)) * A(Zone_Number) * (Tg(i32, Time -
1) - Tw(i33, Time - 1))
            Next i33
         End If
      Next i32

End Sub
Function N_Heat_Coeff_1(Tx, Troom)

   N_Heat_Coeff_1 = 1.42 * (Abs(Tx - Troom) / (H + 4 * Th)) ^ (1 / 4)

End Function
Function N_Heat_Coeff_2(Tx, Troom)

   N_Heat_Coeff_2 = 1.32 * (Abs(Tx - Troom) / (H + 4 * Th)) ^ (1 / 4)

End Function
Function N_Heat_Coeff_3(Tx, Troom)
```

```
   N_Heat_Coeff_3 = 0.59 * (Abs(Tx - Troom) / (H + 4 * Th)) ^ (1 / 4)

End Function
Sub Conduction_1(Zone_Number, Time)

   V1 = (W + 4 * Th) * (H + 4 * Th) * Th / 2
   V2 = (W + 4 * Th) * (H + 4 * Th) * Th
   V3 = V1
   If Zone_Number = 1 Then
      QTw(Zone_Number, Time) = Qv(1, Zone_Number, Time)
   ElseIf Zone_Number = 18 Then
      QTw(Zone_Number, Time) = Qv(4, Zone_Number, Time)
   End If

   For i34 = 1 To 22
      QTw(Zone_Number, Time) = QTw(Zone_Number, Time) + Qr(i34, Zone_Number, Time)
      QTw(Zone_Number, Time) = QTw(Zone_Number, Time) - Qr(Zone_Number, i34, Time)
   Next i34

   Q1 = (k_Enc * (H + 4 * Th) * (W + 4 * Th) / Th) * (Tm(Zone_Number, Time) - Tw(Zone_Number,
Time))
   Tw(Zone_Number, Time + 1) = (Time_Interval / (Density * V1 * SHC)) * (QTw(Zone_Number, Time)
+ Q1) + Tw(Zone_Number, Time)
   Q2 = (k_Enc * (H + 4 * Th) * (W + 4 * Th) / Th) * (Ts(Zone_Number, Time) - Tm(Zone_Number,
Time))
   Tm(Zone_Number, Time + 1) = (Time_Interval / (Density * V2 * SHC)) * (Q2 - Q1) +
Tm(Zone_Number, Time)
   Qn(Zone_Number, Time) = N_Heat_Coeff_1(Ts(Zone_Number, Time), Troom) * H * W * (Troom -
Ts(Zone_Number, Time))
   Ts(Zone_Number, Time + 1) = (Time_Interval / (Density * V3 * SHC)) * (Qn(Zone_Number, Time) -
Q2) + Ts(Zone_Number, Time)

End Sub
Sub Conduction_2(Zone_Number, Time)

   V1 = Zone_Length * (H + 4 * Th) * Th / 2
   V2 = Zone_Length * (H + 4 * Th) * Th
   V3 = V1

   If Zone_Number = 2 Then
      QTw(Zone_Number, Time) = Qv(1, Zone_Number, Time)
   ElseIf Zone_Number = 4 Then
      QTw(Zone_Number, Time) = Qv(1, Zone_Number, Time)
   ElseIf Zone_Number = 6 Then
      QTw(Zone_Number, Time) = Qv(2, Zone_Number, Time)
   ElseIf Zone_Number = 8 Then
      QTw(Zone_Number, Time) = Qv(2, Zone_Number, Time)
   ElseIf Zone_Number = 10 Then
      QTw(Zone_Number, Time) = Qv(3, Zone_Number, Time)
   ElseIf Zone_Number = 12 Then
      QTw(Zone_Number, Time) = Qv(3, Zone_Number, Time)
   ElseIf Zone_Number = 14 Then
      QTw(Zone_Number, Time) = Qv(4, Zone_Number, Time)
```

```
    ElseIf Zone_Number = 16 Then
        QTw(Zone_Number, Time) = Qv(4, Zone_Number, Time)
    End If

    For i35 = 1 To 22
        QTw(Zone_Number, Time) = QTw(Zone_Number, Time) + Qr(i35, Zone_Number, Time)
        QTw(Zone_Number, Time) = QTw(Zone_Number, Time) - Qr(Zone_Number, i35, Time)
    Next i35

    Q1 = (k_Enc * (H + 4 * Th) * Zone_Length / Th) * (Tm(Zone_Number, Time) - Tw(Zone_Number,
Time))
    Tw(Zone_Number, Time + 1) = (Time_Interval / (Density * V1 * SHC)) * (QTw(Zone_Number, Time)
+ Q1) + Tw(Zone_Number, Time)
    Q2 = (k_Enc * (H + 4 * Th) * Zone_Length / Th) * (Ts(Zone_Number, Time) - Tm(Zone_Number,
Time))
    Tm(Zone_Number, Time + 1) = (Time_Interval / (Density * V2 * SHC)) * (Q2 - Q1) +
Tm(Zone_Number, Time)
    Qn(Zone_Number, Time) = N_Heat_Coeff_1(Ts(Zone_Number, Time), Troom) * (H + 4 * Th) *
Zone_Length * (Troom - Ts(Zone_Number, Time))
    Ts(Zone_Number, Time + 1) = (Time_Interval / (Density * V3 * SHC)) * (Qn(Zone_Number, Time) -
Q2) + Ts(Zone_Number, Time)

End Sub
Sub Conduction_3(Zone_Number, Time)

    V1 = Zone_Length * W * Th / 2
    V2 = Zone_Length * W * Th
    V3 = V1

    If Zone_Number = 3 Then
        QTw(Zone_Number, Time) = Qv(1, Zone_Number, Time)
        NC = N_Heat_Coeff_2(Ts(Zone_Number, Time), Troom)
    ElseIf Zone_Number = 5 Then
        QTw(Zone_Number, Time) = Qv(1, Zone_Number, Time)
        NC = N_Heat_Coeff_3(Ts(Zone_Number, Time), Troom)
    ElseIf Zone_Number = 7 Then
        QTw(Zone_Number, Time) = Qv(2, Zone_Number, Time)
        NC = N_Heat_Coeff_2(Ts(Zone_Number, Time), Troom)
    ElseIf Zone_Number = 9 Then
        QTw(Zone_Number, Time) = Qv(2, Zone_Number, Time)
        NC = N_Heat_Coeff_3(Ts(Zone_Number, Time), Troom)
    ElseIf Zone_Number = 11 Then
        QTw(Zone_Number, Time) = Qv(3, Zone_Number, Time)
        NC = N_Heat_Coeff_2(Ts(Zone_Number, Time), Troom)
    ElseIf Zone_Number = 13 Then
        QTw(Zone_Number, Time) = Qv(3, Zone_Number, Time)
        NC = N_Heat_Coeff_3(Ts(Zone_Number, Time), Troom)
    ElseIf Zone_Number = 15 Then
        QTw(Zone_Number, Time) = Qv(4, Zone_Number, Time)
        NC = N_Heat_Coeff_2(Ts(Zone_Number, Time), Troom)
    ElseIf Zone_Number = 17 Then
        QTw(Zone_Number, Time) = Qv(4, Zone_Number, Time)
        NC = N_Heat_Coeff_3(Ts(Zone_Number, Time), Troom)
```

```
    End If

    For i36 = 1 To 22
      QTw(Zone_Number, Time) = QTw(Zone_Number, Time) + Qr(i36, Zone_Number, Time)
      QTw(Zone_Number, Time) = QTw(Zone_Number, Time) - Qr(Zone_Number, i36, Time)
    Next i36

    Q1 = (k_Enc * W * Zone_Length / Th) * (Tm(Zone_Number, Time) - Tw(Zone_Number, Time))
    Tw(Zone_Number, Time + 1) = (Time_Interval / (Density * V1 * SHC)) * (QTw(Zone_Number, Time)
+ Q1) + Tw(Zone_Number, Time)
    Q2 = (k_Enc * W * Zone_Length / Th) * (Ts(Zone_Number, Time) - Tm(Zone_Number, Time))
    Tm(Zone_Number, Time + 1) = (Time_Interval / (Density * V2 * SHC)) * (Q2 - Q1) +
Tm(Zone_Number, Time)
    Qn(Zone_Number, Time) = NC * W * Zone_Length * (Troom - Ts(Zone_Number, Time))
    Ts(Zone_Number, Time + 1) = (Time_Interval / (Density * V3 * SHC)) * (Qn(Zone_Number, Time) -
Q2) + Ts(Zone_Number, Time)

End Sub

Sub Load_Excel()                    'Display results to Excel

   Dim TaskID
   TaskID = Shell("c:\Program Files\Microsoft Office\Office\Excel", vbNormalNoFocus)

End Sub
Sub Display()

'If Flag = 1 Then
If Time = 1 Then

          Label2.LinkMode = 0
          Label2.LinkTopic = "Excel|Sheet1"
          Label2.LinkItem = "R1C1"
          Label2.LinkMode = 2
          Label2.LinkPoke

          Label1.Caption = Text1.Text
          Label1.LinkMode = 0
          Label1.LinkTopic = "Excel|Sheet1"
          Label1.LinkItem = "R1C2"
          Label1.LinkMode = 2
          Label1.LinkPoke

          Label3.LinkMode = 0
          Label3.LinkTopic = "Excel|Sheet1"
          Label3.LinkItem = "R1C3"
          Label3.LinkMode = 2
          Label3.LinkPoke

          Label4.LinkMode = 0
          Label4.LinkTopic = "Excel|Sheet1"
          Label4.LinkItem = "R2C1"
          Label4.LinkMode = 2
```

```
Label4.LinkPoke

Label1.Caption = Text2.Text
Label1.LinkMode = 0
Label1.LinkTopic = "Excel|Sheet1"
Label1.LinkItem = "R2C2"
Label1.LinkMode = 2
Label1.LinkPoke

Label5.LinkMode = 0
Label5.LinkTopic = "Excel|Sheet1"
Label5.LinkItem = "R2C3"
Label5.LinkMode = 2
Label5.LinkPoke

Label7.LinkMode = 0
Label7.LinkTopic = "Excel|Sheet1"
Label7.LinkItem = "R3C1"
Label7.LinkMode = 2
Label7.LinkPoke

Label1.Caption = Text3.Text
Label1.LinkMode = 0
Label1.LinkTopic = "Excel|Sheet1"
Label1.LinkItem = "R3C2"
Label1.LinkMode = 2
Label1.LinkPoke

Label8.LinkMode = 0
Label8.LinkTopic = "Excel|Sheet1"
Label8.LinkItem = "R3C3"
Label8.LinkMode = 2
Label8.LinkPoke

Label1.Caption = "Enclosure Material"
Label1.LinkMode = 0
Label1.LinkTopic = "Excel|Sheet1"
Label1.LinkItem = "R4C1"
Label1.LinkMode = 2
Label1.LinkPoke

Label1.Caption = Combo1.Text
Label1.LinkMode = 0
Label1.LinkTopic = "Excel|Sheet1"
Label1.LinkItem = "R4C3"
Label1.LinkMode = 2
Label1.LinkPoke

Label1.Caption = "Enclosure Thickness"
Label1.LinkMode = 0
Label1.LinkTopic = "Excel|Sheet1"
Label1.LinkItem = "R4C4"
Label1.LinkMode = 2
```

```
Label1.LinkPoke

Label1.Caption = Text4.Text
Label1.LinkMode = 0
Label1.LinkTopic = "Excel|Sheet1"
Label1.LinkItem = "R4C6"
Label1.LinkMode = 2
Label1.LinkPoke

Label10.LinkMode = 0
Label10.LinkTopic = "Excel|Sheet1"
Label10.LinkItem = "R4C7"
Label10.LinkMode = 2
Label10.LinkPoke

Label12.LinkMode = 0
Label12.LinkTopic = "Excel|Sheet1"
Label12.LinkItem = "R5C1"
Label12.LinkMode = 2
Label12.LinkPoke

Label1.Caption = Combo2.Text
Label1.LinkMode = 0
Label1.LinkTopic = "Excel|Sheet1"
Label1.LinkItem = "R5C3"
Label1.LinkMode = 2
Label1.LinkPoke

Label18.LinkMode = 0
Label18.LinkTopic = "Excel|Sheet1"
Label18.LinkItem = "R6C1"
Label18.LinkMode = 2
Label18.LinkPoke

Label1.Caption = Text5.Text
Label1.LinkMode = 0
Label1.LinkTopic = "Excel|Sheet1"
Label1.LinkItem = "R6C4"
Label1.LinkMode = 2
Label1.LinkPoke

Label19.LinkMode = 0
Label19.LinkTopic = "Excel|Sheet1"
Label19.LinkItem = "R6C5"
Label19.LinkMode = 2
Label19.LinkPoke

Label13.LinkMode = 0
Label13.LinkTopic = "Excel|Sheet1"
Label13.LinkItem = "R7C1"
Label13.LinkMode = 2
Label13.LinkPoke
```

```
Label1.Caption = Text6.Text
Label1.LinkMode = 0
Label1.LinkTopic = "Excel|Sheet1"
Label1.LinkItem = "R7C4"
Label1.LinkMode = 2
Label1.LinkPoke

Label14.LinkMode = 0
Label14.LinkTopic = "Excel|Sheet1"
Label14.LinkItem = "R8C1"
Label14.LinkMode = 2
Label14.LinkPoke

Label1.Caption = Text7.Text
Label1.LinkMode = 0
Label1.LinkTopic = "Excel|Sheet1"
Label1.LinkItem = "R8C4"
Label1.LinkMode = 2
Label1.LinkPoke

Label15.LinkMode = 0
Label15.LinkTopic = "Excel|Sheet1"
Label15.LinkItem = "R8C5"
Label15.LinkMode = 2
Label15.LinkPoke

Label16.LinkMode = 0
Label16.LinkTopic = "Excel|Sheet1"
Label16.LinkItem = "R9C1"
Label16.LinkMode = 2
Label16.LinkPoke

Label1.Caption = Text8.Text
Label1.LinkMode = 0
Label1.LinkTopic = "Excel|Sheet1"
Label1.LinkItem = "R9C4"
Label1.LinkMode = 2
Label1.LinkPoke

Label17.LinkMode = 0
Label17.LinkTopic = "Excel|Sheet1"
Label17.LinkItem = "R9C5"
Label17.LinkMode = 2
Label17.LinkPoke

Label1.Caption = "Temperature(Gas Zones),K"
Label1.LinkMode = 0
Label1.LinkTopic = "Excel|Sheet1"
Label1.LinkItem = "R11C2"
Label1.LinkMode = 2
Label1.LinkPoke

Label1.Caption = "Temperature(Surface Zones),K"
```

```
        Label1.LinkMode = 0
        Label1.LinkTopic = "Excel|Sheet1"
        Label1.LinkItem = "R11C7"
        Label1.LinkMode = 2
        Label1.LinkPoke

        Label1.Caption = "Time,s"
        Label1.LinkMode = 0
        Label1.LinkTopic = "Excel|Sheet1"
        Label1.LinkItem = "R12C1"
        Label1.LinkMode = 2
        Label1.LinkPoke

 For i41 = 1 To 4
        Label1.Caption = i41
        Label1.LinkMode = 0
        Label1.LinkTopic = "Excel|Sheet1"
        Label1.LinkItem = "R12C" & i41 + 1
        Label1.LinkMode = 2
        Label1.LinkPoke
 Next i41

 For i42 = 1 To 18
        Label1.Caption = i42
        Label1.LinkMode = 0
        Label1.LinkTopic = "Excel|Sheet1"
        Label1.LinkItem = "R12C" & i42 + 6
        Label1.LinkMode = 2
        Label1.LinkPoke
 Next i42

        Label1.Caption = "0"
        Label1.LinkMode = 0
        Label1.LinkTopic = "Excel|Sheet1"
        Label1.LinkItem = "R13C1"
        Label1.LinkMode = 2
        Label1.LinkPoke

 For i16 = 1 To 4
        Label1.Caption = Tg(i16, 0)
        Label1.LinkMode = 0
        Label1.LinkTopic = "Excel|Sheet1"
        Label1.LinkItem = "R13C" & i16 + 1
        Label1.LinkMode = 2
        Label1.LinkPoke
 Next i16

   For i18 = 1 To 18
        Label1.Caption = Tw(i18, 0)
        Label1.LinkMode = 0
        Label1.LinkTopic = "Excel|Sheet1"
        Label1.LinkItem = "R13C" & i18 + 6
        Label1.LinkMode = 2
```

```
        Label1.LinkPoke
     Next i18
End If

        Label1.Caption = Time * Time_Interval
        Label1.LinkMode = 0
        Label1.LinkTopic = "Excel|Sheet1"
        Label1.LinkItem = "R" & Time + 13 & "C1"
        Label1.LinkMode = 2
        Label1.LinkPoke

     For i16 = 1 To 4
        Label1.Caption = Tg(i16, Time)
        Label1.LinkMode = 0
        Label1.LinkTopic = "Excel|Sheet1"
        Label1.LinkItem = "R" & Time + 13 & "C" & i16 + 1
        Label1.LinkMode = 2
        Label1.LinkPoke
     Next i16

     For i18 = 1 To 18
        Label1.Caption = Tw(i18, Time)
        Label1.LinkMode = 0
        Label1.LinkTopic = "Excel|Sheet1"
        Label1.LinkItem = "R" & Time + 13 & "C" & i18 + 6
        Label1.LinkMode = 2
        Label1.LinkPoke
     Next i18

End Sub
Sub Display1()

If Time = 800 Then

  For k5 = 1 To 22
     For k6 = 1 To 22
        Label1.Caption = Qr(k5, k6, Time - 1)
        Label1.LinkMode = 0
        Label1.LinkTopic = "Excel|Sheet2"
        Label1.LinkItem = "R" & k5 & "C" & k6
        Label1.LinkMode = 2
        Label1.LinkPoke
     Next k6
  Next k5

  For k7 = 1 To 4
     For k8 = 1 To 18
        Label1.Caption = Qv(k7, k8, Time - 1)
        Label1.LinkMode = 0
        Label1.LinkTopic = "Excel|Sheet3"
        Label1.LinkItem = "R" & k7 & "C" & k8
        Label1.LinkMode = 2
        Label1.LinkPoke
```

```
    Next k8
  Next k7

  For k1 = 1 To 18
    For k2 = 1 To 18
      Label1.Caption = SS(k1, k2)
      Label1.LinkMode = 0
      Label1.LinkTopic = "Excel|Sheet4"
      Label1.LinkItem = "R" & k1 + 2 & "C" & k2
      Label1.LinkMode = 2
      Label1.LinkPoke
    Next k2
  Next k1

  For k5 = 1 To 18
    For k6 = 1 To 4
      Label1.Caption = SG(k5, k6)
      Label1.LinkMode = 0
      Label1.LinkTopic = "Excel|Sheet4"
      Label1.LinkItem = "R" & k5 + 2 & "C" & k6 + 18
      Label1.LinkMode = 2
      Label1.LinkPoke
    Next k6
  Next k5

  For k7 = 1 To 4
    For k8 = 1 To 18
      Label1.Caption = GS(k7, k8)
      Label1.LinkMode = 0
      Label1.LinkTopic = "Excel|Sheet4"
      Label1.LinkItem = "R" & k7 + 20 & "C" & k8
      Label1.LinkMode = 2
      Label1.LinkPoke
    Next k8
  Next k7

  For k9 = 1 To 4
    For k10 = 1 To 4
      Label1.Caption = GG(k9, k10)
      Label1.LinkMode = 0
      Label1.LinkTopic = "Excel|Sheet4"
      Label1.LinkItem = "R" & k9 + 20 & "C" & k10 + 18
      Label1.LinkMode = 2
      Label1.LinkPoke.
    Next k10
  Next k9

  For k3 = 1 To 22
    For k4 = 1 To 22
      Label1.Caption = MatrixX1(k3, k4)
      Label1.LinkMode = 0
      Label1.LinkTopic = "Excel|Sheet4"
      Label1.LinkItem = "R" & k3 + 32 & "C" & k4
```

```
        Label1.LinkMode = 2
        Label1.LinkPoke
      Next k4
    Next k3
  End If


  End Sub

  Private Sub Command2_Click()

    End

  End Sub

  Private Sub Form_Load()

    Combo1.AddItem "Brick"
    Combo1.AddItem "Mild Steel"

    Combo2.AddItem "C4H10"

    Msg = "Numerical Value is required!"
    Style = vbOKOnly + vbCritical
    Title = "Input Error"

  End Sub

  Private Sub Text1_LostFocus()

    If Not (IsNumeric(Text1.Text)) Or Text1.Text = "" Then
      Response = MsgBox(Msg, Style, Title)
      If vbOK Then
        Text1.Text = ""
        Command2.SetFocus
      End If
    End If

  End Sub

  Private Sub Text2_LostFocus()

    If Not (IsNumeric(Text2.Text)) Or Text2.Text = "" Then
      Response = MsgBox(Msg, Style, Title)
      If vbOK Then
        Text2.Text = ""
        Command2.SetFocus
      End If
    End If

  End Sub

  Private Sub Text3_LostFocus()
```

```
    If Not (IsNumeric(Text3.Text)) Or Text3.Text = "" Then
       Response = MsgBox(Msg, Style, Title)
       If vbOK Then
          Text3.Text = ""
          Command2.SetFocus
       End If
    End If

 End Sub

 Private Sub Text4_LostFocus()

    If Not (IsNumeric(Text4.Text)) Or Text4.Text = "" Then
       Response = MsgBox(Msg, Style, Title)
       If vbOK Then
          Text4.Text = ""
          Command2.SetFocus
       End If
    End If

 End Sub

 Private Sub Text5_LostFocus()

    If Not (IsNumeric(Text5.Text)) Or Text5.Text = "" Then
       Response = MsgBox(Msg, Style, Title)
       If vbOK Then
          Text5.Text = ""
          Command2.SetFocus
       End If
    End If

 End Sub

 Private Sub Text6_LostFocus()

    If Not (IsNumeric(Text6.Text)) Or Text6.Text = "" Then
       Response = MsgBox(Msg, Style, Title)
       If vbOK Then
          Text6.Text = ""
          Command2.SetFocus
       End If
    End If

 End Sub

 Private Sub Text7_LostFocus()

    If Not (IsNumeric(Text7.Text)) Or Text7.Text = "" Then
       Response = MsgBox(Msg, Style, Title)
       If vbOK Then
          Text7.Text = ""
```

```
         Command2.SetFocus
      End If
   End If

End Sub

Private Sub Text8_LostFocus()

   If Not (IsNumeric(Text8.Text)) Or Text8.Text = "" Then
      Response = MsgBox(Msg, Style, Title)
      If vbOK Then
         Text8.Text = ""
         Command2.SetFocus
      End If
   End If

End Sub
```