BACHELOR OF TECHNOLOGY PROJECT (PART - I)

on

Development of a Generic Model to Analyze Natural Draft Furnace Systems

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Submitted By

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CERTIFICATE

This is to certify that the thesis entitled **'Development of a Generic Model to Analyze Natural Draft Furnace Systems'** submitted by TUSHAR BANSAL and ADITYA JAIN to the Indian Institute of Technology, Delhi for the completion of Bachelor of Technology degree is a bonade record of research work carried out by them under our supervision. This thesis has been prepared in conformity with the rules and regulations of the Indian Institute of Technology, Delhi. We further certify that the thesis has attained a standard required for a B.Tech degree. The research reported and the results presented in the thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

Natural draft furnace systems are being used in widespread applications such as cooking (chulha), bell metal melting, pottery hardening, brick hardening, bangle manufacturing etc. in rural areas, as they do not require electrical power for operation. Scientific community, after observing the poor energy utilization of these traditional kilns, started working on the development of models to gain insights into the energy distribution of these systems so as to improve their efficiency. Since the performance of a natural draft furnace system is majorly dependent on its configuration such as geometry, fuel & application, currently, designers are required to develop separate computational models for each application. By carrying out a transient 1-dimensional analysis of physical phenomena occurring in the system, a model generic with respect to various configurations, fuel and application and capable of estimating energy distribution and other parameters (such as fuel consumption) was developed by Oza et. al. [1].

Further, this work was extended by Baid & Teja [2] and they tried to develop a model incorporating the preheater box in the model. Although, the code developed by Baid & Teja was not functional but it helped to gain insights over various parts of the natural draft furnace. They considered the heat flow through the walls of the component, accounting the non-adiabatic nature of the pipe ensuring the complete burning of the fuel. They even worked upon developing an interface in MATLAB GUIDE (Graphical User Interface Development Environment) wherein the user would input the configuration of the kiln by selecting the components from drop-down menus and then subsequently would enter the dimension of the components. But the interface is currently not in a working condition and is not versatile enough to various types of natural draft furnaces and incorporates assumptions which restricts the usage of it to various designs available of natural draft furnaces subject to the application of use. The current project was intended to make the individual modules functional and expand the usability and versatility of the model. Thus, this separate modules can be used as a

design tool for efficient furnaces in rural industries. These individual modules have now been validated with set of experimental data. Since the temperature of gases in the stack is very high, radiation effects have been considered.

NOMENCLATURE

P	Pressure (Pa)	ρ	Density (kg/m^3)
T	Temperature (K)	v	Velocity (m/s)
g	Acceleration due to gravity(m/s^2)	h	Specific enthalpy (kJ/kg)
f	Darcy friction factor	K	Loss coefficient
e	Specific total energy (kJ/kg)	F	Force (N)
A	Cross sectional area (m^2)	R	Gas constant (J/kg/K)
	Heat Transfer (kW)		Mass flow rate (kg/s)
u	Specific internal energy (kJ/kg)	h	Heat transfer coefficient (W/m^2/K)
d	diameter(m)	s	Grate spacing (m)
th	Grate wire thickness (m)	μ	Coefficient of dynamic viscosity(kg/m/s)
β	absorptivity		Surface roughness (m)
M	Molecular Mass (g/mol)	D	Diameter(m)
L	Length(m)	CV	Calorific value (kJ/kg)
Re	Reynolds Number	Nu	Nusselt number
Cv	Specific heat capacity at constant volume(kJ/kg/K)	Cp	Specific heat capacity at constant pressure (kJ/kg/K)
V	Volume (m^3)	λ	Porosity
l	Length (m)	R	Radius (m)
m	Mass (kg)	Y	Thickness of insulation on stack (m)
α	Thermal diffusivity (m^2/s)	k	Thermal conductivity(W/m/K)
	Emissivity	t	time (s)
n	Number of moles	AF	air fuel ratio
X	Thickness of insulation on combustion chamber		

Subscripts

a	Atmosphere	g	Flue gas

ref	Reference	bend	Bend
b	Bend	c	Compression
e	Expansion	d	damper
i	Inner cylinder	o	Outer cylinder
grate	Due to grate	f	Fuel
cruc	crucible	amb	ambient
ins	insulation	ext	external
int	internal	cv	control volumes

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Chapter 1

Introduction

1.1 Background

A natural draft furnace forces the waste gases of combustion out through the ventilation system by the use of natural atmospheric pressure. The fuel burns in the furnace and generates high volumes of hot air along with the combustion byproducts including carbon monoxide and carbon dioxide. Hot air, at the entry of the exhaust chamber rises naturally, lifting the combustion byproducts along with it. As the hot air rises through the vent, the cooler and denser air from the atmosphere flows inside the furnace and create a natural draft that pushes the air through the system and facilitates the process of combustion.

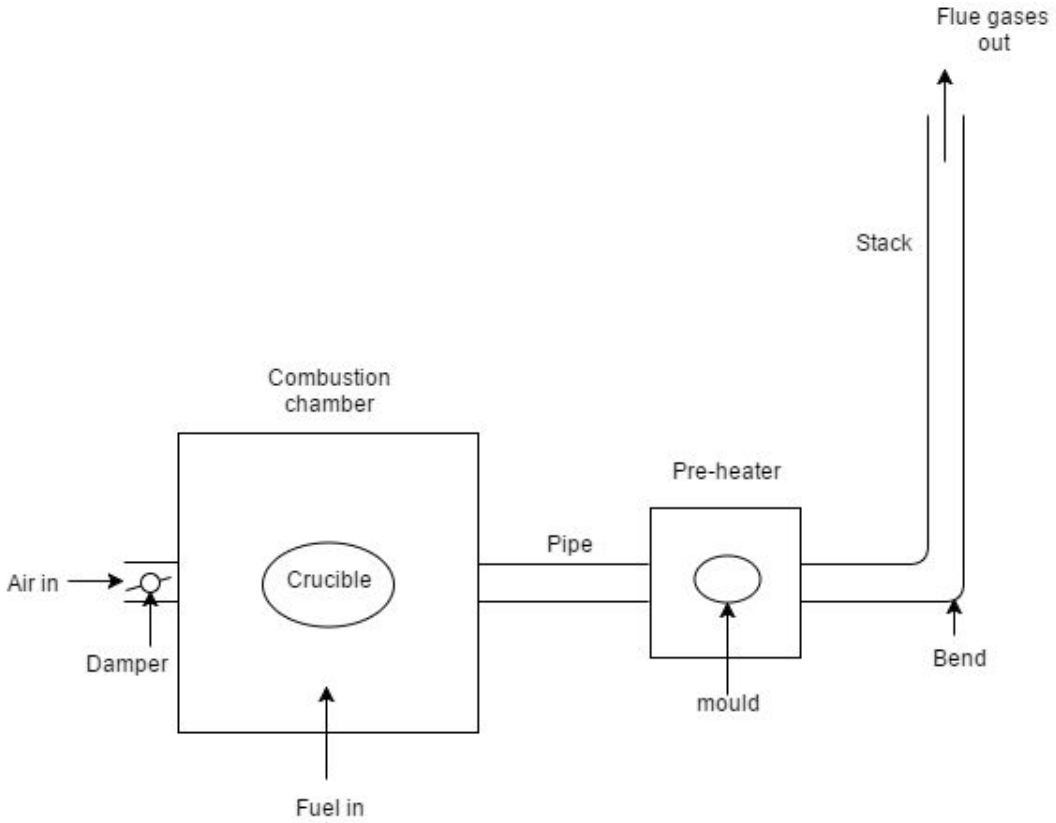


Figure 1: Generic geometry of natural draft furnace system

Natural draft furnace systems have been into existence from long time and since they operate without the consumption of electric power, they are widely used in numerous applications across the rural areas. Unlike the comprehensive understanding of the forced draft furnace systems used in conventional industries, there are limited insights about the natural draft furnaces used in rural industry available to the scientific community. Considering the extensive use of natural draft furnaces over various applications at a poor energy efficiency, the scientific community started working in order to gain insights on the energy distribution and the performance parameters of these systems. Several research works have been conducted in order to improve the design of the natural draft furnaces to improve the fuel efficiency by performing simulations over computational models and optimizing few process parameters like air flow rate, fuel combustion rate etc.

In a forced draft furnace, the rate of air flow and thus the power rating of the furnace remains under control during any operation which is something not possible in the case of natural draft furnace as the pressure across the system directs the air flow rate at any instant. The efficiency of the natural draft furnace depends upon its configuration, geometry, fuel and the purpose of use.

There were previously two B.Tech projects which were carried out in the field of natural draft furnaces to develop a generic computational model for various components of a natural draft furnace. In the first one by Oza et al., the members focused upon developing a generic model which could estimate the energy distribution and parameters (as a function of time) of the system, by taking system's configuration as input and thus aided the designers in carrying out the analysis of furnaces easily and hence improve the designs. The model takes the system's configuration at any instant as its input. One may run iterations and decide how the system's configuration (position of damper) must be (hence the flow rate and the 'firing rate') varied to get the maximum fuel efficiency.

In the second project by Baid & Teja, they worked upon developing a generic simulation model. They added the provision of components like preheater box which are quite often

found in natural draft furnaces. They also took into consideration the presence of walls around different components like combustion chamber etc. accounting the non-adiabatic nature of pipes, and developing a user interface, an attempt to make the code more approachable.

1.2 Problem Definition

The earlier efforts put in by the scientific community aimed to develop models that are specific to the application of interest (ceramics, pottery etc.). Today, members of the scientific community are making distinct designs of system, according to the specifications of application and fuel. A model generic with respect to the configuration if created, can be used to gain insights into energy distribution of natural draft furnace system with different designs and subsequently improve the fuel efficiency by selecting the design with maximum percentage of energy gained by the crucible. Such a model will aid the designers in carrying out the analysis of furnaces easily and eventually quicken the design process. Separate modules for each assembly items can ease the method of simulating any natural draft furnace as these modules can be configured as per requirements and arranged for any specific arrangement of the components of a natural draft furnace. Considering this premise, the intends to create generic modules for each component of a furnace that can estimate the performance and the analysis of energy variation within each segment, depending upon the geometry of the system, the fuel being used and the application for which it is designed. These individual modules can be assembled together as per the configuration requirements. Thus this would increase the scope of use of these individual modules. This can help us gain insights about the distribution of energy of natural draft furnace system with different designs. Such generic model will aid the designers in carrying out the analysis of furnaces easily and eventually quicken the design process.

The utility of the analysis is in predicting and improving the thermal efficiency of the downdraft with minimal computational resources. This project aims to carry out 1-dimensional analysis to model fluid dynamic effects, heat transfer effects, combustion effects and transient effects in its analysis; the 1-dimensional modeling of the system and the assumptions made in the project are justified if the experimental results validate the model's predictions, which can be compared by the field results obtained during the experiments

conducted by Gokhale et al. on different kilns as part of the research conducted in IIT Delhi to gain insights into the energy distribution of natural draft furnace systems. Thus, this project can be used as a design tool by the scientific community in making designs for different kinds of natural draft furnace systems in the future.

Further in this report, Chapter 2 contains a literature review of research work that has been carried out in the past along with the scope of the present work. Following that, Chapter 3 contains the project objective and the methodology used. Chapter 4 describes the work progress that has been done till now which also includes the equations used and the underlying principles along with the assumptions stated clearly, while modelling various components of a natural draft furnace. Chapter 5 describes a short summary and conclusion of the present work and a brief scope of the future work that can be carried out in the same.

Chapter 2

Literature Survey

There have been significant efforts put up in order to develop a versatile model for the natural draft furnaces in order to improve their performance. Gokhale et al. [3] have developed a 1-dimensional model simulating heat transfer effects in ceramic furnaces to predict and improve thermal efficiency. It takes firing rate, fuel flow rate and excess air-fuel ratio as inputs. The model uses central scheme with respect to space and implicit scheme with respect to time to linearize and model the governing equation of fluid; estimates density by making ideal gas assumption at atmospheric pressure; takes variation of Cp into account; accounts for radiation effects without treating objects as black bodies. But the model can be used to estimate energy distribution and performance of ceramic furnaces only. In the earlier stages, the model was more application specific, but over the course of time, the model was extended to a more generalized form. Oza et. al. [1] felt the need of developing a generic mathematical model of natural draft furnace systems with respect to fuel, application and geometry which estimates energy distribution and parameters such as fuel consumption as a function of time by taking system's configuration as input. The model does not take firing rate as an input and estimates the mass flow rate in the system by using the pressure difference available across the system. The model has provision for components like combustion chamber, stack, pipe,

blower and damper. Baid & Teja [2] adopted the modules developed by them for these components and then modified it to overcome the shortcomings in the modelling.

Further, Baid & Teja [2] carried out the work on developing a generic simulation model. They added the provision of components like preheater box which are quite often found in natural draft furnaces. They also took into consideration the presence of walls around different components like combustion chamber etc. accounting the non-adiabatic nature of pipes, and eventually developing a user interface, an attempt to make the model more approachable. The objective was to develop a model applicable to all the natural draft furnace systems and which can be used with ease in design process. They worked upon the model to refine the same and incorporate the provision of a preheater and various other components common in many natural draft furnace systems. They also tried to establish a closer relationship with the field observations by accounting the presence of walls around different components in the geometry like combustion chamber, non - adiabatic nature of pipes, and developed different crucible models for various types of crucibles used in different kilns. Although, the mathematical model has been validated for a few cases, it still suffers from limitations when we try to use it for other furnaces.

The existing model does not allow the provision to put up a bend or a damper even for the models it is functional for while some work has been done around in order to gain insights for the formulations required to simulate the damper and the bend. In this project, we intend to simulate the damper and the bend along with the other components of a natural draft furnace. Addition of damper and bends to the system will lead to greater number of configurations and further would help to resemble the results with the experimental observations. Also, this can then be used to gain the information regarding the optimum position of the damper in order to attain the maximum fuel efficiency. We initially tried to verify the results of the previous models on several systems in order to benchmark the model with the practical observations. We realized that the models are either not very flexible or are suffering from a high order of time complexity. Also, the model developed by Baid & Teja [2] were not understandable easily and thus lacked the feature of user friendliness. We henceforth took up the task to derive inspiration from available codes and theories from the existing work and develop our own individual modules for various components of the natural draft furnace.

2.1 Discussion

Considerable amount of work has been done in gaining insights about the natural draft furnace systems in IIT Delhi. Energy distribution estimation is feasible by 'measuring' (or estimating, if measurement is not practically feasible) the temperature of each component as a function of time or by computing the temperatures of various points at different time instants by simulating the heat transfer effects inside the kilns. So, to gain insights into energy distribution and improve the fuel efficiency of a natural draft furnace system, one may choose the former approach involving experimental estimation or the latter approach purely involving computational modelling. Till now the efforts put in by the scientific community involving computational modelling have been aimed at developing models specific to the configuration such as fuel, application and geometry of the system for estimating the performance. Today, members of the scientific community are making distinct designs of system, according to the specifications of application and fuel. Separate modules for each component, which can be configured as and when needed, if created, can be used to gain insights into energy distribution of natural draft furnace system with different designs and subsequently improve the fuel efficiency by selecting the design with maximum percentage of energy gained by the crucible. Such generic model will aid the designers in carrying out the analysis of furnaces easily and eventually quicken the design process by providing an optimal configuration.

2.2 Scope of the project

Looking at the objectives covered and the limitations that the current models have, there is a significant scope of improvement in existing modules as well as development of new sections. The current modules, if workable at all, are workable for only a set of specific systems but are not usable in a general context (the arrangements of components are restricted and the code doesn't work for a number of test cases). Hence, the project explores the refining of the current modules and also, development of a model finding its applicability in a broader range of cases. There is a scope to reproduce individual modules of each component which could be assembled in any configuration as per requirement in order to analyse the energy distribution among different components by estimating the pressure

variations and pressure drops associated with each component depending upon their properties, dimensions and specifications.

Thus, once these individual modules are functional, these can be integrated together via following the steps as mentioned in the user manual making the computational model user friendly and easy to simulate for a variety of designs of natural draft furnaces and gaining important insights. These generic modules make the model for versatile and find its applicability in easing the designers to design any natural draft furnace maximising the efficiency within the practical limits using the model and thus quickening the design process.

The model can be validated with the results from the experiments conducted by Gokhale et al. [3].

Chapter 3

Project Objectives & Work Plan

3.1 Motivation

Combustion of fuel inside a natural draft furnace is required to heat the ware inside the kiln. For the combustion to happen, air flow is required. Unlike forced draft furnaces, the natural draft furnaces do not use any mechanical device like blower/fan etc. in order to create the draft required for the flow of air. Thus, the combustion inside a natural draft furnace is difficult to control and is dependent upon various parameters such as fuel type, geometry,

configurations, air flow rate etc. Natural draft furnaces, having a widespread application in the rural areas, provides a great motivation to work upon developing models which could be useful in the efficient design of the furnaces maximizing the energy utilization and efficiency of such furnace systems. Since, there is a lot scope to progress the ongoing research work in this field and also there exists a need to develop a more versatile simulation model for the natural draft furnace systems which would eventually help in a better design of the system resulting in the enhanced efficiency of the furnace. Also, there is a need to validate the model with more experiments and also with more diversity in order to make the model comprehensive enough to simulate all kinds of natural draft furnace systems.

3.2 Objectives

1. Studying and analysing the simulation model modified by Baid & Teja [2] and critically validating the assumptions with the experimental data and rectifying the redundant assumptions and errors to modify the modules accordingly.
2. To provide separate modules of the simulation model for various components of the natural draft furnace in order to assemble these modules as per the configuration of natural draft furnaces and model the variation of energy and fuel consumption
3. Incorporate the use of damper and bends in the configurations of natural draft furnace thus gaining detailed insights on the variation of the distribution of energy among various components of a natural draft furnace, which could help us identify the damper position for the configuration with maximum fuel efficiency.
4. The model could previously simulate a natural draft furnace system with only some specific configurations of the components. Hence, there is a scope to improve upon the model in order to simulate furnaces with relatively more complex arrangements. Also, a user manual can be developed for the ease of understanding and ensuring user friendliness of the modules to save time and smoothen the design process.

3.3 Methodology

1. Identification of all possible components of any natural draft furnace system
2. Prepare mathematical models for all such components such as pipes, flow expansion regions, flow contraction regions, bends and dampers etc. separately of a natural draft furnace system

3. Assemble the components in any order (damper may be placed before the bend/after the bend/ at the end of the stack etc.). and simulate for the respective natural draft furnace systems
4. Create a user manual explaining how to modify the model for any particular configuration required

3.4 Gantt Chart

Activity	Aug 1 - Aug 15	Aug 15 - Aug 31	Sept 1 - Sept 15	Sept 15 - Sept 30	Oct 1 - Oct 15	Oct 15 - Oct 30	Nov 1 - Present
Literature Review	Completed						
Identification of Components		Completed					
Developing a simulation model for a simpler component		Completed	Completed				
Refine the simulation model for individual components			Completed	Competed	Completed		
Generation of a user manual					Completed		
Documentation						Completed	Completed
Validate the experimental results							Ongoing

Chapter 4

Modelling of Components

a) Combustion chamber

It has been assumed that as soon as air enters the combustion chamber, combustion of fuel happens inside the chamber and flue gases are formed instantly without any delay. Inside the combustion chamber, the exhaust gas which gains heat due to the combustion of fuel and loses heat to crucible and wallsaq of combustion via convection and radiation. Radiation is treated as a surface phenomenon for crucible and the walls of the combustion chamber whereas it is treated as a volumetric phenomenon for the exhaust gas in the combustion chamber. The combustion chamber has been assumed to have the geometry of a cube as shown in Fig 2; the crucible has been treated as a body whose geometry resembles that of a convex body and is situated in the centre of the combustion chamber, as shown in Fig 2. The volume available for the gas to occupy equals the difference between the volume of the combustion chamber and the volume of the crucible. Crucible and walls of the combustion chamber are assumed to behave like black bodies. Properties of the crucible like mass, density etc. along with insulation material properties are taken as inputs.

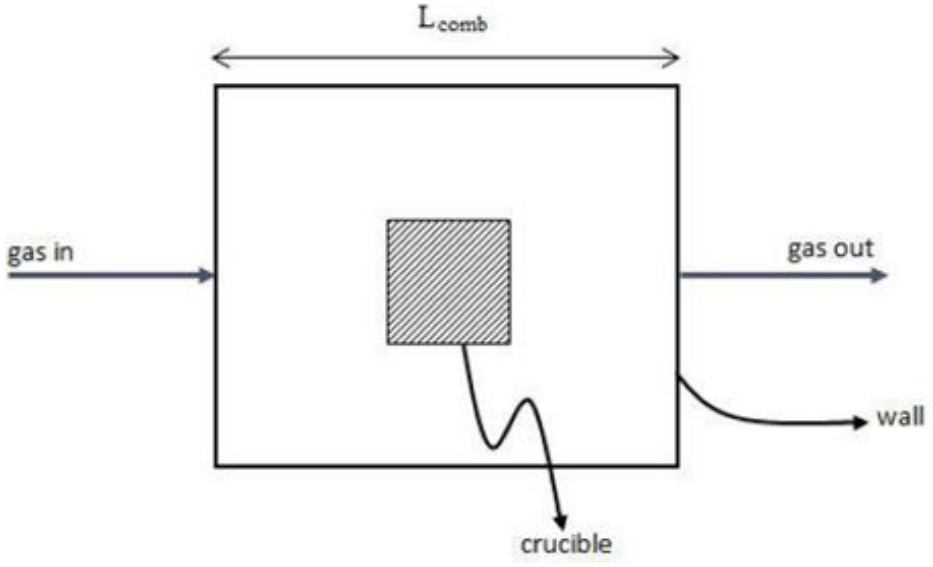


Figure 2: Geometry of the combustion chamber

First law analysis and heat transfer phenomenon occurring inside combustion chamber

The walls of the combustion chamber are usually made of insulating materials. It is desirable to have a high temperature gradient across its thickness so as to have lower temperatures near the side exposed to ambient atmosphere (and thus reduce the heat loss to the environment from the outer walls of the combustion chamber). To obtain the governing equation for heat transfer via conduction in the combustion chamber insulation it has been assumed that the difference in cross sectional surface area of the innermost and outermost walls arising due to wall thickness is negligible. Heat transfer across the walls is assumed to happen in 1 dimension only (from innermost insulation surface to outermost insulation surface). The walls are thus divided into a certain number (specified by user) of control masses of the same cross sectional surface area with a temperature gradient across them. It has been assumed that the properties of the walls (conductivity, diffusivity etc.) remain the same everywhere.

The governing equation for walls, thus is

$$\partial T/\partial t \quad = \quad \alpha_{wall} \frac{\partial^2 T}{\partial x^2} \quad \ldots\ldots (4.1)$$

The governing equation for the walls used after discretization and linearization results in:

$$\frac{T_{wi}^{t+\Delta t} - T_{wi}^{t}}{\Delta t} \quad = \quad \frac{\alpha_{wall}(T_{w(i+1)} + T_{w(i-1)} - 2T_{wi})^{t+\Delta t}}{\Delta x^2} \quad \ldots.(4.2)$$

Where, $\Delta x = \frac{X}{N}$, with X being equal to the sum of insulation thickness. Thus, N-1 equations are generated because of the above equation. Boundary conditions result in the following two equations:

$$-k_{wall}A_{wall}\frac{\partial T}{\partial x}|_{x=0} \quad = \quad \dot{Q}_{gas\rightarrow wall} \; + \; \dot{Q}_{crucible\rightarrow wall} \; - \; \dot{Q}_{emitted\ by\ wall} \qquad \ldots..(4.3)$$

$$-k_{wall}A_{wall}\frac{\partial T}{\partial x}|_{x=X} \quad = \quad H_{ext}A_{wall}(\, T_{w(N+1)} \; - \; T_{amb)}^{\,t+\Delta t} \qquad \ldots..(4.4)$$

The left hand side of the equations 4.3 and 4.4 are discretized as follows

$$\frac{-k_{wall}A_{wall}(T_{w1} - T_{w2})^{t+\Delta t}}{\Delta x} \quad = \quad \dot{Q}_{gas\rightarrow wall} \; + \; \dot{Q}_{crucible\rightarrow wall} \; - \; \dot{Q}_{emitted\ by\ wall} \qquad \ldots..(4.5)$$

$$\frac{k_{wall}A_{wall}\left(T_{wN} - T_{w(N+1)}\right)^{t+\Delta t}}{\Delta x} \quad = \quad H_{ext}A_{wall}(\, T_{w(N+1)} \; - \; T_{amb)}^{\,t+\Delta t} \qquad \ldots..(4.6)$$

Heat is treated as a constant whose value is given by the user as input. The values of the temperatures for the N+1 points must be found at time t+Δt . As mentioned, equation 4.2 generated N-1 equations while 4.3 and 4.4 generated 2 more equations. Thus, there are a total of N+1 equations. However, these equations involve $T_{cruc}^{t+\Delta t}$ *and* $T_{g}^{t+\Delta t}$ terms which are also

unknowns. Thus, two more equations must be generated. These are generated by applying first law equation for the gas and crucible.

As radiation is assumed to be a surface phenomenon for walls and crucible, surface temperatures are the temperature that participate in the radiation network involving walls, crucible and gas. The control volume to analyze the heat transfer for gas is shown below in

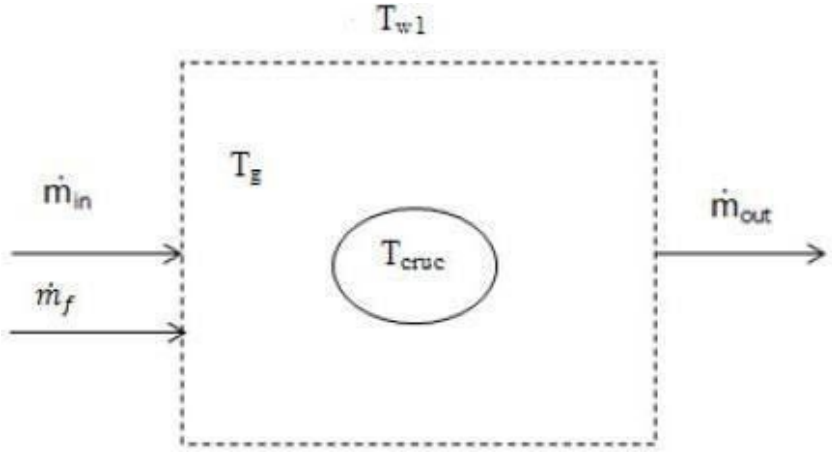


Fig. 3:

Figure 3: Control volume of gas inside combustion chamber

Air enters the combustion chamber while exhaust gas leaves the combustion chamber; the properties of fluid inside the combustion chamber are that of the properties of exhaust gas. The incoming fluid has the properties of air while the outgoing fluid has the properties of the exhaust gas. It is assumed that the heat released ($\dot{m}_f$*C_V) due to the combustion process becomes the $\dot{Q}_{in}$ for the gas. $\dot{m}_f$ is computed as:

$$\dot{m}_f = \frac{\dot{m}_{in}}{AF} \quad \text{.....(4.7)}$$

Where AF = Air-fuel ratio , CV = calorific value of fuel

Taking H_{c1} as the heat transfer coefficient for the convective heat transfer between gas and walls and H_{c2} as the heat transfer coefficient for the convective heat transfer between gas and crucible and applying conservation of energy principle we get:

$$\rho_{cv}^{t} c_v (T_{cv}^{t+\Delta t} - T_{cv}^{t}) v = \dot{m}_{in}^{t} C_p (T_{in}^{t+\Delta t} - T_{ref}) - \dot{m}_{out} C_p (T_{out}^{t+\Delta t} - T_{ref}) + \dot{m}_f^T CV + \varepsilon\sigma A_{cruc} (T_{cruc}^4 - T_g^4)^{t+\Delta}$$

….(4.8)

To linearize the above equation, the following assumptions are made:

$$\varepsilon\sigma A_{wall}(T_{w1}^4 - T_g^4)^{t+\Delta t} = \varepsilon\sigma A_{wall}(T_{w1}^2 + T_g^2)^t (T_{w1} + T_g)^t (T_{w1} - T_g)^{t+\Delta t} = H_{r1}A_{wall}(T_{w1} - T_g)^{t+\Delta t}$$

……..(4.9)

$$\varepsilon\sigma A_{cruc}(T_{cruc}^4 - T_g^4)^{t+\Delta t} = \varepsilon\sigma A_{cruc}(T_{cruc}^2 + T_g^2)^t (T_{cruc} + T_g)^t (T_{cruc} - T_g)^{t+\Delta t} = H_{r2}A_{cruc}(T_{cruc} - T_g)^{t+}$$

……..(4.10)

Thus the simplified form of equation 4.8 after linearizing it is:

$$\rho_{cv}^t c_v(T_{cv}^{t+\Delta t} - T_{cv}^t)v = \dot{m}_{in}^t C_p(T_{in}^{t+\Delta t} - T_{ref}) - \dot{m}_{out}C_p(T_{out}^{t+\Delta t} - T_{ref}) + \dot{m}_f^T CV + (H_{c1} + H_{r1})A_{wall}(T_{w1} -$$

……..(4.11)

For wall,

$$(-k_{wall}A_{wall}\tfrac{\partial T}{\partial x}|_{x=0})^{t+\Delta t} = (1-\epsilon)\sigma A_{cruc}F_{cruc-wall}(T_c^4)^{t+\Delta t} + (1-\epsilon)\sigma A_{wall}F_{wall-wall}(T_{w1}^4)^{t+\Delta t} + \epsilon\sigma A_{wall}(T_g^4)^{t+\Delta t}$$

…….(4.12)

It is assumed that crucible cannot ‘see’ itself(a convex geometry). It can only ‘see’ the walls. The statement mathematically means that $F_{cruc-wall} = 1$. Thus, $F_{cruc-cruc} = 0$. Hence, the radiation that is emitted by the crucible and not absorbed by the gas is completely absorbed by the walls of the combustion chamber. The wall, however, can ‘see’ itself. Hence, part of the radiation emitted by the wall and not absorbed by the gas is absorbed by the wall itself. $F_{wall-cruc}$ is found using the reciprocity equation.

$$A_{wall}F_{wall-cruc} = A_{cruc}F_{cruc-wall} \quad \ldots(4.13)$$

Finally $F_{wall-wall}$ can be obtained by using the following equation.

$$F_{wall-wall} = 1 - F_{wall-cruc} \quad \ldots\ldots(4.14)$$

Using the values, equation 4.12 reduces to

$$(-k_{wall}A_{wall}\tfrac{\partial T}{\partial x}|_{x=0})^{t+\Delta t} = (1-\epsilon)\sigma A_{cruc}(T_{cruc}^4 - T_{w1}^4)^{t+\Delta t} + \epsilon\sigma A_{wall}(T_g^4 - T_{w1}^4)^{t+\Delta t} + H_{c1}A_{wall}(T_g - T_{w1})^{t+}$$

……..(4.15)

To linearize the equation 4.15 following approximation is made,

$$(1-\epsilon)\sigma A_{cruc}(T_{cruc}^4 - T_{w1}^4)^{t+\Delta t} = (1-\epsilon)\sigma A_{cruc}(T_{cruc}^2 + T_{w1}^2)^{t+\Delta t}(T_{cruc} + T_{w1})^{t+\Delta t}(T_{cruc} - T_{w1})^{t+\Delta t} = H_{r3}$$

…….(4.16)

Thus,

$$\frac{k(T_{w1} - T_{w2})^{t+\Delta t}}{\Delta x} = (H_{r1} + H_{c1})\, A_{wall}(T_g - T_{w1})^{t+\Delta t} + H_{r3}A_{cruc}(T_{cruc} - T_{w1})^{t+\Delta t} \quad \text{…..(4.17)}$$

For crucible,

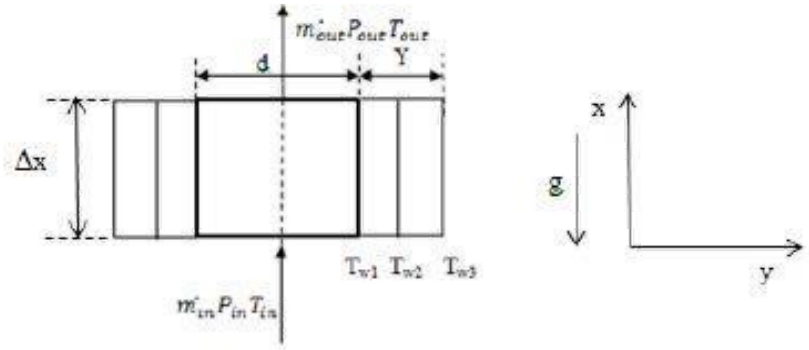
$$\frac{dm_{cruc}c_{cruc}T_{cruc}}{dt} = (1-\epsilon)\sigma A_{wall}F_{wall-cruc}(T_{w1}^4)^{t+\Delta t} + (1-\epsilon)\sigma A_{cruc}F_{cruc-cruc}(T_{cruc}^4)^{t+\Delta t} + \epsilon\sigma A_{cruc}(T_g^4)^{t+\Delta t} + H_{c2}A$$

…(4.18)

It is assumed that the specific heat of the crucible is a constant. It can be thus pulled out of the differential. The view factors required have already been derived. Using approximation made in equations 4.10 & 4.16, equation 4.18 can be simplified as

$$\frac{m_{cruc}c_{cruc}(T_{cruc}^{t+\Delta t} - T_{cruc}^{t})}{\Delta t} = (H_{r2} + H_{c2})A_{cruc}(T_g - T_{cruc})^{t+\Delta t} + H_{r3}A_{cruc}(T_{w1} - T_{cruc})^{t+\Delta t}$$

……(4.19)



As mentioned there are N+3 unknowns (N+1 points on the wall, gas and crucible temperature) at time t+Δt. Further, it was shown how 4.2 generates N-1 equations while equation 4.3, 4.4, 4.17 and 4.19 form the remaining 4 more equations required to solve the N+3 variables. The N+3 equations are linear and form a system of equations. Matrix inversion method has been used to solve the N+3 system of linear equations for N+3 linear equations

Figure 4: Control volume for stack

Continuity Equation

The following equation is obtained when mass balance is applied for the control volume.

$$m_{out}^{t+\Delta t} = m_{in}^{t+\Delta t} - \frac{V((\frac{P_a}{RT_{cv}})^{t+\Delta t} - (\frac{P_a}{RT_{cv}})^{t})}{\Delta t} + m_f^{t+\Delta t} \quad \text{....(4.20)}$$

b) Stack

The stack is treated as a component that has several control volumes, one of the control volume is shown in Fig.4. Analysis for one control volume of the stack is done by using first law analysis and the heat transfer phenomenon occurring inside the stack; the continuity equation; the estimation of pressure drop inside the chamber

First law analysis for the control volume $\dot{Q}_{in} = 0$ for the stack. The heat from the gas is transferred to the insulation by convection. The heat inside the insulation is conducted outwards radially and the heat is lost from the outermost surface to the atmosphere by convection. The heat transfer from the gas to the insulation can be written as :

$$\frac{(\rho_{cv}^{t} C_v (T_{cv} - T_{ref})^{t+\Delta t} - \rho_{cv} (T_{cv} - T_{ref})^{t})v}{\Delta t} = \dot{m}_{cv}^{t} C_v (T_{in} - T_{ref})^{t+\Delta t} - \dot{m}_{out}^{t} C_p (T_{out} - T_{ref})^{t+\Delta t} - H_{int} A (T_{cv} - T_{w1})^{t}$$

$$\text{.....(4.21)}$$

The conduction in the insulation is assumed to be one-dimensional (y-axis) and radial effects are neglected. The surface area of the sections of the insulation is assumed to be constant and is taken to be $2\pi R\Delta x$. Assuming that the properties of the wall and insulation material remains constant, the governing equation becomes:

$$\partial T/\partial t = \alpha_{wall} \frac{\partial^2 T}{\partial y^2} \quad \text{.....(4.22)}$$

By applying central scheme with respect to space and implicit scheme with respect to time for the equation above and the boundary conditions, the following four equations have been obtained:

$$\frac{k_{wall}(T_{w1} - T_{w2})^{t+\Delta t}}{\Delta y} = H_{int} (T_{cv} - T_{w1})^{t+\Delta t} \quad \text{.....(4.23)}$$

$$\frac{k_{wall}(T_{w2} - T_{ws})^{t+\Delta t}}{\Delta y} = H_{ext} (T_{ws} - T_{amb})^{t+\Delta t} \quad \text{.....(4.24)}$$

$$\frac{(T_{w2}^{t+\Delta t} - T_{w2}^{t})}{\Delta t} = \frac{\alpha_{wall}(T_{w1} + T_{w3} - 2T_{w2})^{t+\Delta t}}{\Delta y^2} \quad \text{.....(4.25)}$$

Using these equations, the values of $T_{cv}^{t+\Delta t}$, $T_{w1}^{t+\Delta t}$, $T_{w2}^{t+\Delta t}$, $T_{w3}^{t+\Delta t}$ are obtained.

Continuity Equation

The value of $\dot{m}_{out}^{t+\Delta t}$ can be found using the following equation

$$m_{out}^{t+\Delta t} = m_{in}^{t+\Delta t} - \frac{V\left(\left(\left(\frac{P_a}{RT_{cv}}\right)\right)^{t+\Delta t} - \left(\left(\frac{P_a}{RT_{cv}}\right)\right)^{t}\right)}{\Delta t} \quad \text{.....(4.26)}$$

Linear momentum equation

The value of $P_{out}^{t+\Delta t}$ can be found out using the following equation

$$AP_{out}^{t+\Delta t} = AP_{in}^{t+\Delta t} + \left(\frac{\dot{m}_{in}^2 RT_{in}}{P_a A} - \frac{\dot{m}_{out}^2 RT_{out}}{P_a A} - f\frac{(\frac{P_a}{RT_{cv}})(\Delta x)\, v_{cv}^2}{2d} - \frac{P_a}{RT_{cv}} g\Delta x\right)^{t+\Delta t} - \frac{v}{\Delta t}\left(\left(\frac{\dot{m}_{in}+\dot{m}_{out}}{2A}\right)^{t+\Delta t} - \left(\frac{\dot{m}_{in}+\dot{m}_{out}}{2A}\right)^{t}\right)$$

….(4.27)

The value of the friction factor ‘f’ using [9].

c) Pipe

In order to establish an understanding of the effect of different parameters in a natural draft furnace, a 2-point 1-D problem is taken considering a vertical pipe of length L and diameter D with constant heat flux $\dot{q}$ on its inner surface. It has a mass flow rate $\dot{m}$ of air along the length of the pipe and a varying temperature distribution along the pipe. It is desirable to compute outlet density, optimum mass flow rate and temperature distribution

Owing to the heating of the air inside the pipe due to its heating of the air, there is a pressure difference created across the pipe which may be interpreted as driving potential. The driving potential thus forces the air inside the pipe to flow. As the air flows, pressure drops occur in the pipe which may be interpreted as losses. As the flow rate increases, the pressure drops increase. The amount of flow rate is dependent on both the driving potential and the pressure drop. At a particular flow rate, the driving potential created due to the heat will be balanced by the losses that occur in the pipe. In order to achieve an ambient outlet pressure, the mass flow rate is computed which correspondingly varies with density of the air at the outlet.
Given the flow rate and heat supplied to the pipe (heat flux is given), temperature distribution along the pipe can also be estimated considering the pipe is adiabatic (there is no heat loss with the surroundings).

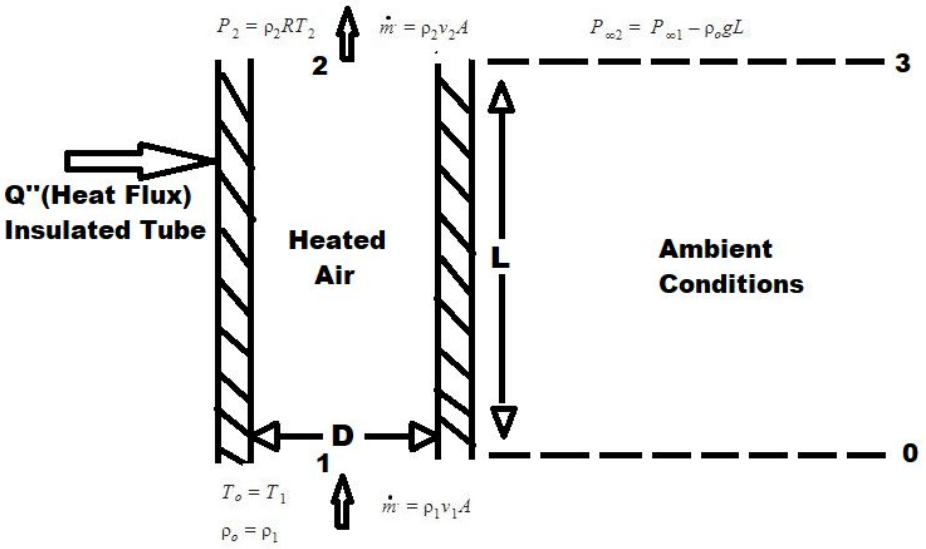


Figure 5: Heating of a pipe at constant flux rate

It is assumed that the component is adiabatic; thus $\dot{Q}_{in} = 0$ and $\dot{Q}_{out} = 0$. It was believed that the amount of heat transferred in the control volumes such as pipe, flow expansion/contraction region, bend, damper would be low as compared to the amount of heat transferred in stack and combustion chamber, because, these control volumes are much smaller in volume (and have less surface area) as compared to stack and combustion chamber. Further heat accumulation and mass accumulation effects were neglected. Hence, these components are treated as control volumes where pressure drop is the only dominant physical phenomenon. The radiation inside the pipe is also neglected due to its small size but not inside stack by virtue of its longer length. There is no pressure drop due to gravity in the pipe as it is generally placed horizontally while stack is kept vertical. Though the pipe is modelled similar to stack the above considerations make it a separate module. The connecting pipes can be of different materials and lengths. Hence an option is provided to the user to use multiple pipes of different material properties and dimensions.

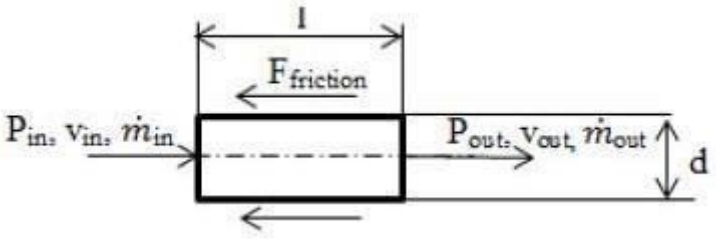


Figure 6: Control volume of pipe

$$P_{drop}^{t+\Delta t} = \left(f\frac{l}{d}\frac{\rho v C_v^2}{2}\right)^{t+\Delta t} \ldots\ldots(4.28)$$

The value of 'f' is calculated using [9]

d) Bend

The bend is assumed to be adiabatic in nature and hence there is no heat exchange. Since its volume is negligible compared to that of the other components, only pressure drop in it is considered. Pressure drop that occurs due to expansion is estimated to be

$$P_{drop} = \left(\frac{1}{2} K_b \rho v^2\right)^{t+\Delta t} \ldots\ldots\ldots(4.29)$$

Where,

$$\alpha_{bend} = 0.95 + 4.42\left(\frac{R_{bend}}{d}\right)^{-1.96} \ldots..(4.30)$$

$$K_b = 0.388\alpha_{bend} Re^{-0.17}\left(\frac{R_{bend}}{d}\right)^{0.84} \ldots..(4.31)$$

e) Flow Expansion Region

It is assumed that the flow expansion region has a small surface area and volume as compared to that of stack/combustion chamber. It is thus treated as a component in which pressure drop is the dominant physical phenomenon occurring in control volume shown in Fig. 6.

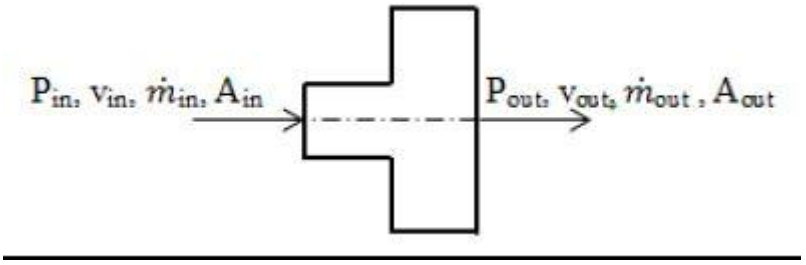


Figure 7: Control volume for flow expansion region

Pressure drop that occurs due to expansion is estimated using the following equation:

$$P_{drop} = \left(\frac{1}{2} K_e \rho v_{in}^2\right)^{t+\Delta t} \ldots\ldots\ldots(4.32)$$

Correlation used to estimate Ke is shown in the following equation [6]:

$$K_e = \left(1 - \frac{d^2}{D^2}\right) \text{.....(4.33)}$$

f) Flow Contraction Region

It is assumed that the flow expansion region has a small surface area and volume as compared to that of stack/combustion chamber. It is thus treated as a component in which pressure drop is the dominant physical phenomenon occurring in control volume shown in Fig. 7

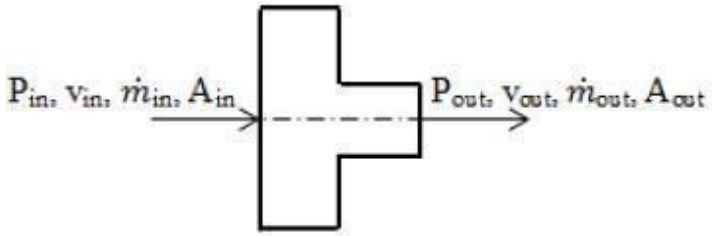


Figure 8: Control volume for flow contraction region

Pressure drop that occurs due to expansion is estimated using the following equation:

$$P_{drop} = \left(\frac{1}{2} K_c \rho v_{out}^2\right)^{t+\Delta t} \text{.....(4.34)}$$

Correlation used to estimate Kc is shown in the following equation [6]:

$$K_c = 0.42\left(1 - \frac{d^2}{D^2}\right) \text{ for } \frac{d}{D} < 0.76, \text{ else } K_c = \left(1 - \frac{d^2}{D^2}\right)^2 \text{.....(4.35)}$$

g) Preheater

The model developed by Oza et al. [1] had no provision for a pre heater which is quite often used in all the natural draft furnace systems. So, the pre heater module was incorporated into the model and the general geometry is as shown in Fig 1. by Baid and Teja [2]. A pre heater is a box placed after the combustion chamber, where the metal to be melted in the furnace is kept. The energy from flue gases is used to raise the temperature of the metal which is then kept in furnace for melting thereby reducing the overall energy required to melt it. Similar to the combustion chamber, preheater compartment has been modelled. Radiation has been treated as a surface phenomenon for mould and the walls of the preheater whereas it has been treated as a volumetric phenomenon for flue gases in the preheater. The geometry of the preheater can be either cubical or cylindrical as specified by the user whereas mould has been assumed to behave like a lumped mass system because it is generally used in bell metal

heating or similar applications wherein the thermal conductivity of mould is high implying minimal temperature variations within the mould. The volume available for the gas to occupy equals the difference between the volume of the preheater and the volume of the mould. Mould and walls of the preheater are assumed to behave like black bodies. Properties of the mould like mass, density etc. along with wall and insulation material properties are taken as inputs. The only difference in the modelling of preheater and combustion chamber is that heat input to the control volume in case of preheater is zero since $\dot{m}_f$ is zero. So only change in combustion chamber and preheater modelling lies in the conservation of energy and conservation of mass equations (Eq. 4.8 and 4.20) and the modified equations are:

$$\frac{\rho_{cv}^{t} c_v (T_{cv}^{t+\Delta t} - T_{cv}^{t}) v}{\Delta t} = \dot{m}_{in}^{t} C_p (T_{in}^{t+\Delta t} - T_{ref}) - \dot{m}_{out} C_p (T_{out}^{t+\Delta t} - T_{ref}) + \dot{m}_f^{T} CV + \varepsilon\sigma A_{mould} (T_{mould}^4 - T_g^4)^{t+\Delta t} + \quad \text{.....(4.36)}$$

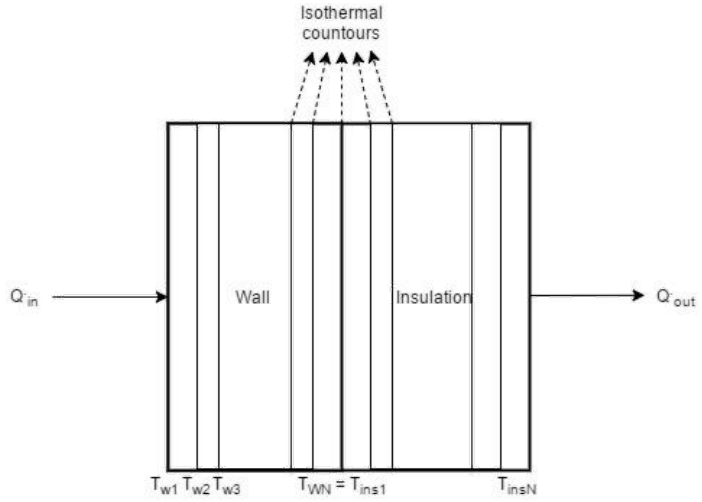
$$m_{out}^{t+\Delta t} = m_{in}^{t+\Delta t} - \frac{V((\frac{P_a}{RT_{cv}})^{t+\Delta t} - (\frac{P_a}{RT_{cv}})^{t})}{\Delta t} \quad \text{.....(4.37)}$$

h) Walls & Insulation

The original model developed by Oza et al.[1] did not account for the wall around combustion chamber, preheater and stack. It considered only an insulating material around the combustion chamber and stack. In practical scenarios wall and insulation both are present around the furnace components and the material properties of wall and insulation differ significantly from each other. Hence in the original model considering only insulation meant that the heat energy storage in the walls present around these components was unaccounted, which shouldn't be ignored as walls have a significant thermal mass. The code was modified so as to include the effect of a wall in the combustion chamber, pre heater, pipes and stack. The thickness of the wall and insulation around each of the components is divided into a certain number of sections as shown in Fig. 8 which are to be given by user as input. Temperature is assumed to be constant along the thickness of each of the section, so more the number of sections more accurate are the results. Equations for solving the temperature at each section of the wall include heat conduction equation in 1-dimension and surface energy balance equations.

Assuming that the properties of the wall and insulation material remains constant, the one-dimensional heat conduction equation becomes:

$$\partial T/\partial t = \alpha_{wall} \frac{\partial^2 T}{\partial x^2} \quad \text{.....(4.38)}$$



The heat coming in from the gas becomes the boundary condition at the inner surface of the wall while the heat lost to environment becomes the boundary condition at the outer surface of the insulation. Boundary conditions in case of walls and insulation around the combustion chamber are given below as an example:

$$-k_{wall}A_{wall}\frac{\partial T}{\partial x}|_{x=0} = \dot{Q}_{gas\rightarrow wall} + \dot{Q}_{crucible\rightarrow wall} - \dot{Q}_{emitted\ by\ wall} \quad \text{.....(4.39)}$$

$$-k_{wall}A_{wall}\frac{\partial T}{\partial x}|_{x=X} = H_{ext}A_{wall}(T_{w(N+1)} - T_{amb})^{t+\Delta t} \quad \text{.....(4.40)}$$

Figure 9: Isothermal contours in the wall and insulation around different components

Equation used for the interface between wall and insulation where material properties change is given below:

$$\frac{k_{wall}(T_{w(s-1)} - T_{ws})^{t+\Delta t}}{\Delta x^2} - \frac{k_{ins}(T_{ins1} - T_{ins2})^{t+\Delta t}}{\Delta y^2} = \frac{\rho_{wall}C_{v_{wall}}(T_{ws}^{t+\Delta t} - T_{ws}^{t})}{\Delta t} \quad \text{.....(4.41)}$$

Similar methodology has been applied to model wall and insulation around each of the components.

i) Damper

In the original model it was found that the modelling of damper was incorrect as even after closing the damper completely, the mass flow rate of air in the system did not become zero. We found that only pressure drop due to damper was taken into account in the model so we altered the model introducing the changes in mass flow rates that are observed in practical cases due to change in damper opening. We modelled the damper as butterfly valve wherein

the flow past it is governed by valve angle and pressure difference, governing equations for which are taken from paper written by J.D. Taylor et al.[7].

A schematic of the butterfly valve (taken from [7]) used to derive the nonlinear relationship between volumetric flow rate, pressure difference, and valve plate angle of attack, α, is presented in Fig. 11.

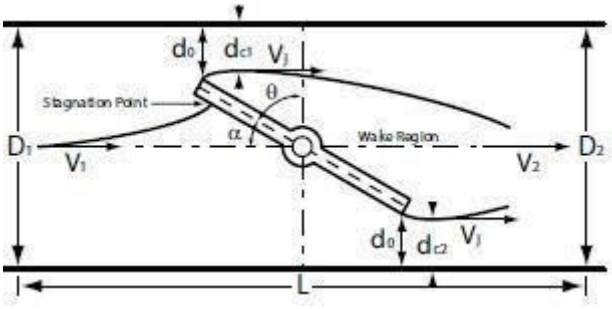


Figure 10: Schematic of butterfly valve damper

D1, D2 and V1,V2 are the diameters and average velocities of the inlet and outlet respectively, $d0$ and $V0$ are the width and average velocity of the orifices between the valve plate and wall. d_0 is maximum when the valve is fully open ($\alpha = 0^0$) and minimum when the valve is fully closed ($\alpha = 90^0$). d_{c1} and d_{c2} are the widths of the upper and lower jets at their minimum points and Vj is the corresponding jet velocity. We assume in this case that the inlet and outlet diameters are equal $D_1 = D_2$=D implying $V_1 = V_2 = V$. The variation of coefficients of contraction, C_{c1} and C_{c2} with alpha is given by the equations below:

$$C_{c1} = -0.0044 * \alpha + 1 \ldots\ldots(4.42)$$

$$C_{c2} = -0.04 * \alpha + 1 \quad for\ \alpha < 10^0$$

$$= 0.6, \text{otherwise}\ldots\ldots\ldots(4.43)$$

The pressure loss coefficient due to flow expansion, ς_e , from the minimum points to the outlet of butterfly valve is given by:

$$\varsigma_e = \left[\frac{2}{(C_{c1}+C_{c2})(1-\sin sin\,\alpha)} - 1\right]^2 \ldots\ldots.(4.44)$$

This coefficient characterizes the pressure loss due to flow expansion. However, at small angles when the valve is nearly open and the wake region is very small, C_{c1} and C_{c2} approach unity, and the predicted pressure loss is zero. This result is unphysical, and an additional term due to pipe friction must be included. Therefore, the pressure loss coefficient due to laminar

pipe friction, ςf, obtained from the well known Darcy-Weisbach equation and moody chart is given by –

$$\varsigma_f = \frac{64\,\mu L}{\rho v D^2} \quad \text{.....(4.45)}$$

The fluid resistance, R, is defined as the ratio of the overall static pressure difference, $P2 - P1$ across the valve to the mass flow rate through the valve, $\dot{m}$. Since the inlet and outlet diameters are equal, there is no convective acceleration, and the static pressure difference is equal to the total pressure lost due to both flow expansion and pipe friction, $P2 - P1 = \Delta P$. Hence, the pressure drop is given by the equation:

$$\Delta P = \dot{m} * \frac{V}{2D} * \left(\varsigma_f + \varsigma_e\right) \text{.....(4.46)}$$

j) Crucible

The model developed by Oza et al. assumed the crucible to behave like a lumped mass system i.e. assumed that the entire crucible is at same temperature. This assumption is reasonably good in case of bell metal heating furnace and similar kilns where crucible has high thermal conductivity. Thus, the crucible models made is the solid crucible model where solid crucible body is assumed to behave like a lumped mass system.

As stated above this model is well suited to simulate applications in which crucible has high thermal conductivity. The entire crucible is taken to be at same temperature which is calculated from the governing equation given below:

$$\frac{m_{cruc} c_{cruc} (T_{cruc}^{t+\Delta t} - T_{cruc}^{t})}{\Delta t} = (H_{r2} + H_{c2}) A_{cruc} (T_g - T_{cruc})^{t+\Delta t} + H_{r3} A_{cruc} (T_{w1} - T_{cruc})^{t+\Delta t}$$

……(4.47)

Other unknown temperatures involved in this equation are calculated from the set of equations discussed above in the modelling of combustion chamber.

k) Stack Radiation

The conduction inside the stack is assumed to be one-dimensional and radial effects are neglected. The surface area of the sections of the wall and insulations vary from innermost section to outermost section. The variation cannot be neglected due to considerable thickness

of wall and insulation. Hence the surface area of the section is assumed to be increasing radially by a value of $2\pi*(d)*\Delta x$.

The gas inside the stack is generally of high temperature and hence the radiation effects of the gas are significant inside it and cannot be neglected. So, the heat transfer between the gas and the walls of the stack is mainly due to convection and radiation. The stack is divided into N control volumes and each control volume surface 'j' is considered to be at a uniform temperature of T_{wj} as shown in Fig.13.

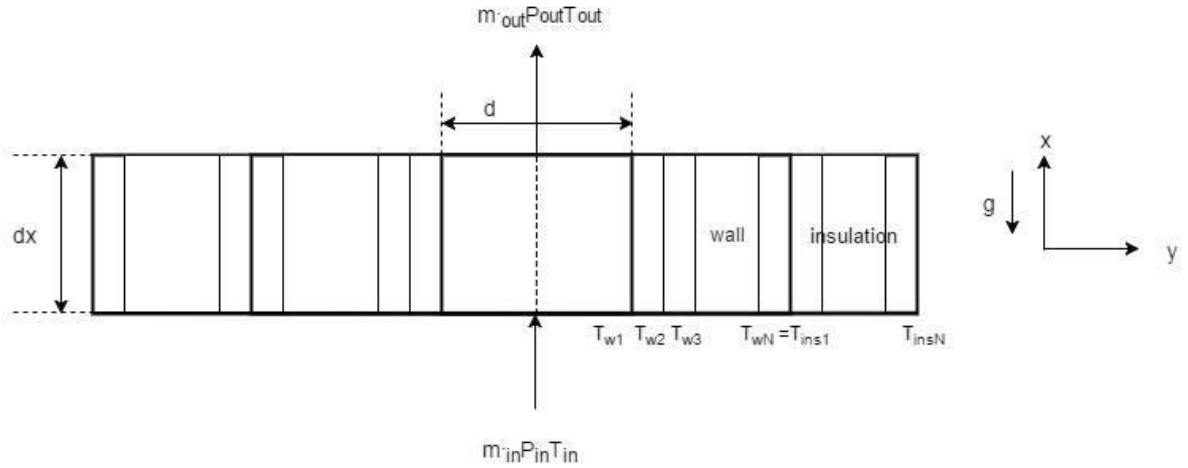


Figure 11: Control volume of stack

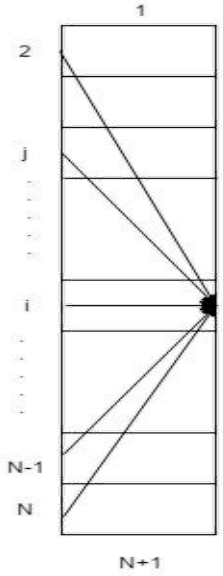


Figure 12: Radiation heat transfer from all surfaces onto a single surface of stack

The gas in the stack and every control volume surface radiates heat onto every other control volume surface of the stack and the fraction of heat radiated by each surface onto another is

given by form factor. The form factors for a single control volume as shown below in Fig. 14 (taken from [8]) and it was used to find out the form factors for N control volumes by solving iteratively

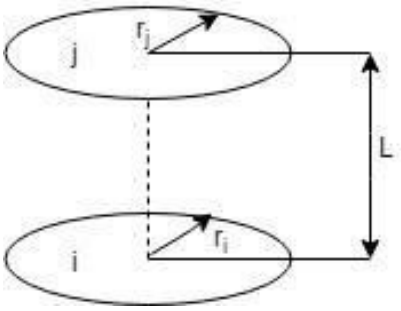


Figure 13: Form factor for two parallel discs

$$For\ r_j = r_i = r\ and\ R = \frac{r}{l} \quad \text{.....(4.48)}$$

$$\text{We get, } F_{i\to j} = F_{j\to i} = 1 + \frac{1-\sqrt{4R^2+1}}{2R^2} \quad \text{.....(4.49)}$$

After the form factors are calculated for the entire stack column, the corresponding heat transfer equation 4.12 modifies to

$$\frac{k_{wall}(T_{w1}-T_{w2})^{t+\Delta t}}{\Delta y} = \epsilon\sigma A_{wall}(T_{cv}^4)^{t+\Delta t} + H_{int}(T_{cv} - T_{w1})^{t+\Delta t} - \sigma A_{wall}(T_{w1}^4)^{t+\Delta t} + \sum_{j=1}^{N} F_{j\to i}(1-\epsilon)\sigma A_{wall}(T_{wj}^4)^{t+\Delta}$$

.....(4.50)

Here, $F_{j\to i}$ is the form factor i.e., the fraction of the energy radiated from the jth surface onto the ith surface of the wall.

$$\frac{k_{wall}(T_{w1}-T_{w2})^{t+\Delta t}}{\Delta y} = \epsilon\sigma A_{wall}\left((T_{cv}^4)^{t+\Delta t} - (T_{w1}^4)^{t+\Delta t}\right) + H_{int}(T_{cv} - T_{w1})^{t+\Delta t} - (1-\varepsilon)\sigma A_{wall}(T_{wj}^4)^{t+\Delta t} + \sum_{j=1}^{N} F$$

.....(4.51)

To linearize the equation the following assumptions are made

$$\epsilon\sigma A_{wall}\left((T_{cv}^4)^{t+\Delta t} - (T_{w1}^4)^{t+\Delta t}\right) = \epsilon\sigma A_{wall}(T_{cv} - T_{w1})^{t+\Delta t}\left((T_{cv})^t + (T_{w1})^t\right)\left((T_{cv}^2)^t + (T_{w1}^2)^t\right)$$

.....(4.52)

Hence the simplified equation is

$$\frac{k_{wall}(T_{w1}-T_{w2})^{t+\Delta t}}{\Delta y} = (H_{int} + H_{rad})(T_{cv} - T_{w1})^{t+\Delta t} -$$

$$(1-\epsilon)\sigma A_{wall}(T_{wj}^4)^{t+\Delta t} + \sum_{j=1}^{N} F_{j\to i}(1-\epsilon)\sigma A_{wall}(T_{wj}^4)^{t+\Delta t} \text{.....(4.53)}$$

$$where,\ H_{rad} = \varepsilon\sigma A_{wall}^{t+\Delta t}\left((T_{cv})^t + (T_{w1})^t\right)\left(\left(T_{cv}^2\right)^t + \left(T_{w1}^2\right)^t\right) \text{.....(4.54)}$$

After the above modifications made to the model, the effect of each of the modifications was analyzed and the model was reiterated until they were in coherence with theoretical estimates. Subsequently the model was validated with varying sets of experimental data available from the research done in IIT Delhi. The observations of the validation are discussed in the following chapter

Algorithm used to solve the problem when the system is treated as a union of multiple control volumes:

1. The components of the system are treated to be 'modules'. The modules like the Combustion chamber, Preheater, Damper, Bend, and Pipe are treated as single control volumes whereas stack is treated to be made of multiple control volumes due to significant variation in the temperature along it's length.

2. The governing equations are written down for each control volume based on the analysis done in the earlier sections (mass balance equation, linear momentum equation/modified Bernoulli's equation, first law equation for a control volume) and by making the assumptions stated earlier, $\dot{Q}_{in} - \dot{Q}_{out}$ as a function of temperature and pressure drops are estimated for each control volume based on how the flow happens in the control volume (Reynolds number, Nusselt's number, geometry etc.).

3. For the first control volume, the value of $m_{in}^{t+\Delta t}$ is guessed and taken to be 0.8* m_{in}^{t} .

4. First $T_{cv}^{t+\Delta t}$ is found out by applying the first law equation for the control volume. Then by applying continuity equation $m_{out}^{t+\Delta t}$ is found out. Then the value of $P_{out}^{t+\Delta t}$ is estimated by applying linear momentum equation and/ modified Bernoulli's equation.

5. For a control volume in the middle, the values $m_{out}^{t+\Delta t}$, $T_{out}^{t+\Delta t}$, $P_{out}^{t+\Delta t}$ become the input conditions i.e. $m_{in}^{t+\Delta t}$, $T_{in}^{t+\Delta t}$, $P_{in}^{t+\Delta t}$ for the next control volume. For the last control volume, the estimate of $P_{out}^{t+\Delta t}$ is compared with $P_{out}^{t+\Delta t}$ from boundary conditions; if the estimate is higher, the value of the guess is modified by adding 0.001 kg/s to the inlet mass flow rate's previous estimate of the first control volume and the process is repeated until the estimated $P_{out}^{t+\Delta t}$ becomes just lower than boundary condition.

Results & Discussion

The project takes the excess air ratio and damper position at every instant as inputs. As a part of this project, a model generic to fuel type, air flow rate, and configuration has been developed which can be used to ease the process of designing a natural draft furnace. Since, several assumptions are made, the need to validate is a must which has been explained below in details. The set of experimental results as found by Gokhale et al. [3] are used as reference for this validation.

Experimental Validation

Reasons for comparison with experimental data

The generic model developed in the project has tried to model the natural phenomenon occurring in the natural draft furnace systems. Several assumptions have been made so as to solve the governing equations and compute the parameters at every time instant. The model developed can thus compute model various parameters (such as fuel flow rate, total fuel consumer, pressure distribution, temperature distribution) as a function of time. The model can be used by the members of the scientific community in making new designs only if the predictions made by the model have a close proximity to that of the experimental data. Thus, the model needs to be validated by experimental data.

It is assumed that the temperature of gas at the exit of the control volume would be an indicator for the chamber top temperature, measured by Gokhale. Thus, the model's estimate of temperature of the exhaust gas at the exit of the combustion chamber at different instants is compared with the chamber top temperature measured by Gokhale et al. Further, the model's

estimate of the total fuel consumed, the mass flow rate of the fuel as a function of time are compared with the experimental data collected by Gokhale et al.

Below mentioned are the configurations of the kiln that will be used for validating the results with the experimental observations recorded during the past research at IIT Delhi.

Kiln Specifications		
1	Inner dimensions	1.2m*1.2m*1.2m
2	Inner lining	0.1143m insulating brick
	Density	1300 kg/m3
	Thermal Conductivity	0.66 W/K.m
	Specific Heat	960 J/kg K
3	Outer Insulation	0.1143m insulating brick
	Density	150 kg/m3
	Thermal Conductivity	0.15 W/K.m
	Specific Heat	1070 J/kg K
4	Pottery-ware	Terracotta fired ware
	Density	2000 kg/m3
	Thermal Conductivity	1.32 W/K.m
	Specific Heat	840 J/kg K
5	Pottery-ware	110kg of dry pre-fired terracotta ware
6	Fuel used	LPG, ~64kg was used. NCV = 45.71 MJ/kg
7	Burner	Torch type, 8 No, capacity of 1.5kg/hr each
8	Fuel Flow rate	By measuring weight of LPG cylinders at an interval of 1/2 hr using dial type weighing scale of +/- 0.5kg least count
9	Firing cycle	13 hour and 35 minutes, the ware were glazed at a temperature of 1075 C
10	Gas composition	Measured using a portable gas analyzer of CO2 . H2O are estimated using CO2 % and fuel composition. Measured every 30 minutes
11	Chamber Temperature	Measured using R-type thermocouple at 30 minutes interval

User Guide

This user guide has been developed in order to ensure the user-friendliness of the system. The motive of this guide is to serve as a manual for a designer who can walk through the model as and when required and configure the system for any possible configuration required. Thus, this manual will lead to the introduction of generality and usability of the code not only by the developer but even by the designers.

Below mentioned are the steps that needs to be followed :

Chapter 5

Conclusion & Future Scope

5.1 Conclusion

- The model developed as a part of this project is generic with respect to configuration, fuel and application which can predict the fuel consumption, fuel flow rate, temperature distribution and pressure distribution of a natural draft system consisting of combustion chamber, pre-heater, damper and a stack connected to each other

- The separate individual modules generated for each component of the natural draft furnaces can be used separately for analysing the variations of several parameters within each segment and thus improving upon the dimensions and the shape of the component providing an ease to the designers for a better and efficient design

- The model generated as a part of the project resembles to the experimental data obtained during the previous researches at IIT Delhi. It can validated for a set of experiments which proves its usability in various applications.

- The model was developed after a successful integration of the damper and the bend extending the scope of usage of the model and easing the designers to quickly design natural draft furnaces with maximum fuel efficiency within the practical limits

- The user manual developed acts as a guide to operate the model and configure the model for various configurations as and when required increasing the versatility and the user friendliness of the model.

- The radiation effects in the stack were observed to be significant in the later stage of combustion process due to the high gas temperatures. The gas lost a greater amount of heat to the stack walls because of radiation and hence recorded a lower temperature when compared to the gas temperature without radiation effects

5.2 Scope of Future Work

- The simulation model must be validated with more experiments and also with more diversity in order to make the model comprehensive enough to simulate all kinds of natural draft furnace systems

- The user interface can be made more user friendly by developing a simulation interface providing an option to drag the components to the workspace and to connect them with simple lines can make the integration of modules easier.

- The model can currently simulate a natural draft furnace system having only one combustion chamber and one preheater. Hence, there is a scope to improve upon the model in order to simulate furnaces having multiple combustion chambers and multiple preaheaters

- A provision for a blower can be provided to initiate the mass flow rate within the furnace system.

Advances over the years....

	Oza et al. [2015]	Baid & Teja [2017]	Current Project [2019]
Workability	Yes	No	Yes
Generalization	No	No	Yes
User friendliness	Low	Moderate	Extended
Time Complexity	Low	High	Low

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Appendix

	Parameter		Values
Atmosphere	Ambient Temperature (K)		298
	Gas constant for air (J kg^{-1} K^{-1})		287
	Viscosity (kg/m/s)	a	-5E-12
	mu=aT^2+bT+c	b	4E-08
		c	0.000006
	Prandtl Number		0.7
	Thermal Conductivity (W/m/K)	a	4E-09
	k_air=aT^2+bT+c	b	0.00005
		c	0.0112
	heat transfer coefficient (W/m^2/K)		3.5
	Cp for air (J/kg/K)		1005.7

Fuel	Gas constant for flue gas (J/kg/K)		283.63
	Calorific Value (kJ/kg)		10300
	Reference Temperature (K)		298
	Stoichiometric Air Fuel Ratio		8.03
	Cp for flue gas (J/kg/K)		1140
	Viscosity (kg/m/s)	a	3E-08
	mu=aT+b	b	0.000007
	Thermal Conductivity (W/m/K)	a	0.00007
	k_air=aT+b	b	0.0031
Fuel bed	Porosity		0.3
	Fuel bed thickness (m)		0.1
	Fuel particle effective diameter (m)		0.007
Grate	Side of square openings (m)		0.01
	Grate thickness (m)		0.005
Bend	Bend radius (m)		0.23
Crucible	Mass (kg)		581
	Specific heat (J/kg/K)		880
	Density(Kg/m^3)		2000
	Thermal Conductivity(W/m/K)		1.32
	Thickness(m)		0.2
	Sections of crucible		10
Mould	Mass (kg)		527
	Specific heat (J/kg/K)		880
	Density(Kg/m^3)		2000
CC wall	Wall thickness(m)		0.2286
	Thermal conductivity(W/m/K)		0.82361
	Specific heat (J/kg/K)		880
	Density(Kg/m^3)		1556
	sections		20
PH wall	Wall thickness(m)		0.2286
	Thermal conductivity(W/m/K)		0.82361
	Specific heat (J/kg/K)		880
	Density(Kg/m^3)		1556
	sections		20
Stack	Roughness (m)		0.000045
	number of control volumes		10
	Wall thickness(m)		0.2286
	Thermal conductivity(W/m/K)		0.82361
	Specific heat (J/kg/K)		880
	Density(Kg/m^3)		1556
	sections		20
Insulation	Thermal Conductivity (W/m/K)		1.32
	Specific heat (J/kg/K)		880
	Density(Kg/m^3)		2000

	Insulation thickness(m)		0.1524
			0.1524
			0.1524
Pipe	number of control volumes		10
	Sections		20
blower	Pressure added by the blower	P_b	0
	P = P_b - (1/2*K_b*Q^2)	K_b	0
Time	dt (s)		4
	time_heating(min)		0
	time_combustion (min)		420

1. Main function

```
global all m T Pd value
all = xlsread ('input','1','F3:F67');
global M_stack MM_stack T_stack T1T_stack T1TT_stack TT_stack AF
global Tg Tgi TTgi T_cc T_cruc TT_cc TTcruc MMi MMo Mi Mo Mpi_p MMpi_p Mpo_p MMpo
global TTgpi TTgpo Tgpi Tgpo
T = 298;
T_amb=all(1);                    %Ambient Temperature
air_constant=359.5;
den_air=air_constant*T^(-1);
g = 9.81;
Pd = 0;
len_stack %=input value
bc = den_air*g*len_stack;
value = 0;
N=all(47);                       %Stack is divided into N-1 control volumes
s_stack=all(52);                 %Number of sections into which wall and insulation are divided individually
        for control volume analysis
T_stack = zeros(N,1);
```

```
dt = all(41);
time_stack = all()
for i=1:N
   T_stack(i)=T_amb;                          %Initializing the value
end
T1T_stack=zeros((N-1)*(2*s_stack-1),1);          %Temperatures of the wall and insulation surfaces in
        'N-1' control volumes at time 't+dt'
for i=1:(N-1)*(2*s_stack-1)
   T1T_stack(i)=T_amb;                          %Initializing the value
end
M_stack=zeros(N,1);
for i=1:N
   M_stack(i)=0.001;                          %Initializing the value
end
for i=1:2*s_pre-1
   T1_p(i)=T_amb;                %Initializing the temperatures of sections of wall and insulation to ambient
        temperature
end

Tgi = T_amb;
TTgi = T_amb;
Tgo = T_stack(1);
Tg = 0.5*(Tgi+Tgo);
T_cruc = T_amb;
T_cc = T_amb;
TT_cc=zeros(2*s_cc-1,1);          %Matrix storing the temperatures of the sections of wall and insulation
        around combustion chmaber at time = t+dt.
for i = 1:2*s_cc-1
   TT_cc(i) = T_amb;
end
for rr = 1:time_stack*60/dt
[X_cc,Y_cc,Z_cc,energy_wall_stack,energy_wallloss_stack] = stack(d_stack,len_stack);
while bc > Pd
[ps1,ps2] = pressure_stack(d_stack,l_stack);
 if bc > Pd
   MM_stack(1) = MM_stack(1)+0.001;
 end
end
M_stack = MM_stack;
m = MM_stack(N);
T_stack = TT_stack;
T1T_stack = T1TT_stack;
end
time_combustion=all(43);
time_AF1=all(44);
time_AF2=all(45);
time_AF3=all(46);
time_AF4=all(47);
time_AF5=all(48);
AFS=all(15);                    %Stoichiometric air fuel ratio for fuel combusted in the system
for rr = 1:time_combustion*60/dt
   if rr<=(time_AF1*60/dt)
      AF=(1+all(49)/100)*AFS;
      eps_gas=all(55);
```

```
    elseif rr>(time_AF1*60/dt) && rr<=(time_AF2*60/dt)
        AF=(1+all(50)/100)*AFS;
        eps_gas=all(56);
    elseif rr>(time_AF2*60/dt) && rr<=(time_AF3*60/dt)
        AF=(1+all(51)/100)*AFS;
        eps_gas=all(57);
    elseif rr>(time_AF3*60/dt) && rr<=(time_AF4*60/dt)
        AF=(1+all(52)/100)*AFS;
        eps_gas=all(58);
    elseif rr>(time_AF4*60/dt) && rr<=(time_AF5*60/dt)
        AF=(1+all(53)/100)*AFS;
        eps_gas=all(59);
    elseif rr>(time_AF5*60/dt)
        AF=(1+all(54)/100)*AFS;
        eps_gas=all(60);
    end
[c1,c2,c3,c4,c5,c6]=CC(dia_cc,len_cc);
[X_cc,Y_cc,Z_cc,energy_wall_stack,energy_wallloss_stack] = stack(dia_stack,len_stack);
while bc > Pd
pipe(Dh1,Dh2);
[ps1,ps2] = pressure_stack(Dh1,Dh2,l_stack);

  if bc > Pd
    MM_stack(1) = MM_stack(1)+0.001;
  end
end
T_cruc = TTcruc;
T_cc = TT_cc;
Tgi = TTgi;
Tgpo =TTgpo;
Tgpi = TTgpi;
Mi = MMi;
Mo = MMo;
T_stack = TT_stack;
T1T_stack = T1TT_stack;
Mpi_p = MMpi_p;
Mpo_p = MMpo;
end
```

2. Module for pressure drop in pipe

```
function pipe(Dh1,Dh2)
global all value
global Pd
global m T
A1=pi()*(Dh1/2)^2;
e=all(30);
l=all(29);
T_amb = all(1);
if value == 0 %pipe before combustion chamber
     T_pipe = T_amb;
elseif value ==1 %pipe after combustion chamber
       T_pipe = T;
end
air_constant=359.5;
den_air=air_constant*T_pipe^(-1);
```

```
mu_air=all(3)*T_pipe^2+all(4)*T_pipe+all(5);
R_air=all(2);
R_gas=all(12);
gas_constant=air_constant*R_air/R_gas;
den_gas=gas_constant*T_pipe^(-1);
mu_gas=all(17)*T_pipe+all(18);
if value == 0 %pipe before combustion chamber
    den = den_air;
     mu = mu_air;
     constant = air_constant;
elseif value ==1 %pipe after combustion chamber
       den = den_gas;
       mu = mu_gas;
       constant = gas_constant;
end
u=m/(den*A1);
Re=den*u*Dh1/mu;
if Dh1==Dh2
   p_areachange=0;
elseif Dh1<Dh2
   k=(1-(Dh1/Dh2)^2)^2;
   p_areachange=(k*0.5*den*u*u)+0.5*m^2*T_pipe/constant*((16/pi()^2)*(1/Dh2^4-1/Dh1^4));
elseif Dh1>Dh2
   if Dh2/Dh1<0.76
      k=0.42*(1-(Dh2/Dh1)^2);
      u_comp=u*(Dh1^2)/(Dh2^2);
      p_areachange=(k*0.5*den*u_comp*u_comp)+0.5*m^2*T_pipe/constant*((16/pi()^2)*(1/Dh2^4-
           1/Dh1^4));
   else
      k=(1-(Dh2/Dh1)^2)^2;
      u_comp=u*(Dh1^2)/(Dh2^2);
      p_areachange=(k*0.5*den*u_comp*u_comp)+0.5*m^2*T_pipe/constant*((16/pi()^2)*(1/Dh2^4-
           1/Dh1^4));
   end
end
      f=0.25/(log10((e/(7.4*(Dh1/2)))+(5.74/Re^0.9)))^2;
      p_drop=f*(l/Dh1)*(u^2)/2*den;
      Pd = Pd + p_drop+p_areachange;
end
```

3. Module for pressure drop in bend

```
function bend(value,Dh1,Dh2)

global all

global m

global T

global Pd

if value == 0 %pipe before combustion chamber

    T_bend = T_amb;

elseif value ==1 %pipe after combustion chamber
```

```
        T_bend = T;
end
A1=pi()*(Dh1/2)^2;
R_bend=all(31);
alpha_bend=0.95+4.42*(R_bend/Dh1)^-1.96;
air_constant=359.5;
den_air=air_constant*T_bend^(-1);
mu_air=all(3)*T_bend^2+all(4)*T_bend+all(5);
R_air=all(2);
R_gas=all(12);
gas_constant=air_constant*R_air/R_gas;
den_gas=gas_constant*T_bend^(-1);
mu_gas=all(17)*T_bend+all(18);
if value == 0 %bend before combustion chamber
      den = den_air;
      mu = mu_air;
      constant = air_constant;
elseif value ==1 %bend after combustion chamber
        den = den_gas;
        mu = mu_gas;
        constant = gas_constant;
end
u=m/(den*A1);
Re=den*u*Dh1/mu;
if Dh1==Dh2
    p_areachange=0;
elseif Dh1<Dh2
k=(1-(Dh1/Dh2)^2)^2;
p_areachange=(k*0.5*den*u*u)+0.5*m^2*T_bend/constant*((16/pi()^2)*(1/Dh2^4-1/Dh1^4));
elseif Dh1>Dh2
    if Dh2/Dh1<0.76
        k=0.42*(1-(Dh2/Dh1)^2);
        u_comp=u*(Dh1^2)/(Dh2^2);
```

```
        p_areachange=(k*0.5*den*u_comp*u_comp)+0.5*m^2*T_bend/constant*((16/pi()^2)*(1/Dh2^4-
        1/Dh1^4));
    else
        k=(1-(Dh2/Dh1)^2)^2;
        u_comp=u*(Dh1^2)/(Dh2^2);
        p_areachange=(k*0.5*den*u_comp*u_comp)+0.5*m^2*T_bend/constant*((16/pi()^2)*(1/Dh2^4-
        1/Dh1^4));
    end
end
k_bend=0.388*alpha_bend*(Re^-0.17)*((R_bend/Dh1)^0.84); p_bend=(k_bend*0.5*den*u*u);
Pd=Pd+p_bend+p_areachange;
End
```

4. Module for pressure drop in damper

```
function y=damper(Dh1,Dh2,rr)        %defining a function that returns the value of pressure drop in damper as
    output
global all time_damper angle_damper value T m      %Defining global variables so as can be used by other
    modules
dt=all(63);                          %Discretization time step
```

```
A_damper=pi()*(Dh1/2)^2;                %Area of cross section of damper
if value == 0 %pipe before combustion chamber
    T_dam = T_amb;
elseif value ==1 %pipe after combustion chamber
     T_dam = T;
end
air_constant=359.5;                     %Value of PM/R for air
den_air=air_constant*T_dam^(-1);        %Density of preheater
R_air=all(2);                           %Gas constant for air
R_gas=all(12);                          %Gas constant for flue gas
gas_constant=air_constant*R_air/R_gas;  %Value of PM/R for flue gas
den_gas=gas_constant*T_dam^(-1);        %Density of flue gas
mu_air=all(4)*T_dam+all(3)*T_dam^2+all(5);   %Viscosity of air
mu_gas=all(17)*T_dam+all(18);           %Viscosity of flue gas
if value ==0
   den = den_air;
   mu = mu_air;
   constant = air_constant;
elseif value ==1
   den = den_gas;
   mu = mu_gas;
   constant = gas_constant;
end
u=m/(den*A_damper);                     %Velocity of air through damper
CC1=0; CC2=0;alpha=0;                   %Initialization of constants
for i= 1:time_damper
   if rr<= (time_damper(i))*60/dt
      alpha = angle_damper(i);
      if alpha < 10
         CC2 = -0.04*alpha + 1;         %Constants used in the pressure drop calculation
      else
         CC2 = 0.6;
      end
      CC1 = -0.0044*alpha + 1;
```

```
        break
    end
end
p_damper = (m*u/(2*Dh1))(64*mu/(den*u*Dh1) + (2/((CC1+CC2)(1-sin(alpha*pi()/180))) - 1)^2);
      %pressure drop acroos the damper modelled as butterfly valve
%if loop to check if the dimater of damper and diameter of component placed after
%the damper are same or different to compute the expansion/contraction losses
if Dh1==Dh2
    p_areachange=0;
elseif Dh1<Dh2                      %expansion loss
    k=(1-(Dh1/Dh2)^2)^2;              %loss coefficient for sudden expansion
    p_areachange=(k*0.5*den*u*u)+0.5*m^2*T_dam/constant*((16/pi()^2)*(1/Dh2^4-1/Dh1^4));
      %pressure drop due to area change
elseif Dh1>Dh2                      %contraction loss
    if Dh2/Dh1<0.76
        k=0.42*(1-(Dh2/Dh1)^2);         %loss coefficient for sudden contraction
        u_comp=u*(Dh1^2)/(Dh2^2);

       p_areachange=(k*0.5*den*u_comp*u_comp)+0.5*m^2*T_dam/constant*((16/pi()^2)*(1/Dh2^4-1/Dh1^4))
       ;   %pressure drop due to area change
    else
        k=(1-(Dh2/Dh1)^2)^2;            %loss coefficient for sudden contraction
        u_comp=u*(Dh1^2)/(Dh2^2);

       p_areachange=(k*0.5*den*u_comp*u_comp)+0.5*m^2*T_dam/constant*((16/pi()^2)*(1/Dh2^4-1/Dh1^4))
       ;   %pressure drop due to area change
    end
end
y=p_areachange + p_damper;                          %total pressure drop
end
```

5. Module for pressure drop in damper

```
function pressure_CC(Dh1,Dh2,l_c)      %Defining a function that returns the value of pressure drop and mass flow rate in combustion chamber as output

global all Pd Mi Mo MMi MMo m Tg TTg TTgi AF    %Defining global variables so as can be used by other modules

dt=all(63);                          %Discretization time step

T_amb=all(1);                        %Surrounding air temperature

air_constant=359.5;                  %Value of PM/R for air

R_air=all(2);                        %Gas constant for air

R_gas=all(12);                       %Gas constant for flue gas

gas_constant=air_constant*R_air/R_gas;     %Value of PM/R for flue gas

den_air=air_constant*T_amb^(-1);          %density of air

l_cc=l_c;                            %Length of combustion chamber

A_cc=pi*Dh1^2/4;                     %Cross sectional area perpendicular to the flow of air in the combustion chamber

mu=all(3)*T_amb^2+all(4)*T_amb+all(5);     %viscosity of air

por=all(21);                         %Porosity of fuel bed

Dp=all(23);                          %effective diameter of fuel particles

t_fuelbed=all(22);                   %Thickness of fuel bed

   TTgo=TTg;                         %equating the temperature of flue gas in combustion chamber to the outlet temperature of combustion chamber

      MMo=MMi+MMi/AF -(l_cc*A_cc/dt)gas_constant(1/TTg - 1/Tg);    %Mass flow rate at outlet of combustion chamber

           %pressure drop

      u_comb=MMi/((A_cc)*den_air);                                  %velocity of air inside combustion chamber


p_comb=150*mu*((1-por)^2)u_comb*t_fuelbed/((por^3)(Dp^2))+1.75*(1-por)den_air(u_comb^2)*t_fuelbed/((por^3)*Dp);          %pressure drop due to fuel bed

      p_drop_cc = l_cc/A_cc/dt/2*(MMi+MMo-Mi-Mo)- MMi^(2)*TTgi/air_constant/A_cc^(2) + MMo^(2)*TTgo/gas_constant/A_cc^(2) + p_comb;

           %GRATE

         grate_side=all(24);             %Grate side

         grate_area=grate_side^2;        %Grate area

         grate_thick=all(25);            %Thickness of grate

         grate_eq_area=(grate_side+grate_thick)^2;      %Equivalent grate area

         ke_grate=(1-(grate_side/(grate_side+grate_thick))^2)^2;       %expansion loss coefficient
```

```
        if grate_side/(grate_side+grate_thick)<0.76
            kc_grate=0.42*(1-(grate_side/(grate_side+grate_thick))^2); %contraction loss coefficient
        else
            kc_grate=(1-(grate_side/(grate_side+grate_thick))^2)^2;
        end
        u_grate=u_comb*grate_eq_area/grate_area;                    %velocity of air inside grate
        p_grate=0.5*(ke_grate+kc_grate)*den_air*u_grate^2 ;          %pressure drop due to grate
          p_drop_c = p_drop_cc + p_grate;
          %to calculate the pressure drop due to sudden change in area
      %between combustion chamber and component placed just after it
      if Dh1<Dh2                  %expansion loss
         k=(1-(Dh1/Dh2)^2)^2;        %expansion loss coefficient
         p_drop_c = p_drop_c +
(k*0.5*gas_constant/TTgo*(MMo*TTgo/(pi()((Dh1)^2)/4)/gas_constant)^2+0.5*MMo^2*TTgo/gas_constant((
16/pi()^2)*(1/Dh2^4-1/Dh1^4)));
      elseif Dh1>Dh2
         if Dh2/Dh1<0.76            %contraction loss
            k=0.42*(1-(Dh2/Dh1)^2);   %contraction loss coefficient
            p_drop_c = p_drop_c +
(k*0.5*TTgo/gas_constant*(MMo/(pi()((Dh2)^2)/4))^2+0.5*MMo^2*TTgo/gas_constant((16/pi()^2)*(1/Dh2^4
-1/Dh1^4)));
         else
            k=(1-(Dh2/Dh1)^2)^2;      %contraction loss coefficient
            p_drop_c = p_drop_c +
(k*0.5*TTgo/gas_constant*(MMo/(pi()((Dh2)^2)/4))^2+0.5*MMo^2*TTgo/gas_constant((16/pi()^2)*(1/Dh2^4
-1/Dh1^4)));
         end
       end
      Pd = Pd +p_drop_c;
      m = MMo;
end
```

6. Module for Temperature variation in combustion chamber

```
function [c1,c2,c3,c4,c5,c6]=CC(Dh1,l_c)          %Defining the function that returns the values of temperatures in the combustion chamber

global all value Mi Mo                    %Defining global variables so as can be used by other modules

global Tg TTg TTgi T_cc T_cruc TT_cc TTcruc

dt=all(63);                          %Discretization time step


sig=5.67*10^(-8);                     %Stefan-boltzmann constant

value = 1;

T_amb=all(1);                         %Surrounding air temperature

T_ref=all(14);                        %Temperature at which specific internal energy/ specific enthalpy of flue gas is assumed zero

h_ext= all(10);                       %Convective heat transfer coefficient for system's external surface


air_constant=359.5;                   %Value of PM/R for air

R_air=all(2);                         %Gas constant for air

R_gas=all(12);                        %Gas constant for flue gas

gas_constant=air_constant*R_air/R_gas;      %Value of PM/R for flue gas

Cp_air=all(11);                       %Specific heat at constant pressure for air

Cp_gas=all(16);                       %Specific heat at constant pressure for flue gas

Cv_gas=Cp_gas-R_gas;                  %Specific heat at constant volume for flue gas

den_gas=gas_constant/Tg;              %Density of flue gas inside combustion chamber

k_gas=all(19)*Tg+all(20);             %Linear equation for estimation of flue gas thermal conductivity as a function of temperature

eps_gas =.16;                         %Emissivity of flue gas


CV=all(13);                           %Calorific value of fuel combusted in the system


m_cruc=all(27);                       %Mass of the crucible

C_cruc=all(28);                       %Specific heat of the crucible material

rho_cruc = all(29);                   %Density of the crucible material
```

```
V_cruc = m_cruc/rho_cruc;                %Volume of the crucible

d_cruc = (6*V_cruc/pi())^(1/3);          %Diameter of the crucible based on the assumption that it has spherical
geometry

A_cruc=pi()*(d_cruc)^2;                  %Area of the crucible


t_wall_cc = all(36);                     %Combustion chamber wall thickness

s_cc=all(40);                            %Number of sections into which wall and insulation are divided individually
for control volume analysis

dx_wall_cc = t_wall_cc/(s_cc-1);         %Thickness of each section of wall. Temperature is constant in each of
the sections

k_wall_cc = all(37);                     %Thermal conductivity of combustion chamber wall material

Cp_wall_cc = all(38);                    %Specific heat of combustion chamber wall material

rho_wall_cc = all(39);                   %Density of combustion chamber wall material

alpha_wall_cc = k_wall_cc/(Cp_wall_cc*rho_wall_cc);     %Thermal diffusivity of combustion chamber wall
material


t_ins_cc=all(57);                        %Thickness of insulation around combustion chamber

dx_ins_cc=t_ins_cc/(s_cc-1);             %Thickness of each section of insulation. Temperature is constant in
each of the sections

k_ins=all(53);                           %Thermal conductivity of insulation material

rho_ins = all(55);                       %Density of insulation material

Cp_ins = all(54);                        %Specific heat of insulation material

alpha_ins=k_ins/(rho_ins*Cp_ins);        %Thermal diffusivity of insulation material


l_cc=l_c;                                %Length of combustion chamber

A_cc=pi*Dh1^2/4;                         %Cross sectional area perpendicular to the flow of air in the combustion
chamber

A_wall_cc=2*A_cc*(1+(2*l_cc/Dh1));       %Total surface area of the inside surfaces of the walls around
combustion chamber

dV_cc=A_cc*l_cc;                         %Volume of combustion chamber

d_ratio=d_cruc/Dh1;                      %Ratio fo diameter of crucible to hydraulic diameter of combustion chamber


TT_cc=zeros(2*s_cc-1,1);                 %Matrix storing the temperatures of the sections of wall and insulation
around combustion chmaber at time = t+dt.


energy_cruc =0;                          %Initializing the value to calculate the energy absorbed by the crucible
```

```
%to calculate the convective heat transfer coefficient between surface of crucible
%and gas and also between gas and combustion chamber surface.
Nu_cruc=4.4438*((d_ratio)^(-0.43)); %nusselt number for crucible surface
Nu_wall=0.994*d_ratio+3.9102;       %nusselt number for wall surface
h_cruc=Nu_cruc*k_gas/(Dh1-d_cruc);  %heat transfer coefficient for crucible
h_wall=Nu_wall*k_gas/(Dh1-d_cruc);  %heat transfer coefficient for wall

%to calculate the radiative + convective heat transfer coefficient for radiation
%network between gas, crucible and wall
hr1=h_wall*A_wall_cc+eps_gas*sig*A_wall_cc*(T_cc(1,1)^(2)+Tg^(2))*(Tg+T_cc(1,1));
hr2=h_cruc*A_cruc+eps_gas*sig*A_cruc*(T_cruc^(2)+Tg^(2))*(Tg+T_cruc);
hr3=(1-eps_gas)sig*A_cruc(T_cc(1,1)^(2)+T_cruc^(2))*(T_cruc+T_cc(1,1));
hr4=h_ext*A_wall_cc;



%solving the temperatures by matrix inversion.
%'A_mat', 'C_mat' and 'B_mat' are defined such that
%A_mat*B_mat=C_mat. B_mat gives the value of temperature for gas,
%crucible, sections of wall and insulation at time=t+dt.

A_mat=zeros(2*s_cc+1,2*s_cc+1);
C_mat=zeros(2*s_cc+1,1);

%Energy balance in the control volume
A_mat(1,1)=dV_cc/dt*(den_gas*Cv_gas)+Mo*Cp_gas+hr1+hr2;
A_mat(1,2)=-hr2;
A_mat(1,3)=-hr1;
C_mat(1,1)=den_gas*Cv_gas*dV_cc*Tg/dt+Mi*Cp_air*(TTgi-T_ref)+Mo*Cp_gas*T_ref+
Mf_actual*1000*CV;

%Energy balance for crucible
A_mat(2,1)=-hr2;
A_mat(2,2)=m_cruc*C_cruc/dt+hr2+hr3;
```

```
A_mat(2,3)=-hr3;

C_mat(2,1)=m_cruc*C_cruc*T_cruc/dt;


%Surface energy balance at innermost surafce of the wall

A_mat(3,1)=-hr1;

A_mat(3,2)=-hr3;

A_mat(3,3)=hr3+hr1+k_wall_cc*A_wall_cc/dx_wall_cc;

A_mat(3,4)=-k_wall_cc*A_wall_cc/dx_wall_cc;


%Interface between wall and insulation

A_mat(s_cc+2,s_cc+1)= -k_wall_cc/dx_wall_cc;

A_mat(s_cc+2,s_cc+2)= rho_wall_cc*Cp_wall_cc*dx_wall_cc/dt + k_wall_cc/dx_wall_cc +
k_ins/dx_ins_cc;

A_mat(s_cc+2,s_cc+3) = -k_ins/dx_ins_cc;

C_mat(s_cc+2,1) = rho_wall_cc*Cp_wall_cc*T_cc(s_cc,1)*dx_wall_cc/dt;


%Surface energy balance at outermost surafce of the insulation

A_mat(2*s_cc+1,2*s_cc)=k_ins*A_wall_cc/dx_ins_cc;

A_mat(2*s_cc+1,2*s_cc+1)= (-k_ins*A_wall_cc/dx_ins_cc)-hr4 -
A_wall_cc*dx_ins_cc*rho_ins*Cp_ins/dt ;

C_mat(2*s_cc+1,1)=-hr4*T_amb - A_wall_cc*dx_ins_cc*rho_ins*Cp_ins*T_cc(2*s_cc-1)/dt ;


%Heat conduction equation for interior sections of wall

for i=4:s_cc+1

   C_mat(i,1)=T_cc(i-2,1);

   A_mat(i,i-1)=-alpha_wall_cc*dt/((dx_wall_cc)^2);

   A_mat(i,i)=1+2*alpha_wall_cc*dt/((dx_wall_cc)^2);

   A_mat(i,i+1)=-alpha_wall_cc*dt/((dx_wall_cc)^2);

end


%Heat conduction equation for interior sections of insulation

for i=s_cc+3:2*s_cc

   C_mat(i,1)=T_cc(i-2,1);

   A_mat(i,i-1)=-alpha_ins*dt/((dx_ins_cc)^2);
```

```
    A_mat(i,i)=1+2*alpha_ins*dt/((dx_ins_cc)^2);
    A_mat(i,i+1)=-alpha_ins*dt/((dx_ins_cc)^2);
  end

  xxx=A_mat\C_mat;
  B_mat=xxx;
  TTg=B_mat(1,1);              %Temperature of flue gases inside combustion chmaber at time=t+dt;
  TTcruc=B_mat(2,1);           %Temperature of crucible at time=t+dt.

  for i=1:2*s_cc-1
    TT_cc(i,1)=B_mat(i+2,1);   %Temperature of sections of wall and insulation around combustion
chamber
  end

  c1 = TTg;
  c2 = TTcruc;
  c3= TT_cc;

  c4 = dt*k_wall_cc*A_wall_cc/dx_wall_cc*(TT_cc(1,1)-TT_cc(2,1))-dt*hr4*(TT_cc(2*s_cc-1)-T_amb);
%Energy that gets stored in the walls and insulation during every time interval dt
  c5 = dt*hr4*(TT_cc(2*s_cc-1)-T_amb);                                    %Energy that is lost to
the ambient from the outermost surface of the insulation during every time interval dt

  energy_cruc = energy_cruc + m_cruc*C_cruc*(TTcruc-T_cruc);                    %Energy that
gets stored in the crucible during every time interval dt
  c6 = energy_cruc;
end
```

7. Module for Pressure drop in stack

```
function [ps1,ps2] = pressure_stack(Dh1,Dh2,l_stack)   %defining a function that returns the value of pressure drop and mass flow rate in the stack


global all  %defining global variables so as can be used by other modules

global M_stack

global Pd value

global T_stack TT_stack

N=all(47);                          %Stack is divided into N-1 control volumes

dt=all(63);                         %Discretization time step

g = 9.81;                           %acceleration due to gravity

dx_CV_stack= l_stack /(N-1);            %Length of each control volume in stack



MM_stack = zeros(N,1);                  %mass flow rates at 'N' surfaces in the control volumes


A_stack=pi*Dh1^2/4;                     %Cross sectional area of stack

e_stack=all(46);                    %Surface roughness of stack material


air_constant=359.5;

mu_air=all(3)*T_stack(N)^2+all(4)*T_stack(N)+all(5);

R_air=all(2);

R_gas=all(12);

gas_constant=air_constant*R_air/R_gas;

mu_gas=all(17)*T_stack(N)+all(18);
```

```
if value == 0 %pipe before combustion chamber
    mu = mu_air;
    constant = air_constant;
elseif value ==1 %pipe after combustion chamber
     mu = mu_gas;
     constant = gas_constant;
end

p_drop_stack=0;                          %Initializing the value for calculation of pressure drop
     %mass flow rate and pressure drop calculation

     u_gas_stack=M_stack(N)*T_stack(N)/(constant*A_stack);                    %velocity of flue gas at exit of
stack
     Re_inf_stack=constant*u_gas_stack*d_stack/mu/T_stack(N);          %reynolds number at exit of stack
     f_inf_stack=0.25/(log10((e_stack/(7.4*(d_stack/2)))+(5.74/Re_inf_stack^0.9)))^2;    %Swammee-Jain
friction factor at exit of stack

     MM_stack(1) = 0.8 * M_stack(1);    %Inlet mass flow rate of the stack

     for i=1:N-1

       %if loop to determine the value of friction factor for each
       %value of x along the length of stack
       if((i*dx_CV_stack)/d_stack>=0 && (i*dx_CV_stack)/d_stack<0.32)
           f_x_stack=f_inf_stack*2.6;
       elseif(i*dx_CV_stack/d_stack>=0.32 && i*dx_CV_stack/d_stack<26.67)
           f_x_stack=f_inf_stack*(2.0315*((i*dx_CV_stack/d_stack)^(-0.217)));
       else
           f_x_stack=f_inf_stack;
       end

MM_stack(i+1)=MM_stack(i)-constant*A_stack*dx_CV_stack/dt*2*(1/(TT_stack(i)+TT_stack(i+1))-1/(T_stac
k(i)+T_stack(i+1)));     %Mass flow rate at each section of the control volumes
```

```
p_turb_gas=f_x_stack*dx_CV_stack*((M_stack(i)+M_stack(i+1))/2/A_stack)^2*(T_stack(i)+T_stack(i+1))/(8*(d_stack/2)*constant); %pressure drop due to viscous forces in each control volume

        p_drop_stack = p_drop_stack - (dx_CV_stack/A_stack/dt/2*(M_stack(i)+M_stack(i+1)-MM_stack(i)-MM_stack(i+1))+1/constant/A_stack/A_stack*(MM_stack(i)^(2)TT_stack(i)-MM_stack(i+1)^(2)*TT_stack(i+1))-constant*g*dx_CV_stack*2(1/(TT_stack(i)+TT_stack(i+1)))-p_turb_gas); %pressure drop in each control volume

    end


   %to calculate the pressure drop due to sudden change in area between stack and component placed just after it

    if Dh1<Dh2                  %expansion loss

       k=(1-(Dh1/Dh2)^2)^2;         %expansion loss coefficient

       p_drop_stack = p_drop_stack + (k*0.5*constant/TT_stack(N)(MM_stack(N)*TT_stack(N)/(pi()((Dh1)^2)/4)/constant)^2+0.5*MM_stack(N)^2*TT_stack(N)/constant*((16/pi()^2)*(1/Dh2^4-1/Dh1^4)));

    elseif Dh1>Dh2

       if Dh2/Dh1<0.76            %contraction loss

          k=0.42*(1-(Dh2/Dh1)^2);   %contraction loss coefficient

          p_drop_stack = p_drop_stack + (k*0.5*TT_stack(N)/constant*(MM_stack(N)/(pi()((Dh2)^2)/4))^2+0.5*MM_stack(N)^2*TT_stack(N)/constant((16/pi()^2)*(1/Dh2^4-1/Dh1^4)));

       else

          k=(1-(Dh2/Dh1)^2)^2;      %contraction loss coefficient

          p_drop_stack = p_drop_stack + (k*0.5*TT_stack(N)/constant*(MM_stack(N)/(pi()((Dh2)^2)/4))^2+0.5*MM_stack(N)^2*TT_stack(N)/constant((16/pi()^2)*(1/Dh2^4-1/Dh1^4)));

       end

    end


    Pd = Pd + p_drop_stack;

    ps1 = MM_stack;

    ps2 = p_drop_stack;

end
```

8. Module for temperature variation in stack

```
function [y1_s,y2_s,y3_s,y4_s,y5_s] = stack(Dh1,l_stack)   %Defining the function that returns the values of temperatures in the stack

global all                          %defining global variable so as can be used by other modules

global T value

global M_stack T_stack T1T_stack T1TT_stack TT_stack


T_amb=all(1);                       %Ambient Temperature

T_ref=all(14);                      %reference temperature

Pr=all(6);                          %Prandlt number

dt=all(63);                         %Discretization time step

N=all(47);                          %Stack is divided into N-1 control volumes


air_constant=359.5;                 %value of PM/R for air

R_air=all(2);                       %gas constant for air

R_gas=all(12);                      %gas constant for flue gas

gas_constant=air_constant*R_air/R_gas;     %value of PM/R for flue gas

Cp_air=all(14);                     %specific heat at constant pressure for air

Cv_air=Cp_air-R_air;                %specific heat at constant volume for air

Cp_gas=all(16);                     %specific heat at constant pressure for flue gas

Cv_gas=Cp_gas-R_air;                %specific heat at constant volume for flue gas
```

```
mu_air_stack=all(3)*T^2+all(4)*T+all(5);
mu_gas_stack=all(17)*T_stack(N)+all(18);   %viscosity of flue gas at exit of stack

if value == 0 %pipe before combustion chamber
     constant = air_constant;
      mu_stack = mu_air_stack;
      Cp = Cp_air;
      Cv = Cv_air;
elseif value ==1 %pipe after combustion chamber
       constant = gas_constant;
       mu_stack = mu_gas_stack;
       Cp = Cp_gas;
      Cv = Cv_gas;
end

s_stack=all(52);                    %Number of sections into which wall and insulation are divided individually
for control volume analysis
A_stack=pi*Dh1^2/4;                 %Cross sectional area of stack
dx_CV_stack=l_stack/(N-1);          %Length of each control volume in stack

t_wall_stack = all(48);                          %Thickness of stack wall
k_wall_stack = all(49);                          %Thermal conductivity of stack wall
Cp_wall_stack = all(50);                         %Specific heat of stack wall
rho_wall_stack = all(51);                        %Density of stack wall
alpha_wall_stack = k_wall_stack/(Cp_wall_stack*rho_wall_stack); %Thermal diffusitivity of stack
dx_wall_stack = t_wall_stack /(s_stack-1);       %Thickness of each of the stack wall sections

t_ins_stack=all(56);                             %Thickness of insulation on stack
k_ins_stack=all(53);                             %Thermal conductivity of insulation material
rho_ins_stack = all(55);                         %Density of insulation material
Cp_ins_stack = all(54);                          %Specific heat of insulation material
alpha_ins_stack=k_ins_stack/(rho_ins_stack*Cp_ins_stack);     %Thermal diffusivity of insulation
```

```
dx_ins_stack=t_ins_stack/(s_stack-1);                    %Thickness of each of the insulation sections

energy_wall_stack = 0;                                   %Initializing value to calculate energy absorbed by stack wall

energy_wallloss_stack = 0;                               %Initializing value to calculate energy lost by stack wall to
atmosphere

TT_stack=zeros(N,1);                                     %Temperatures of the gas at 'N' sections at time 't+dt'

T1TT_stack=zeros((N-1)*(2*s_stack-1),1);                 %Temperatures of the wall and insulation surfaces in
'N-1' control volumes at time 't+dt'

TT_stack(1) = T;                                         %Inlet gas temperature of the stack

%calculations of form factor in stack solved iteratively (refer to 'stack radiation' section of the report)

r=Dh1/2;

R=r/dx_CV_stack;

ff = 1+ ((1-sqrt(4*R*R + 1))/(2*R*R));     %form factor when two discs of equal radii are placed parallel to each
other

A1 = pi()*r*r;

A2 = 2*pi()*r*dx_CV_stack;

FF = zeros(3,3);

FF(1,2)= 1-ff;

FF(1,3)= ff;

FF(3,1)=ff;

FF(3,2) = 1-ff;

FF(2,1)=A1*(1-ff)/A2;

FF(2,3)=FF(2,1);

FF(2,2) = 1-(2*FF(2,1));

for i=3:N
```

```
    R=r/(dx_CV_stack*(i-1));
    ff = 1+ ((1-sqrt(4*R*R + 1))/(2*R*R)) ;


    F1=FF(2:i,2:i);
    FF(3:i+1,3:i+1) =F1 ;

    FF(1,i+1) = ff;
    FF(1,i)=FF(1,i)-ff;
    FF(2,i+1) = A1*FF(i,1)/A2;
    FF(2,i) = FF(2,i)-FF(2,i+1);


    FF(i,1) = FF(2,i+1);
    FF(i,2) = FF(2,i);
    FF(i+1,1) = FF(1,i+1);
    FF(i+1,2) = FF(1,i);

end
eps =.16;         %emissitivity of the gas in the stack
sig=5.67*10^(-8);     %Stefan-Boltzmann constant

h_ext_stack=all(10);  %Convective heat transfer coefficient for external surface of the stack
       u_stack=M_stack(N)*T_stack(N)/(constant*A_stack);                  %velocity of flue gas/air at exit of stack
       Re_inf_stack=constant*u_stack*Dh1/mu_stack/T_stack(N);        %Reynolds number at exit of stack
       Nu_inf_stack=0.0397*(Re_inf_stack^0.73)*(Pr^0.33);                    %Nusselt number at exit of stack
      T_wall = zeros(1,N+1);                          %Innermost surface temperatures of walls in 'N-1' control
volumes
       for i=1:N-1
          T_wall(i) = T1T_stack((i-1)*((2*s_stack)-1) + 1);   %Innermost surface temperatures of walls in 'N-1'
control volumes
       end
```

```
T_wall(N) = TT_stack(1);                    %gas temperature of the bottom control volume in stack
(refer to 'stack radiation' section of the report)

T_wall(N+1) = T_amb;                        %gas temperature of the top volume in stack


%loop for calculating value of temperature at each point of stack at time=t+dt.

for i=1:N-1


  %if loop to obtain the value of nusselt number at a particular x along the lenght of stack

  if(i*dx_CV_stack/Dh1>=0 && i*dx_CV_stack/Dh1<0.32)

     Nu_stack=Nu_inf_stack*2.6;

  elseif(i*dx_CV_stack/Dh1>=0.32 && i*dx_CV_stack/Dh1<26.67)

     Nu_stack=Nu_inf_stack*(2.0315*((i*dx_CV_stack/Dh1)^(-0.217)));

  else

     Nu_stack=Nu_inf_stack;

  end

  if value == 0 %pipe before combustion chamber

    k = k_air;

  elseif value ==1 %pipe after combustion chamber

    k = k_gas;

  end

        h_int=Nu_stack*k/Dh1;                 %convective heat transfer coefficient for inner surface of
stack for each control volume

   h_rad = eps*sig*(((T_stack(i)+T_stack(i+1))/2)^2 + (T_wall(i))^2 )*( (T_stack(i)+T_stack(i+1))/2 +
T_wall(i) );  %Effective radiative heat transfer coefficient


  heat_rad =0;                                                    %Initializing the value for
calculating radiative heat onto a wall surface from other wall surfaces.

  for j=1:N-1

    heat_rad = heat_rad + (1-eps)sig*FF(N+1-j,N+1-i)(T_wall(j)^4);
%radiative heat from other wall surfaces

  end

  heat_rad = heat_rad + (1-eps)sig*eps(A1/A2)(FF(N+1,N+1-i)(T_wall(N)^4) +
FF(1,N+1-i)*(T_wall(N+1)^4));  %radiative heat transfer from top and bottom gas in the stack


  %Defining matrices 'AS', 'CS', 'TTS' which are in the form of
```

```
%AS*TTS=CS. By matrix inversion TTS is obtained. From TTS the value

%of T1TT is obtained. To understand how to define the elements of

%'AS', 'CS', 'TTS', one must refer to the final report section 4.7

AS=zeros(2*s_stack,2*s_stack);

CS=zeros(2*s_stack,1);


%Control Volume energy balance

AS(1,1)=A_stack*dx_CV_stack/dt*(Cv*constant/(T_stack(i)+T_stack(i+1)))+M_stack(i+1)Cp+(h_int +
h_rad)*pi()(Dh1/2)*dx_CV_stack; %Eqn 4.58 of report

AS(1,2)=-(h_int + h_rad)2*pi()(Dh1/2)*dx_CV_stack;

CS(1)=M_stack(i)Cp(TT_stack(i)-T_ref)+M_stack(i+1)Cp*T_ref-(h_int +
h_rad)*pi()(Dh1/2)dx_CV_stack*TT_stack(i)-A_stack*dx_CV_stack/dt*Cv*constant/(T_stack(i)+T_stack(i+1)
)(TT_stack(i)-T_stack(i)-T_stack(i+1));


%Surface energy balance at innermost surface of wall

AS(2,1)=-(h_int + h_rad)*dx_wall_stack/2;

AS(2,2)=k_wall_stack+(h_int+h_rad)*dx_wall_stack;

AS(2,3)=-k_wall_stack;

CS(2)= (h_int + h_rad)(dx_wall_stack/2)*TT_stack(i)  - (1-eps)*sig*dx_wall_stack(T_wall(i))^4 +
heat_rad*dx_wall_stack ;

    %Interface between wall and insulation

AS(s_stack+1,s_stack) = -k_wall_stack*2*pi()(Dh1/2 + dx_wall_stack(s_stack-2))/dx_wall_stack;

AS(s_stack+1,s_stack+1) = rho_wall_stack*Cp_wall_stack*dx_wall_stack*2*pi()(Dh1/2 +
dx_wall_stack(s_stack-2))/dt + k_wall_stack*2*pi()(Dh1/2 + dx_wall_stack(s_stack-2))/dx_wall_stack +
k_ins_stack*2*pi()*(Dh1/2 + t_wall_stack)/dx_ins_stack ;

AS(s_stack+1,s_stack+2) = -k_ins_stack*2*pi()*(Dh1/2 + t_wall_stack)/dx_ins_stack;

CS(s_stack+1,1) = rho_wall_stack*Cp_wall_stack*dx_wall_stack*2*pi()(Dh1/2 +
dx_wall_stack(s_stack-2))T1T_stack(s_stack+(2*s_stack-1)(i-1))/dt;


%Surface energy balance at outermost surface of insulation

AS(2*s_stack,2*s_stack-1)=k_ins_stack*2*pi()(Dh1/2 + t_wall_stack + dx_ins_stack(s_stack-2));

AS(2*s_stack,2*s_stack)=-k_ins_stack*2*pi()(Dh1/2 + t_wall_stack +
dx_ins_stack(s_stack-2))-h_ext_stack*2*pi()*(Dh1/2 +t_wall_stack+t_ins_stack)*dx_ins_stack;

CS(2*s_stack,1)=-h_ext_stack*T_amb*dx_ins_stack*2*pi()*(Dh1/2 +t_wall_stack+t_ins_stack);


%Heat conduction equation for interior sections of wall
```

```
for j=3:s_stack

   CS(j,1)=T1T_stack((2*s_stack-1)(i-1)+j-1,1)((dx_wall_stack)^2)/(alpha_wall_stack*dt);

   AS(j,j-1)=-1;

   AS(j,j)=1+((dx_wall_stack)^2)/(alpha_wall_stack*dt) + ((Dh1/2) + (j-2)*dx_wall_stack)/((Dh1/2) +
(j-3)*dx_wall_stack);

   AS(j,j+1)=-((Dh1/2) + (j-2)*dx_wall_stack)/((Dh1/2) + (j-3)*dx_wall_stack);

end


%Heat conduction equation for interior sections of insulation

for j=s_stack+2:2*s_stack-1

   CS(j,1)=T1T_stack((2*s_stack-1)(i-1)+j-1,1)((dx_ins_stack)^2)/(alpha_ins_stack*dt);

   AS(j,j-1)=-1;

   AS(j,j)=1+((dx_ins_stack)^2)/(alpha_ins_stack*dt) + ((Dh1/2) + t_wall_stack + (j-(s_stack +
1))*dx_ins_stack)/((Dh1/2) + t_wall_stack + (j-(s_stack + 2))*dx_ins_stack);

   AS(j,j+1)=-((Dh1/2) + t_wall_stack + (j-(s_stack +1))*dx_ins_stack)/((Dh1/2) + t_wall_stack +
(j-(s_stack + 2))*dx_ins_stack);

end

TTS=AS\CS;


TT_stack(i+1)=TTS(1);                          %Temperatue of the gas in ith control volume

for j= 1:2*s_stack-1

   T1TT_stack((2*s_stack-1)*(i-1)+j)= TTS(j+1,1);        %Temperatures of the wall and insulation
sections at time 't+dt' in ith control volume

end

      energy_wall_stack = energy_wall_stack +
dt*(h_int+h_rad)2*pi()(Dh1/2)dx_CV_stack(0.5*TT_stack(i)+0.5*TT_stack(i+1)-T1TT_stack((i-1)(2*s_stack-
1)+1))-dt*2*pi()(Dh1/2+t_wall_stack+t_ins_stack)dx_CV_stack*h_ext_stack(T1TT_stack((2*s_stack-1)*i)-T_
amb); %energy absorbed by wall and insulation in each control volume of the stack in time 'dt'.

energy_wallloss_stack = energy_wallloss_stack +
dt*2*pi()(Dh1/2+t_wall_stack+t_ins_stack)*dx_CV_stack*h_ext_stack(T1TT_stack((2*s_stack-1)*i)-T_amb);
%energy lost to atmosphere by wall and insulation in each control volume of the stack in time'dt'

end


T = TT_stack(N);

y1_s = TT_stack(N);

y2_s = T1TT_stack;
```

```
y3_s = TT_stack;
y4_s = energy_wall_stack;
y5_s = energy_wallloss_stack;

end
```

9. Module for Pressure drop in Preheater

```
function [pph1,pph2] = pressure_PH(Dh1,Dh2,l_p)
global all m Pd            %Defining global variables so as can be used by other modules
global TTgpi TTgpo Tgpi Tgpo Mpi_p MMpi_p Mpo_p MMpo
dt=all(41);                %Discretization time step

air_constant=359.5;        %Value of PM/R for air
R_air=all(2);              %Gas constant for air
R_gas=all(12);             %Gas constant for flue gas
gas_constant=air_constant*R_air/R_gas;     %Value of PM/R for flue gas
```

```
l_pre=l_p;                          %Length of preheater

A_pre=pi*Dh1^2/4;                   %Cross sectional area perpendicular to the flow of air of preheater


MMpo=MMpi_p-(l_pre*A_pre/dt)2*gas_constant(1/(TTgpo+TTgpi)-1/(Tgpi+Tgpo));      %Mass flow rate at
the exit of preheater

        p_drop_ph=l_pre/A_pre/dt/2*(MMpi_p+MMpo-Mpi_p-Mpo_p)-
MMpi_p^(2)*TTgpi/air_constant/A_pre^(2) + MMpo^(2)*TTgpo/gas_constant/A_pre^(2) + p_gravity;


      p_drop_p = p_drop_ph;


      pph1 = MMpo;


      %to calculate the pressure drop due to sudden change in area

      %between preheater and component placed just after it

      if Dh1<Dh2                    %expansion loss

         k=(1-(Dh1/Dh2)^2)^2;         %expansion loss coefficient

         p_drop_p = p_drop_p +
(k*0.5*gas_constant/TTgpo*(MMpo*TTgpo/(pi()((Dh1)^2)/4)/gas_constant)^2+0.5*MMpo^2*TTgpo/gas_con
stant((16/pi()^2)*(1/Dh2^4-1/Dh1^4)));

      elseif Dh1>Dh2

         if Dh2/Dh1<0.76             %contraction loss

            k=0.42*(1-(Dh2/Dh1)^2);   %contraction loss coefficient

            p_drop_p = p_drop_p +
(k*0.5*TTgpo/gas_constant*(MMpo/(pi()((Dh2)^2)/4))^2+0.5*MMpo^2*TTgpo/gas_constant((16/pi()^2)*(1/D
h2^4-1/Dh1^4)));

         else

            k=(1-(Dh2/Dh1)^2)^2;      %contraction loss coefficient

            p_drop_p = p_drop_p +
(k*0.5*TTgpo/gas_constant*(MMpo/(pi()((Dh2)^2)/4))^2+0.5*MMpo^2*TTgpo/gas_constant((16/pi()^2)*(1/D
h2^4-1/Dh1^4)));

         end

      end

       m = MMpo;

      pph2 = p_drop_p;

      Pd = Pd+pph2;
```

10. Module for temperature variations in preheater

```
function [y1_p,y2_p,y3_p,y4_p,y5_p]= preheater(d_p,l_p)    %Defining the function that returns the values of temperatures in the preheater

global all T m Mpo_p                    %Defining global variables so as can be used by other modules

dt=all(63);                         %Discretization time step

sig=5.67*10^(-8);                   %Stefan-boltzmann constant
```

```
T_amb=all(1);                    %Surrounding air temperature

T_ref=all(14);                   %Temperature at which specific internal energy/ specific enthalpy of flue gas is
assumed zero


Tgp= T;                          %Temperature of flue gas at the inlet of preheater at time = t.


h_ext= all(10);                  %Convective heat transfer coefficient for system's external surface


air_constant=359.5;              %Value of PM/R for air

R_air=all(2);                    %Gas constant for air

R_gas=all(12);                   %Gas constant for flue gas

gas_constant=air_constant*R_air/R_gas;     %Value of PM/R for flue gas

Cp_gas=all(16);                  %Specific heat at constant pressure for flue gas

Cv_gas=Cp_gas-R_gas;             %Specific heat at constant volume for flue gas

den_gas=gas_constant/Tgp;        %Density of flue gas inside preheater

k_gas=all(19)*Tgp+all(20);       %Linear equation for estimation of flue gas thermal conductivity as a
function of temperature

eps_gas =.16;                    %Emissivity of flue gas


m_mould=all(33);                 %Mass of mould

C_mould=all(34);                 %Specific heat of mould

rho_mould = all(35);             %Density of mould

A_mould=(36*pi()*(m_mould/rho_mould)^2)^(1/3);    %Area of mould

d_mould=(A_mould/pi())^(0.5);    %Diameter of mould based on the assumption that it has spherical
geometry


t_wall_pre = all(41);            %Preheater wall thickness(m)

s_pre=all(45);                   %Number of sections into which wall and insulation are divided individually
for control volume analysis

dx_wall_pre = t_wall_pre/(s_pre-1);       %Thickness of each section of wall. Temperature is constant in each of
the sections

k_wall_pre = all(42);            %Thermal conductivity of preheater wall material

Cp_wall_pre = all(43);           %Specific heat (J/kg/K) of preheater wall

rho_wall_pre = all(44);          %Density of preheater wall material
```

```
alpha_wall_pre = k_wall_pre/(Cp_wall_pre*rho_wall_pre);     %Thermal diffusivity of preheater wall material


t_ins_pre=all(58);                    %Thickness of insulation around preheater

dx_ins_pre=t_ins_pre/(s_pre-1);          %Thickness of each section of insulation. Temperature is constant in
each of the sections

k_ins=all(53);                        %Thermal conductivity of insulation material

rho_ins = all(55);                    %Density of insulation material

Cp_ins = all(54);                     %Specific heat of insulation material

alpha_ins=k_ins/(rho_ins*Cp_ins);         %Thermal diffusivity of insulation material


l_pre=l_p;                            %Length of preheater

A_pre=pi*(d_p)^2/4;                       %Cross sectional area perpendicular to the flow of air in the preheater

A_wall_pre=2*A_pre*(1+(2*l_pre/d_p));     %Total surface area of the inside surfaces of the walls around
preheater

dV_pre=A_pre*l_pre;                   %Volume of preheater

d_ratiop=d_mould/d_pp;                %Ratio fo diameter of mould to hydraulic diameter of preheater


T_mould=T2_p;                         %Temperature of mould at time = t.

TTgpi=Tin_p;                          %Temperature of flue gas at the inlet of preheater at time = t+dt. It equals to
the temperature at the outlet of the component before it.


T_pre=T1_p;                           %Matrix storing the temperatures of the sections of wall and insulation around
preheater at time = t.

TT_pre=zeros(2*s_pre-1,1);            %Matrix storing the temperatures of the sections of wall and insulation
around preheater at time = t+dt.


for i=1:2*s_pre-1

   TT_pre(i)=T_amb;                   %Initializing the temperatures of sections of wall and insulation to ambient
temperature

end


      %to calculate the heat transfer coefficient between surface of mould

      %and gas and also between gas and preheater surface. Refer section 4.6

      Nu_mould=4.4438*((d_ratiop)^(-0.43)); %nusselt number for mould surface

      Nu_wallp=0.994*d_ratiop+3.9102;       %nusselt number for preheater wall surface
```

```
h_mould=Nu_mould*k_gas/(d_pp-d_mould);  %heat transfer coefficient for mould
h_wallp=Nu_wallp*k_gas/(d_pp-d_mould);  %heat transfer coefficient for wall

%to calculate the radiative heat transfer coefficient for radiation
%network between gas, mould and preheater wall
hr1p=h_wallp*A_wall_pre+eps_gas*sig*A_wall_pre*(T_pre(1,1)^(2)+Tgp^(2))*(Tgp+T_pre(1,1));
hr2p=h_mould*A_mould+eps_gas*sig*A_mould*(T_mould^(2)+Tgp^(2))*(Tgp+T_mould);
hr3p=(1-eps_gas)sig*A_mould(T_pre(1,1)^(2)+T_mould^(2))*(T_mould+T_pre(1,1));
hr4p=h_ext*A_wall_pre;                  %external heat transfer coefficient

%solving the temperatures by matrix inversion. Refer section 4.6.
%'A_matp', 'C_matp' and 'B_matp' are defined such that
%A_matp*B_matp=C_matp. B_matp gives the value of temperature for gas,
%mould, wall inner surface and at points between the insulation
%at time=t+dt.
A_matp=zeros(2*s_pre+1,2*s_pre+1);
C_matp=zeros(2*s_pre+1,1);

%Energy balance in the control volume
A_matp(1,1)=dV_pre/dt*(den_gas*Cv_gas)+2*Mpo_p*Cp_gas+hr1p+hr2p;
A_matp(1,2)=-hr2p;
A_matp(1,3)=-hr1p;
C_matp(1,1)=den_gas*Cv_gas*dV_pre*Tgp/dt+m*Cp_gas*(TTgpi-T_ref)+Mpo_p*Cp_gas*(TTgpi+T_ref);

%Energy balance for mould
A_matp(2,1)=-hr2p;
A_matp(2,2)=m_mould*C_mould/dt+hr2p+hr3p;
A_matp(2,3)=-hr3p;
C_matp(2,1)=m_mould*C_mould*T_mould/dt;

%Surface energy balance at the innermost surafce of the wall
A_matp(3,1)=-hr1p;
```

```
A_matp(3,2)=-hr3p;

A_matp(3,3)=hr3p+hr1p+k_wall_pre*A_wall_pre/dx_wall_pre;

A_matp(3,4)=-k_wall_pre*A_wall_pre/dx_wall_pre;


%Interface between wall and insulation

A_matp(s_pre+2,s_pre+1)= -k_wall_pre/dx_wall_pre ;

A_matp(s_pre+2,s_pre+2)= rho_wall_pre*Cp_wall_pre*dx_wall_pre/dt + k_wall_pre/dx_wall_pre +
k_ins/dx_ins_pre;

A_matp(s_pre+2,s_pre+3) = -k_ins/dx_ins_pre;

C_matp(s_pre+2,1) = rho_wall_pre*Cp_wall_pre*T_pre(s_pre,1)*dx_wall_pre/dt;


%Surface energy balance at outermost surafce of the insulation

A_matp(2*s_pre+1,2*s_pre)=k_ins*A_wall_pre/dx_ins_pre;

A_matp(2*s_pre+1,2*s_pre+1)=-k_ins*A_wall_pre/dx_ins_pre-hr4p;

C_matp(2*s_pre+1,1)=-hr4p*T_amb;


%Heat conduction equation for interior sections of wall

for i=4:s_pre+1

   C_matp(i,1)=T_pre(i-2,1);

   A_matp(i,i-1)=-alpha_wall_pre*dt/((dx_wall_pre)^2);

   A_matp(i,i)=1+2*alpha_wall_pre*dt/((dx_wall_pre)^2);

   A_matp(i,i+1)=-alpha_wall_pre*dt/((dx_wall_pre)^2);

end


%Heat conduction equation for interior sections of insulation

for i=s_pre+3:2*s_pre

   C_matp(i,1)=T_pre(i-2,1);

   A_matp(i,i-1)=-alpha_ins*dt/((dx_ins_pre)^2);

   A_matp(i,i)=1+2*alpha_ins*dt/((dx_ins_pre)^2);

   A_matp(i,i+1)=-alpha_ins*dt/((dx_ins_pre)^2);

end


xxx=(A_matp)\C_matp;
```

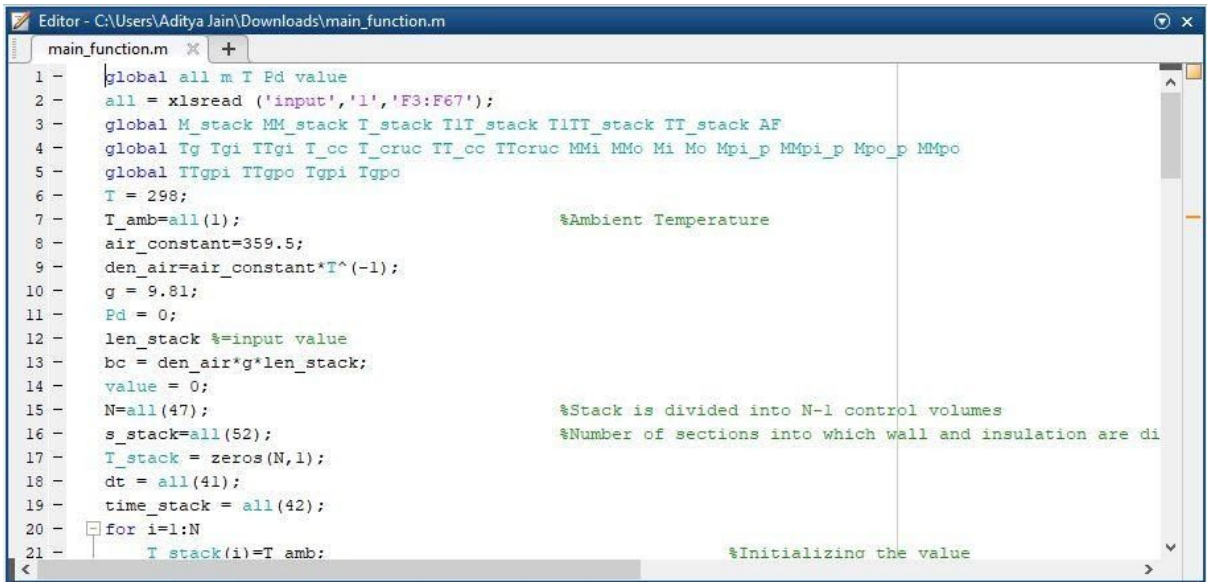
```
B_matp=xxx;
y1_p=B_matp(1,1);
y2_p=B_matp(2,1);

for i=1:2*s_pre-1
   TT_pre(i,1)=B_matp(i+2,1);          %Temperature of sections of wall and insulation around preheater
end

y3_p = TT_pre;
y4_p = dt*k_wall_pre*A_wall_pre/dx_wall_pre*(TT_pre(1,1)-TT_pre(2,1))-dt*hr4p*(TT_pre(2*s_pre-1)-T_amb); %Energy that gets stored in the walls and insulation during every time interval dt
y5_p = dt*hr4p*(TT_pre(2*s_pre-1)-T_amb);                                    %Energy that is lost to the ambient from the outermost surface of the insulation during every time interval dt


end
```

USER GUIDE

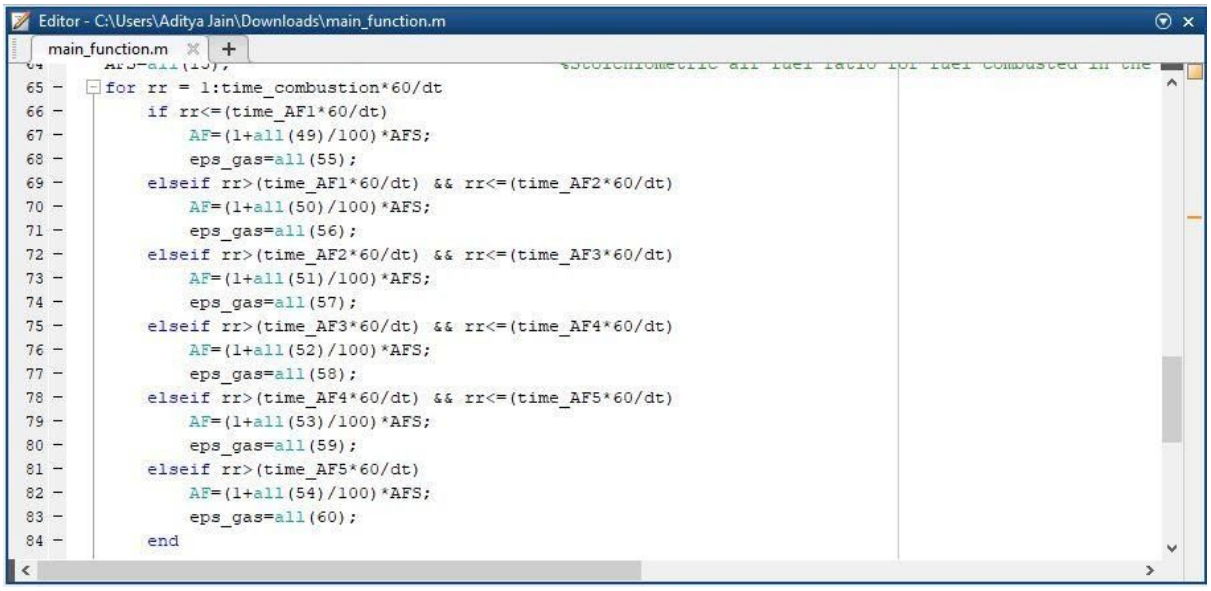
This user guide has been developed in order to ensure the user-friendliness of the system. The motive of this guide is to serve as a manual for a designer who can walk through the model as and when required and configure the system for any possible configuration required. Thus, this manual will lead to the introduction of generality and usability of the code not only by the developer but even by the designers.

Below mentioned are the steps that needs to be followed :

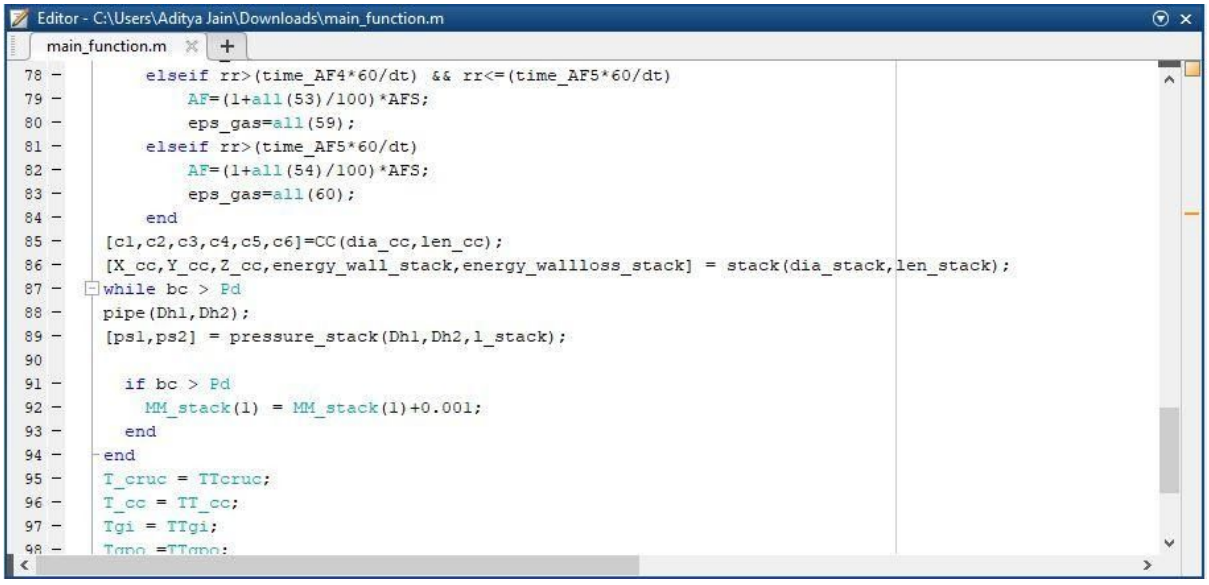
a. Go to the Main function



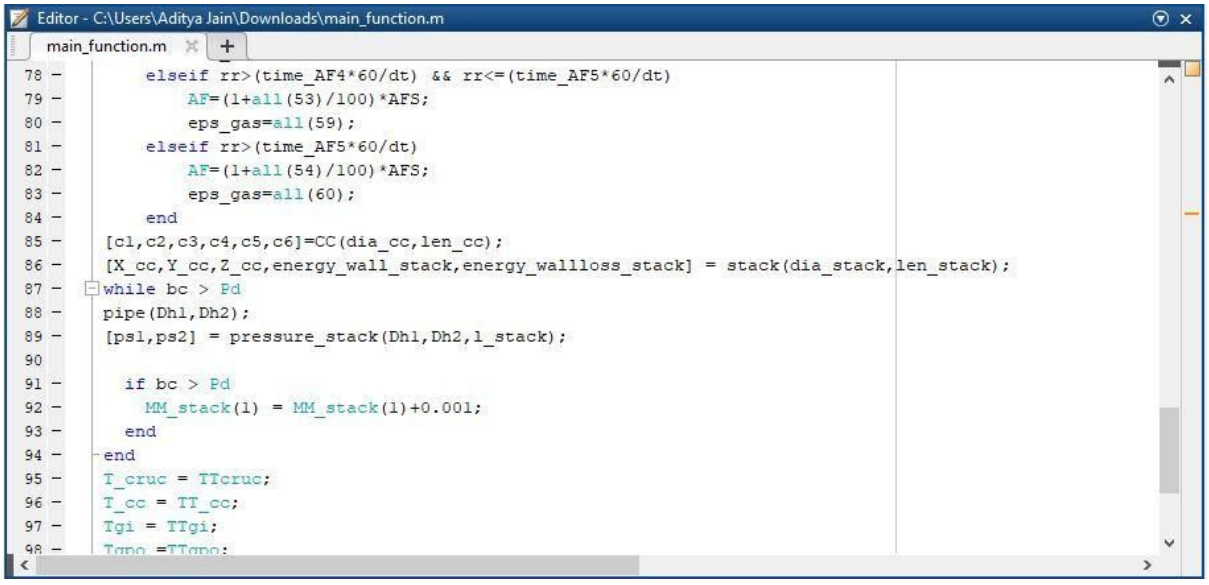
b. Identify the part where combustion begins as shown below



c. On scrolling down a bit, a function code for “CC” and “stack” can be observed. They can be arranged along with “preheater” in order of their position in the furnace. Make sure you input the relevant dimensions for each part when introducing their function.



d. After the while loop begins, all the functions for pressure drop (including for combustion chamber, stack and preheater) can be introduced in the order that goes in accordance with the furnace. Make sure you input the relevant dimensions for each part when introducing their function.



e. Also make sure that all the codes and excel sheet are open and use “add to path” option to integrate all the codes together.