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# Development of a Computer Program to Compute Approximate Heat Balance for Furnace Design

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**Abstract:** This study presents the description of a computer program developed for purpose of carrying out an approximate heat balance for a rectangular furnace at the design stage. This is often necessary in order to determine the heat input, its expenditure and the fuel consumption. The program which was written in MATLAB estimates surface areas, calorimetric and actual furnace temperatures, input heat from fuel combustion and the heat output for metal melting, waste gases, and lining losses. Fuel requirement was obtained by equating total heat input and output. The various percentages were determined as well as the thermal indicators. The result of the application of the program to a furnace design of dimension 700×600×600 mm using gaseous fuel (Butane) is presented. The percentage of heat lost through the waste gases, the unit energy consumption and coefficient of total heat utilization compare well with what is obtainable in practice as revealed in literatures. The program will be useful for furnace design purposes.

**Key words:** Aluminium, computer program, furnace, heat balance, matlab

## INTRODUCTION

It is necessary to know beforehand the probable fuel consumption of a furnace in order to select the correct size of burner; to dimension ports, vents and stacks; and to select auxiliary equipment of correct size (Trinks *et al*., 2004). Heat balance calculations are therefore made for this purpose. The furnace is treated as a batch-type furnace which operate periodically. Heat balance calculations are therefore made per period and the heat output focuses on that used in melting the metal, that lost to waste gases and lining. The heat balance consists of input and output items (E.C.C, 1998; E.C.C, 1993). The primary source of heat input to the furnace is from the combustion heat of fuel and also the sensible heat of the combustion air and fuel when these are preheated. A part of this heat input liberated in the furnace chamber is absorbed by the stock, while the remaining is either carried as sensible heat by the exiting fuel gas or is lost by radiation through the furnace walls or casing (Mullinger and Jenkins, 2008).

By using an estimated furnace temperature from the adiabatic flame temperature of fuel used, the fuel used can be calculated by setting up a heat balance equation where total heat input is equated to the total heat output. The expression for determining the above quantities have been given by Krivandrin and Markov (1980).

The thermal condition of a furnace is assessed using certain indicators which are, the specific fuel consumption, coefficients of useful heat and total heat utilization. These are also given by Krivandin and Markov (1980), as well as Glinkov and Glinkov (1980).

By making use of the appropriate expressions a Matlab program was written which carries out the heat balance, determine the thermal condition coefficients and prints the result. The aim of this paper is to describe the program which was so developed for this purpose.

## MATERIALS AND METHODS

**Program structure:** The program starts with definitions of global quantities. Then furnace dimensions and properties, metal properties, fuel and combustion properties are entered into their various sections. The calculations begins with furnace surface areas and volumes, specific heat of waste gases and preheated air control input 0 and 1 is inbuilt into the program for no preheating and preheating, respectively.

Next, is the calculation of the calorimetric temperature of burning and actual furnace temperature. The program does the balancing of the input and output and the fuel requirement per period is obtained. This leads to the estimation of the heat quantities utilized by various parts of the furnace based on the fuel per period and then their percentages are determined. Finally, the coefficients for the thermal conditions of the furnace are also determined and the program ends with the printing of the results. The program flow chart is shown in Fig. 1, while the program is given in the Appendix.

**Test case:** The furnace design considered is a rectangular furnace with external dimensions 700 x 600 x 600 mm. The furnace is too used for recycling Aluminium. The refractory castable thickness is 110 mm for the walls and

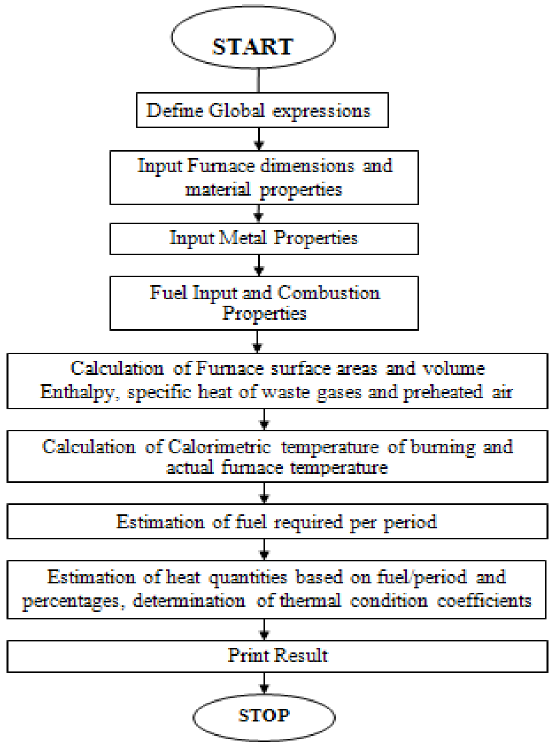


Fig. 1: Program flow chart for furnace heat balance

roof. Density of refractory is 1900 kg/m$^3$, emisivity = 0.75 and thermal conductivity = 0.75. Butane, a gaseous fuel is selected for use and an excess air of 10% is assumed for fuel combustion. 10 mm of glasswool insulation is sandwiched between the refractory wall and outer steel casing of 1.5 mm thickness.

The material to be melted is Aluminium and 50 kg of metal melting capacity based on the combustion chamber dimensions is used for design. Furnace operation without combustion air preheating is considered. Since the calculation is approximate, the following output items were disregarded; heat losses by radiation through open furnace doors; losses due to chemical incompleteness of combustion; losses due to mechanical incompleteness of combustion.

## RESULTS AND DISCUSSION

The approximate heat balance output from the program for the furnace operation is given in Table 1. The output from the heat balance shows that 11.087 kg/h of fuel will be required for the furnace; this value will be used to size the burner and other accessories. The output also show that 10.3% of the total heat supply will be utilized in melting the charge while 41.6% will be lost with the waste gases. The heat accumulated and lost through the walls and roof is 32.6% and that from the surfaces is 0.5%. The highest percentage of heat loss is through the waste gases and this is usually the case with all fuel fired furnaces and in practice the percentage loss is of the order of 50 to 60% (Baillargeon *et al*., 1998). The low percentage of the heat loss from surfaces is an indication of effective insulation. The thermal condition indicators show unit Energy consumption per kilogram of metal of approximately 10.16 MJ/kg and a specific fuel consumption per kilogram of metal of 17.31 kg/kg. According to CCMA and Technikon, (2001), Gas or oil fired basic furnaces use about 880 to 1990 kWh per ton of Energy (3.168 to 66.864 MJ/kg), the estimated unit energy consumption falls within this range.

The value of the coefficient of useful heat utilization relates to the energy absorbed by the charge and is 10.29% while the value of coefficient of total heat utilization which is also synonymous with the overall thermal efficiency is 58.41%. According to METALS Advisor, (2008), the energy required for remelting processed scrap is a function of the melting furnace efficiency and melting efficiencies can vary from 10 to 80%. Mullinger and Jenkins, (2008) also stated that most furnaces, as opposed to boilers, have a low thermal efficiency in the range 5 to 35%. The coefficients of useful and total heat utilization fall within this range. The percentages estimated are indicators of the quality of operation of the designed furnace and shows that the

Table 1: Theoretical heat balance for normal furnace operation

```
Enter 0 for no air preheating or 1 for preheating:0
Enthalpy of waste gases hwg =    521.445 kJ/kg
Specific heat of waste gases in kJ/kg.k =      1.109 kJ/kg.k
calometric temperature of burning Tcal =   1390.997ºC
Actual furnace temp Tac  =   1112.797ºC
Average inside wall surface temperature =    757.599ºC
Average wall temperature =    403.800ºC
Fuel required per period B =     11.087 kg/h
A. heat input in kJ/kg   (percent)
= = = = = = = = = = = = = = = = = = = = = = = = = = =
1.      Heat of fuel combustion.
        QCH = 507788.22 (100.0%)
2.      Heat of preheated air.
        QPA = 0.00 (0.0%)
---------------------------------------------------------------
Total Heat Input = 5.08e+005 (100.0%)
---------------------------------------------------------------
B. heat output in kJ/kg  (percent)
= = = = = = = = = = = = = = = = = = = = = = = = = = =
1. Heat spent to melt metal.
QM =   52267.50 (10.3%)
2. Heat spent to heat metal container.
QC =       0.00 (0.0%)
3. Heat lost with waste gases.
QWG = 211190.76 (41.6%)
4. Heat accumulated & lost through walls &roof.
QTWR = 165429.32 (32.6%)
5. Heat lost by outer wall surfaces.
QTS = 2732.40 (0.5 %)
6. Unaccounted Heat loss.
QUN = 76168.23 (15.0%)
---------------------------------------------------------------
Total Heat output = 5.08e+005 (100.0%)
---------------------------------------------------------------
C. Thermal condition indicators
= = = = = = = = = = = = = = = = = = = = = = = = = = =
Unit Heat Consumption kJ/kg of metal = 10155.76 kJ/kg of metal
Specific fuel Consumptionkg/kg of metal = 17.31 kg/kg
coefficient of useful heat utilization Nuhu = 10.29%
coefficient of total heat utilization Nhu = 58.41%
furnace productivity FP = 200.00 kg/day
```

furnace when constructed will perform well. The furnace productivity of 200 kg/day is estimated based on 6 hours of operation per day.

## CONCLUSION

The Matlab computer program developed for carrying out the heat balance for the design of rectangular furnaces has been described and tested. It can be used for determining the probable fuel consumption, the heat input to the furnace and the various heat output. The program also estimates the thermal condition indicators. The estimates obtained were validated by comparison with values reported in literatures. The program will be useful for preliminary design of rectangular furnaces.

**Appendix:**

Matlab computer program

```
%-----------------------------------------------------------------------%
%Program 1              %
%Main programe name: Thbalance2.m          %
%link to function program to calculate fuel required : Thbal.m           %
%link to function program to calculate specific heat of combustion gases: Cp2.m   %
%MATLAB program to compute approximate heat balance for furnace design    %
%by O.Ighodalo         %
%Mechanical Engineering Department          %
%Ambrose Alli University,Ekpoma             %
%-----------------------------------------------------------------------%
Global rec QLH QPH Va ha M Cm Tm Tamb Lf Vwg hwg den Cref Alpha Tos Tor QAW QAR Volw Volr ...
Saw Sar time twav lambda twg Eta Tcal Tac nol kq Mc Cc
%-----------------------------------------------------------------------
%FURNACE DIMENSIONS AND MATERIAL PROPERTIES
lfur=0.7;%lenght of furnace in meters
bfur=0.6;%breadth of furnace in meters
hfur=0.6;%height of furnace in meters
tfur=0.11;%thickness of furnace walls
den = 1900; %density of refractory in kg/m3
Cref = 0.99;%specific heat of refractory kj/kg k
lambda = 1.08;%(3.96kJ/m.oc) % Thermal conductivity W/m oc
%-----------------------------------------------------------------------
%Metal Properties
M=50; %Mass of metal
Cm = 1.045; %specific heat of metal kj/kg.k
Tm = 660; %melting temp for metal in oC
time = 1.5;% melting time in hours
Lf = 387; %latent heat of fusion for metal kJ/kg
Mc = 0;% mass of metal container (set to zero for direc charge firing)
Cc = 0.46;% specific heat of container(steel) kJ/kg.k
%-----------------------------------------------------------------------
%Fuel and combustion properties
%rec = 1; %control for air preheating
%rec = 0; %no air preheating
QLH = 45800; % lower heating value for fuel kJ/kg
Va = 34.03; %vol of preheated air m3
Tamb =30; %ambient temperature in ºC
twg = 500; %assumed temperature of waste gases in ºC
tpre = 300.0; % temperature of preheated air in ºC
Eta = 0.8; % pyrometric coefficient
%-----------------------------------------------------------------------
%CALULATIONS
Sar = lfur*bfur; %roof surface area, m2
Saw = 2*(lfur*hfur) + 2*(bfur*hfur);%surface area for walls, m2
Volr = Sar*tfur; % volume of roof, m3
Volw = Saw*tfur; % volume of walls, m3
%%Compute enthalpy, specific heat of waste gases and preheated air
nol = [0.65 26.88 4 5];% no of moles of combustion products 02,N2,CO2,H20
sumn = 0;
for knol = 1:4
   sumn = sumn + nol(knol);
end
Vwg = sumn;%total vol. of waste gases
%mol = [32 28 44 18];% molecular wt. of O2, N2,CO2 and H20 resp.
perc = [0.00178 0.7358 0.1095 0.1369];% percentage of waste gas components
sumh = 0;
for kq = 1:4
H(kq) = quad('cp2',30,twg);
sumh = sumh + perc(kq)*H(kq);
end
hwg = sumh;%enthalpy of waste gases in kj/kg
Cwg = hwg/(twg-30);%specific heat of waste gases
ha = quad('cpa',30,tpre);%enthalpy of preheated air kj/m3
Ca = ha/(tpre - 30);%specific heat of preheated air kj/m3.k
QPH = Va*ha;%physical heat of air kj
%-----------------------------------------------------------------------
%calculate calorimetric temperature of burning Tcal & actual furnace temp Tac
```

```
rec = input('Enter 0 for no air preheating or 1 for preheating:');
if rec==1
Tcal = (QLH+QPH)/Vwg*Cwg;%calorimetrictemperature ofburningelse
Tcal = QLH/Vwg*Cwg;% calorimetric temperature of burning end
Tac = Eta*Tcal;% actual furnace temp
fprintf('enthalpy of waste gases hwg = %10.3f %s\n',hwg,'kJ/kg');
fprintf('specific heat of waste gases in kJ/kg.k = %10.3f %s\n',Cwg,'kJ/kg.k');
fprintf('calometric temperature of burning Tcal = %10.3f %s\n',Tcal,'oC');
fprintf('actual furnace temp Tac  = %10.3f %s\n',Tac,'oC');
% calculate average wall temperature
tav= (twg +Tm+Tac)/3; %average  inside wall furnace temperature
fprintf('average inside wall surface temperature = %10.3f %s\n',tav,'oC');
Alpha = 46;% surface heat transfer coeff
Tos = 50.;%326.1;%ave outer wall surface temperature
Tor = 50;%327 ;%ave outer roof surface tempperature
twav = (tav+Tos)/2;% average wall temperature
fprintf('average wall temperature = %10.3f %s\n',twav,'oC');
%---------------------------------------------------------------------------
%Estimate fuel required per period
B =  fzero('Thbal',0);%fuel flow rate /period,kg/hr
fprintf('fuel required per period B = %10.3f %s\n',B,'kg/hr')
%---------------------------------------------------------------------------
%calculate heat quantities based on estimated fuel/period B& print
%HEAT INPUT
QCH =QLH*B;% heat of fuel KJ/period
if rec==1
QPA = B*QPH; %heat of preheated air
else
QPA = 0;
end
%heat output
QM = M*(Cm*(Tm - Tamb) + Lf); %heat of metal melting
QC = Mc*Cc*Tac; % Heat absorbed by container
QWG = B*Vwg*hwg; %heat of waste gases
%heat accumulated by walls and roof
QAW = Volw*den*Cref*twav;% heat accumulated by walls
QAR = Volr*den*Cref*twav;% heat accumulated by walls(roof)
QTWR = QAW +QAR;% total heat accumulated by walls and roof
QWoloss = Alpha*(Tos - Tamb)*Saw*time;% surface heat loss for walls surface
Qors = Alpha*(Tor - Tamb)*Sar*time;%surface heat loss for roof surface
QTS = QWoloss + Qors;%total surface loss kj/period
QUN = 0.15*QCH;%unaccounted heat loss
QTLOSS = QWG + QTWR+ QTS+ QUN;% total heat loss
QTOTIN = QCH + QPA;%total heat input
QTOTOU = QM + QC + QWG + QTWR + QTS + QUN;%total heat output
Qu = QTOTIN/M;%UNIT HEAT CONSUMPTION/kg of metal
%calculate percentages
PQCH = 100*QCH/QTOTIN;% percentage heat of fuel input
PQPA = 100*QPA/QTOTIN; % percentage heat of preheated air
PQM = 100*QM/QTOTOU; % percentage heat of metal melting
PQC = 100*QC/QTOTOU; % percentage heat absorbed by metal container
PQWG = 100*QWG/QTOTOU; % percentage heat of waste gases
PQTWR = 100*QTWR/QTOTOU; % percentage total heat accumulated walls and roof
PQTS = 100*QTS/QTOTOU; % percentage total surface heat loss
PQUN = 100*QUN/QTOTOU; % percentage unaccounted heat lossl
PQTOTIN = PQCH+PQPA; % percentage total heat input
PQTOTOU = PQM+PQC+PQWG+PQTWR+PQTS+PQUN; % percentage total heat output
% OTHER QUANTITIES
SFC = B*QLH/29330;%Specific fuel consumption
Nuhu = 100*(QCH + QPA - QTLOSS)/(QCH + QPA);%coefficint of useful heat utilization
Nhu = 100*(QCH + QPA - QWG)/(QCH + QPA);%coefficient of total heat utilization
FP = (6*M)/time;%furnace productivity kg/day
fprintf('A. heat input in kJ/kg   (percent)\n');
fprintf('======================================\n');
fprintf('1. Heat of fuel combustion.\n');
fprintf('QCH = %10.2f %s %5.1f %s %s\n',QCH,'(',PQCH,'%',')');
fprintf('2. Heat of preheated air.\n');
fprintf('QPA = %10.2f %s %3.1f %s %s\n',QPA,'(',PQPA,'%',')');
fprintf('-------------------------------------------------\n');
fprintf ('Total Heat Input = %10.2e %s %5.1f %s %s\n',QTOTIN,'(',PQTOTIN,'%',')');
fprintf('---------------------------------------------------');
fprintf('\n');
fprintf('B. heat output in kJ/kg  (percent)\n');
fprintf('=====================================\n');
fprintf('1. Heat spent to melt metal.\n');
fprintf('QM = %10.2f %s %3.1f %s %s\n',QM,'(',PQM,'%',')');
fprintf('2. Heat spent to heat metal container.\n');
fprintf('QC = %10.2f %s %3.1f %s %s\n',QC,'(',PQC,'%',')');
fprintf('3. Heat lost with waste gases.\n');
fprintf('QWG = %10.2f %s %5.1f %s %s\n',QWG,'(',PQWG,'%',')');
fprintf('4. Heat accumulated & lost through walls &roof.\n');
fprintf('QTWR = %10.2f %s %5.1f %s %s\n',QTWR,'(',PQTWR,'%',')');
fprintf('5. Heat lost by outer wall surfaces.\n');
fprintf('QTS = %10.2f %s %3.1f %s %s\n',QTS,'(',PQTS,'%',')');
fprintf('6. Unaccounted Heat loss.\n');
fprintf('QUN = %10.2f %s %3.1f %s %s\n',QUN,'(',PQUN,'%',')');
fprintf('---------------------------------------------------\n');
fprintf('Total Heat output = %10.2e %s %5.1f %s %s\n',QTOTOU,'(',PQTOTOU,'%',')');
fprintf('---------------------------------------------------\n');
fprintf('\n');
fprintf('C. Thermal condition indicators\n')
fprintf('===================================\n');
fprintf('Unit Heat Consumption kJ/kg of metal = %10.2f %s\n',Qu,'kJ/kg of metal');
fprintf('Specific fuel Consumptionkg/kg of metal = %10.2f %s\n',SFC,'kg/kg');
fprintf('coefficient of useful heat utilization Nuhu = %5.2f %s\n',Nuhu,'%');
fprintf('coefficient of total heat utilization Nhu = %5.2f %s\n',Nhu,'%');
fprintf('furnace productivity FP = %5.2f kg/day\n',FP);
```

---

```
%FUNCTION TO Calculate fuel/period B
function fb = Thbal(xb)
%HEAT INPUT
global rec QLH M Cm Tm Tamb Lf Vwg twg den Cref Alpha Tos Tor QAW QAR Volw Volr ...
Saw Sar time twav Cwg Tac Mc Cc
QCH =QLH*xb;%KJ/period
if rec==0
%    QPA = B*QPH; %heat of preheated air
%else
QPA = 0;
end
%heat output
QM = M*(Cm*(Tm - Tamb) + Lf); %heat of metal melting
QC = Mc*Cc*Tac; % Heat absorbed by container
QWG = xb*Vwg*Cwg*twg; %heat of waste gases
%heat accumulated by walls and roof
QAW = Volw*den*Cref*twav;% heat accumulated by walls
QAR = Volr*den*Cref*twav;% heat accumulated by walls
QTWR = QAW +QAR;
QWoloss = Alpha*(Tos - Tamb)*Saw*time;% surface heat loss for walls surface
Qors = Alpha*(Tor - Tamb)*Sar*time;%surface heat loss for roof surface
```

```
QTS = QWoloss + Qors;%total surface loss kj/period
QUN = 0.15*QCH;%unaccounted heat loss
QTLOSS = QWG + QTWR+ QTS+ QUN;% total heat loss
QTOTIN = QCH + QPA;%total heat input
QTOTOU = QM + QC + QTLOSS;%total heat output
fb = QTOTIN - QTOTOU;
```

```
%function (cp2) to calculate specific heat of combustion gases%
function y = cp2(t)
global  kq  nol
%global a b c d kq nol mol
%coef for specific heat polynomial,02,N2,CO2,H20
a = [25.48 28.9 22.26 32.24];
b = [1.520 -0.157 5.981 0.1923];
c = [-0.7155 0.8081 -3.501 1.055];
d = [1.312 -2.873 7.469 -3.595];
nol = [0.65 26.88 4 5];%no of moles of combustion products 02,N2,CO2,H20
%mol = [32 28 44 18];% molecular wt. of O2, N2,CO2 and H20 resp.
%y = (1/mol(kq))*(a(kq) + (b(kq)*10.^-2)*t + (c(kq)*10.^-5)*t.^2 + (d(kq)*10.^-9)*t.^3);
y = a(kq) + (b(kq)*10.^-2)*t + (c(kq)*10.^-5)*t.^2 + (d(kq)*10.^-9)*t.^3;
```

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