



HOKKAIDO UNIVERSITY

Title	Digital Simulation of Radiative and Convective Heat Transfer in a Three Dimensional Furnace
Author(s)	Taniguchi, Hiroshi; Sugiyama, Ken-ichiro
Citation	Memoirs of the Faculty of Engineering, Hokkaido University, 13(Suppl), 117-125
Issue Date	1972-05
Doc URL	https://hdl.handle.net/2115/37904
Type	departmental bulletin paper
File Information	13Suppl_117-126.pdf



Digital Simulation of Radiative and Convective Heat Transfer in a Three Dimensional Furnace

Hiroshi TANIGUCHI
Associate Professor
Faculty of Engineering
Hokkaido University
Sapporo, Hokkaido, Japan

Ken-ichiro SUGIYAMA
Graduate Student
Faculty of Engineering
Hokkaido University
Sapporo, Hokkaido, Japan

ABSTRACT

The authors make an attempt to analyze radiative and convective heat transfer in a three dimensional furnace through digital simulation. The analysis is developed in the case where furnace is rectangular solid, it contains two kinds of radiant media and various regions of wave lengths are applied for each medium. Furthermore, this is also developed in the case where temperature and absorption coefficient are not uniform in each part of the media and various temperatures and emissivities are employed for each wall. The numerical calculation is conducted by Monte Carlo method for radiation and finite-difference method for convection. Its program is coded by FORTRAN IV for digital computer (HITAC 5000E or FACOM 230/60).

The followings are calculated by the above; results as affected by furnace size, temperature and emissivity of wall, results as affected by flame shape, absorption coefficient and region of wave length, and results as affected by convection are presented in this paper. And, as possible to calculate each performance of furnace, some effects in actual operation would be predicted by this simulation.

1. INTRODUCTION

In order to analyze the heat transfer in a furnace, some complex conditions must be applied for this system. The heat transfer between flame and wall is strongly influenced by radiation. But it is not desirable to omit convection or flow effect. The furnace contains two kinds of radiant media (flame and surrounding combustion gas) and its wall is constructed by refractory and heating surface. Many paper have been published on this analysis under simplified condition in which furnace contains one kind of radiant medium and has uniform temperature. Such study should be applied for rough estimation of temperature in furnace

outlet, but not for temperature distribution and heat absorption rate. Lately, as an electronic digital computer have been widely used for each study, it is possible to obtain a solution of complex system through numerical or digital simulating method.^{(1)~(5)}

The authors make an attempt to analyze the above-mentioned heat transfer system through this simulating method in which the furnace is rectangular solid, it contains two kinds of radiant media and has the other actual conditions as required. Furthermore, this is developed in case of non-uniform temperature and absorption coefficient of the media. The calculation is conducted by Monte Carlo method, finite-difference method and summerized method for each procedure. Some results as affected by furnace conditions, characteristics of radiant media, convection and flow effect are obtained by the simulation in this study.

2. DIGITAL SIMULATION OF HEAT TRANSFER

A consideration is made on rectangular solid furnace which contains two kinds of radiant media (flame and surrounding combustion gas). The flame is defined as gray gas with heat source and the gas is defined as non-gray gas with a certain region of wave length λ_1 to λ_2 . Temperature and absorption coefficient is not uniform in each part of media. Another consideration is made on the case where heat is transferred by radiation, convection and flow effect. Various temperatures and emissivities are employed for each wall. An emissive power is defined by

$$\left. \begin{aligned} E_f &= (1 - \epsilon_{kf}) \sigma T^4 && \text{for flame} \\ E_g &= (1 - \epsilon_{kg}) \sigma T^4 F(\tau) && \text{for gas} \\ E_w &= \epsilon_w \sigma T^4 && \text{for wall} \end{aligned} \right\} \quad (1)$$

where E_f, E_g, E_w : emissive power
 k_f, k_g : absorption coefficient
 T, T_w : temperature
 ℓ : thickness ϵ_w : emissivity of wall

Imaginary thickness

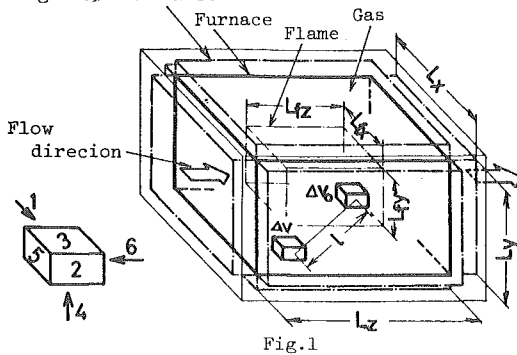


Fig. 1

δ: Stefan-Boltzmann's constant

$$F(T) = C_1 \frac{\lambda_1^{\lambda_2}}{\lambda_1^{\lambda_2} \exp(C_2/\lambda_1 T) - 1} \div \exp\{\sum A_i (\log e \lambda_i T)^i - \sum A_i (\log e \lambda_i T)^i\} : \text{correction factor}$$

for region of wave length λ_1 to λ_2 The following Eq. is obtained for small volume ΔV in Fig. 1.

$$H_e = H_g + H_r + H_c \quad \text{for flame and gas} \quad (2)$$

where H_e : emissive power H_g : heat generation H_r : heat transferred by radiation H_c : heat transferred by convection and flow effectThen, the following Eq. is obtained for ΔV_w .

$$H_a = H_w - (H_r + H_c) \quad \text{for wall} \quad (3)$$

where H_a : heat absorption H_w : emissive power

The calculation is conducted by Monte Carlo method for radiation and finite-difference method for convection or flow effect. A concept of energy bundle should be applied to employ Monte Carlo method and another concept of imaginary thickness may be employed to simulate each emission of media and wall by a common procedure. This thickness has the following characteristics.

- (1) The thickness is connected to 0 °K black surface and has zero absorption coefficient.
- (2) A energy bundle is reflected by boundary of thickness and media.
- (3) A direction of bundle through thickness is perpendicular to boundary.

In Fig. 1, the furnace with imaginary thickness is subdivided into M_x, M_y and M_z for each axis. An equivalent intensity J of bundle from ΔV is obtained by

$$J = C_g Q_g F(T)/N + C_g Q_g \{1 - F(T)\}/N \quad (4)$$

where N : number of bundles Q_g : heat generating rate $C_g = (H_g + H_r + H_c)/(H_g + H_r)$: correction factor for convection and flow effect

In Fig. 2, an emitting probability R_η, R_θ in each direction of media is obtained by

$$R_\eta = \int_0^\pi \frac{\sin \eta d\eta}{2} = \frac{1 - \cos \eta}{2}, \quad R_\theta = \int_0^\pi \frac{d\theta}{2\pi} = \frac{\theta}{2\pi} \quad (5)$$

Transforming the above to normal coordinates

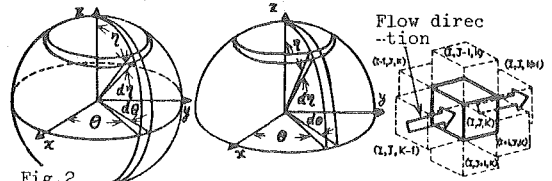


Fig. 2

Flame or Gas

Fig. 3

Wall

Fig. 4

$$R_r = 1 - 2R_\eta, R_x = \sqrt{1 - R_\eta^2} \cos 2\pi R_\theta, R_y = \sqrt{1 - R_\eta^2} \sin 2\pi R_\theta \quad (6)$$

where R_x, R_y, R_z : emitting probability in each axis. Then, an intensity J of bundle from ΔV_w is obtained by

$$J = E_w \delta T^4 F(T) \Delta A_w / N + E_w \delta T^4 \{1 - F(T)\} \Delta A_w / N \quad (7)$$

where ΔA_w : small area of ΔV_w

In Fig. 3, an emitting probability R_η, R_θ in each direction of wall, applying Lambert's cosine law, is obtained by

$$R_\eta = \int_0^\pi 2 \sin \eta \cos \eta d\eta = 1 - \cos^2 \eta, \quad R_\theta = \int_0^\pi \frac{d\theta}{2\pi} = \frac{\theta}{2\pi} \quad (8)$$

Transforming the above

$$R_x = \sqrt{1 - R_\eta}, R_y = \sqrt{1 - R_\eta^2} \cos 2\pi R_\theta, R_z = \sqrt{1 - R_\eta^2} \sin 2\pi R_\theta \quad (9)$$

An absorbing probability R_e is applied for bundle absorbed at distance

$$R_e = 1 - e^{-\sum K_i \Delta L}, \quad U = \sum K_i \Delta L = -\log_e(1 - R_e) \quad (10)$$

where K_i : K_g or K_w U : optical thickness. When the bundle reaches boundary of imaginary thickness, a passing probability R_p is obtained by

$$R_p = E_w \quad (11)$$

Furthermore, each volume must be distinguished between flame, gas and imaginary thickness. A control variable I_s may be used for this purpose.

$$I_s = 1 \sim 6 \text{ for wall, } I_s = 7 \text{ for gas, } I_s = 8 \text{ for flame} \quad (12)$$

Thus, in order to simulate the heat transfer, a passage of energy bundle should be determined by the following procedure. At first, C_g and $F(T)$ may be assumed to determine intensity of the bundle, which is emitted from center of ΔV , through Eq. (4), and direction, absorption and passing conditions are calculated by Eqs. (6), (10) and (11). A flow of calculation can be controlled by I_s . And, the same items for the other bundle, which is emitted from ΔV_w , are calculated by Eqs. (7), (9), (10) and (11). Next, when each bundle is reflected by boundary of the thickness or re-emitted after absorbed by these media, a passage can be determined by the same way as the above. Then, if the bundle passes through the boundary, a history of the bundle is terminated and new history of another bundle may begin in accordance with the same procedure. Summing up total energy bundles, a total equivalent absorbing energy in ΔV is obtained by

$$C_g H_r = \sum \sum \sum [C_g Q_g R_\eta F(T) \Delta V + C_g Q_g R_{\eta r} \{1 - F(T)\} \Delta V] + \sum \sum [E_w \delta T^4 R_\eta F(T) \Delta A_w + E_w \delta T^4 R_{\eta r} \{1 - F(T)\} \Delta A_w] \quad (13a)$$

for flame

$$C_g H_r = \sum \sum C_g Q_g R_{fg} F(T) \Delta V + \sum \sum E_w \delta T_w^4 R_{wg} F(T) \Delta A_w$$

for gas (13b)

$$H_r = \sum \sum [C_g Q_g R_{fg} F(T) \Delta V + C_g Q_g R_{fg} \{1 - F(T)\} \Delta V] + \sum \sum [E_w \delta T_w^4 R_{wg} F(T) \Delta V + E_w \delta T_w^4 R_{wg} \{1 - F(T)\} \Delta V]$$

for wall (14)

where $R_{fg}, R_{fg}, R_{fg}, R_{wg}, R_{wg}, R_{wg}$: absorbing probability for region of wave length λ_1 to λ_2 , $R_{fg}, R_{fg}, R_{fg}, R_{wg}, R_{wg}$: absorbing probability for region except λ_1 to λ_2
An equivalent heat generation of ΔV_0 in Fig.1 is obtained by

$$C_g H_g = C_g Q_g \Delta V_0 \text{ for flame, } C_g H_g = 0 \text{ for gas (15)}$$

$$H_w = E_w \delta T_w^4 \Delta A_w \text{ for wall (16)}$$

In order to calculate the correction factor for convection and flow effect, the following Eq. is applied for case of steady flow in Fig.4. In the calculation, mass velocity, specific heat and equivalent thermal conductivity are uniform in each part of media, because H_c is relatively small to H_r .

$$H_c = P_{tg} \left\{ \frac{T_{i,j,k} - T_{i,j,k}}{\Delta L_x} \Delta L_y \Delta L_z + \frac{T_{i,j,k} - T_{i,j,k}}{\Delta L_x} \Delta L_y \Delta L_z \right. \\ \left. + \frac{T_{i,j,k} - T_{i,j,k}}{\Delta L_y} \Delta L_x \Delta L_z + \frac{T_{i,j,k} - T_{i,j,k}}{\Delta L_y} \Delta L_x \Delta L_z \right\} \\ + W C_p \frac{T_{i,j,k} - T_{i,j,k}}{\Delta L_x} \Delta V \text{ for flame (17a)}$$

$$H_c = P_{tg} \left\{ \frac{T_{i,j,k} - T_{i,j,k}}{\Delta L_x} \Delta L_y \Delta L_z + \frac{T_{i,j,k} - T_{i,j,k}}{\Delta L_x} \Delta L_y \Delta L_z \right. \\ \left. + \frac{T_{i,j,k} - T_{i,j,k}}{\Delta L_y} \Delta L_x \Delta L_z + \frac{T_{i,j,k} - T_{i,j,k}}{\Delta L_y} \Delta L_x \Delta L_z \right\} \\ + W C_p \frac{T_{i,j,k} - T_{i,j,k}}{\Delta L_x} \Delta V \text{ for gas (17b)}$$

$$H_c = d \Delta T \Delta A_w \text{ for wall (18)}$$

where P_{tg}, P_{tg} : equivalent thermal conductivity
 W : mass velocity C_p : specific heat
 α : convective heat transfer rate
 ΔT : temperature difference between wall and outside of boundary layer
Therefore, correction factor C_g is decided by the above value.

Then, a total emissive power of ΔV_0 is defined by

$$\left. \begin{aligned} H_e &= 4 K_g \delta T^4 \Delta V_0 && \text{for flame} \\ H_e &= 4 K_g \delta T^4 F(T) \Delta V_0 && \text{for gas} \end{aligned} \right\} (19)$$

The following non-dimensional emissive power may be available to check each results.

$$F_a = H_e / (Q_m \Delta V_0) (20)$$

where F_a : non-dimensional emissive power

$$Q_m = \frac{\sum \sum Q_g \Delta V + \sum \sum E_w \delta T_w^4 \Delta A_w}{V_t} : \text{mean heat generating rate}$$

$V_t = \sum \sum \Delta V + \sum \sum \Delta A_w \Delta L$: imaginary total volume
An addition of Eqs. (13) and (15) makes

$$C_g H_r + C_g H_g = \frac{H_g + H_r + H_c}{H_g + H_r} (H_g + H_r) = H_e \text{ equal to (2)}$$

A subtraction of Eqs. (14) and (18) from Eq. (16) makes

$$H_w - (H_r + H_c) = H_a \text{ equal to (3)}$$

3. PROGRAM FOR DIGITAL SIMULATION

In order to apply the above method to digital computation, a program is coded by FORTRAN IV through a flow chart in Fig.5. However, as C_g and $F(T)$ are employed for correction of convection and wave range, it is necessary to apply trial and error method. This program is constructed by a main program and seven subprograms (generation of random number, direction of energy bundle, absorbing length for region of R_1 to R_2 , absorbing length except R_1 to R_2 , heat flow by convection and flow effect, and symmetrical conversion of three dimensional matrix). Main parts of the program are shown in Fig.6 and the following input data are used for this calculation.

- (1) N : number of bundles
 MX, MY, MZ : number of meshes
- (2) MF_X, MF_Y, MF_Z : number of meshes of flame
 MZ_1, MZ_0 : position of flame and air intake
- (3) AKF, AKG : absorption coefficient η^4
 R_1, R_2 : wave length μ
- (4) ALX, ALY, ALZ : furnace dimension m
 QF : heat generating rate in flame $Kcal/m^3 h$
- (5) CP : specific heat $Kcal/kg^{\circ}K$
 W : mass velocity $Kg/m^2 h$
 PRF, PRG : equivalent thermal conductivity $Kcal/mh^{\circ}K$
 HC, HO : convective heat transfer rate $Kcal/m^2 h^{\circ}K$
- (6) $E_1 \sim E_6$: emissivity of wall
 $T_1 \sim T_6$: temperature of wall $^{\circ}K$
 TOF, TOG : temperature of air and recirculating gas $^{\circ}K$

4. NUMERICAL CALCULATED RESULTS

The following examples are calculated by computer (HITAC 5020E or FACOM 230/60); results as affected by furnace size, temperature and emissivity of wall, results as affected by flame shape, absorption coefficient and region of wave length, and results as affected by convection and flow effect are presented.

At first, numerical calculations are performed in case of rectangular solid furnace which is filled with flame and has no convection and flow effect. Then, Figs.7 to 9 show distributions of non-dimensional emissive power, temperature and heat absorption under influence of furnace

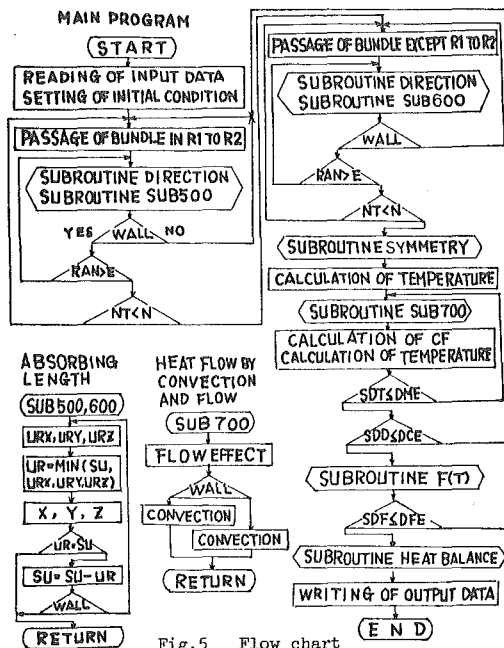


Fig.5 Flow chart

```

34 DO 60 IT=1,MX
   DO 60 JT=1,MY
   DO 60 KT=1,MZ
   NT=0
40 I=IT
   J=JT
   K=KT
   S0=(0(I,J,K)-0R(I,J,K))*DUM(I,J,K)
   IF(S0.E0.0.) GO TO 60
   NT=NT+1
   X=DLX*(FLOAT(I)-0.5)
   Y=DLY*(FLOAT(J)-0.5)
   Z=DLZ*(FLOAT(K)-0.5)
   IS1=IS(I,J,K)
41 SG(I,J,K)=SG(I,J,K)+S0
   CALL SUB900(NRAN,RAN)
   SUM=ALOG(RAN)
42 CALL SUB400(NRAN,PA1,IS1,RX,RY,RZ)
   CALL SUB500(MX,MY,MZ,ALX,ALY,ALZ,AKP,DLX,DLY,DLZ,RX,RY,RZ,
1 IS,IS1,SU,I,J,K,X,Y,Z)
   IF(IS1.LE.6) GO TO 43
   S0=S0+DUM(I,J,K)
   GO TO 41
43 CALL SUB900(NRAN,RAN)
   IF(RAN.GT.E(I,J,K)) GO TO 42
   SG(I,J,K)=SG(I,J,K)-S0
   IF(NT.LT.N) GO TO 40
44 NT=0
50 I=IT
   J=JT
   K=KT
   S0R=0R(I,J,K)*DUM(I,J,K)
   IF(S0R.E0.0.) GO TO 54
   NT=NT+1
   X=DLX*(FLOAT(I)-0.5)
   Y=DLY*(FLOAT(J)-0.5)
   Z=DLZ*(FLOAT(K)-0.5)
   IS1=IS(I,J,K)
51 SG(I,J,K)=SG(I,J,K)+S0R
   CALL SUB900(NRAN,RAN)
   AL=-ALOG(RAN)/AKF
52 CALL SUB400(NRAN,PA1,IS1,RX,RY,RZ)
   CALL SUB600(MX,MY,MZ,ALX,ALY,ALZ,DLX,DLY,DLZ,RX,RY,RZ,
1 IS,IS1,AL,I,J,K,X,Y,Z)
   IF(IS1=7) 53,54,55
53 S0R=S0R+DUM(I,J,K)
   GO TO 51
53 CALL SUB900(NRAN,RAN)
   IF(RAN.GT.E(I,J,K)) GO TO 52
   SG(I,J,K)=SG(I,J,K)-S0R
   IF(NT.LT.N) GO TO 50
54 NTT=NTT+N

```

```

60 CONTINUE
C FINAL POINT OF INNER LOOP OF CALCULATION
57 AN=1
  IF (IXY.E0.0) GO TO 58
  CALL SYCO(SG,MX,MY,MZ,IZ)
58 DO 61 I=1,MX
  DO 61 J=1,MY
  DO 61 K=1,MZ
61 SG(I,J,K)=SG(I,J,K)/AN
  DO 70 I=2,MX-1
  DO 70 J=2,MY-1
  DO 70 K=2,MZ-1
  IF(SG(I,J,K).LT.0.) GO TO 70
  IF(DGE.E0.0.) GO TO 63
  IF(ISC(I,J,K).E0.7) GO TO 64
63 T(I,J,K)=(SG(I,J,K)*OM/(4.*AKP(I,J,K)*S))*0.25
  GO TO 70
64 IF(F(I,J,K).E0.0.) GO TO 70
62 T(I,J,K)=(SG(I,J,K)*OM/(4.*AKP(I,J,K)*F(I,J,K)*S))*0.25
  DUMF=F(I,J,K)
  CALL SFMO(T(I,J,K),R1,R2,F(I,J,K))
  IF(F(I,J,K).E0.0.) GO TO 70
  DF=ABS((F(I,J,K)-DUMF)/F(I,J,K))
  IF(DF.LE.DGE) GO TO 70
  F(I,J,K)=(F(I,J,K)+DUMF)/2.
  GO TO 62
70 CONTINUE
69 IF(LS1.E0.0) GO TO 71
  LS1=0
  GO TO 90
71 IF(DME.E0.0.) GO TO 80
  P=0.5
72 CALL SUB700(P,T,IS,MX,MY,MZ,MZ0,DLX,DLY,DLZ,T0G,T0F,OM,CP,W,
1 PRG,PRF,PRO,HC,H0,DSG)
  DO 77 I=2,MX-1
  DO 77 J=2,MY-1
  DO 77 K=2,MZ-1
  IF(SG(I,J,K).E0.0.) GO TO 59
  IF((SG(I,J,K)-DSG(I,J,K)).E0.0.) GO TO 59
  DUM(I,J,K)=(SG(I,J,K)+DSG(I,J,K))*PM/SG(I,J,K)+SG(I,J,K)*(1.-PM)
1 /((SG(I,J,K)-DSG(I,J,K)))
  IF(DUM(I,J,K).GT.0.) GO TO 59
  DUM(I,J,K)=DUMS(I,J,K)
59 DUMT(I,J,K)=T(I,J,K)
  IF(SG(I,J,K)*DUM(I,J,K)/DUMS(I,J,K).GT.0.) GO TO 73
  IF(K=MZ0) 77,65,67
65 IF(ISC(I,J,K).E0.7) GO TO 66
  T(I,J,K)=(T(I,J,K)+T0F)/2.
  GO TO 77
66 T(I,J,K)=(T(I,J,K)+T0G)/2.
  GO TO 77
67 T(I,J,K)=(T(I,J,K)+T(I,J,K-1))/2.
  GO TO 77
73 IF(DGE.E0.0.) GO TO 75
  IF(ISC(I,J,K).E0.7) GO TO 74
75 T(I,J,K)=(SG(I,J,K)*DUM(I,J,K)/DUMS(I,J,K)*OM/(4.*AKP(I,J,K)*S))
1 **0.25
  GO TO 77
74 IF(F(I,J,K).E0.0.) GO TO 77
76 T(I,J,K)=(SG(I,J,K)*DUM(I,J,K)/DUMS(I,J,K)*OM/(4.*AKP(I,J,K)*
1 F(I,J,K)*S))*0.25
  DUMF=F(I,J,K)
  CALL SFMO(T(I,J,K),R1,R2,F(I,J,K))
  IF(F(I,J,K).E0.0.) GO TO 77
  DF=ABS((F(I,J,K)-DUMF)/F(I,J,K))
  IF(DF.LE.DGE) GO TO 77
  F(I,J,K)=(F(I,J,K)+DUMF)/2.
  GO TO 76
77 CONTINUE
68 SDT=0.
  DO 78 I=2,MX-1
  DO 78 J=2,MY-1
  DO 78 K=2,MZ-1
  IF(T(I,J,K).E0.0.) GO TO 78
  SDT=SDT+ABS((T(I,J,K)-DUMT(I,J,K))/T(I,J,K))
78 CONTINUE
  SDT=SDT/FLOAT((MX-2)*(MY-2)*(MZ-2))
  IF(SDT.LE.DME) GO TO 85
  DO 79 I=2,MX-1
  DO 79 J=2,MY-1
  DO 79 K=2,MZ-1
79 T(I,J,K)=(T(I,J,K)+DUMT(I,J,K))/2.
  P=0.5*P/2.
  GO TO 72
85 CALL SUB800(SG,OM,T,MX,MY,MZ,MFX,MFY,ALX,ALY,T0G,T0F,OM,CP,W,OSG,
1 OT,TM,OTG,DOT,DSG,DV)
  SDD=0.
  DO 84 I=2,MX-1
  DO 84 J=2,MY-1
  DO 84 K=2,MZ-1
  IF(DUM(I,J,K).E0.0.) GO TO 84
  SDD=SDD+ABS((DUM(I,J,K)-DUMS(I,J,K))/DUM(I,J,K))

```

```

84 CONTINUE
SDD=SDD/FLOAT((MX-2)*(MY-2)*(MZ-2))
IF(SDD.LE.DCE) GO TO 290
IF((QSG+DOT).GE.0.) GO TO 280
DO 83 I=2,MX-1
DO 83 J=2,MY-1
DO 83 K=2,MZ-1
DUM(I,J,K)=DUM(I,J,K)*(0.5-PD/2.)+DUMS(I,J,K)*(0.5+PD/2.)
83 CONTINUE
PM=PM/3.
GO TO 32
280 IF(PD.GT.0.1) GO TO 310
290 IF(ABS((QSG+DOT)/DOT).LE.DCE) GO TO 80
310 DO 303 I=2,MX-1
DO 303 J=2,MY-1
DO 303 K=2,MZ-1
303 DUM(I,J,K)=DUM(I,J,K)*(1.+(QSG+DOT)/DOT/2.)
PD=PD*0.5
GO TO 32
80 IF(DFE.E0.0.) GO TO 89
SDF=0.
DO 82 I=MX1,MX2
DO 82 J=MY1,MY2
DO 82 K=MZ1,MZ2
DUMT(I,J,K)=F(I,J,K)
CALL SFMO(T(I,J,K),R1,R2,F(I,J,K))
IF(F(I,J,K).E0.0.) GO TO 82
SDF=SDF+ABS((F(I,J,K)-DUMT(I,J,K))/F(I,J,K))
82 CONTINUE
SDF=SDF/FLOAT(MFX*MFY*MFZ)
IF(SDF.LE.DFE) GO TO 90
DO 87 I=MX1,MX2
DO 87 J=MY1,MY2
DO 87 K=MZ1,MZ2
F(I,J,K)=(F(I,J,K)+DUMT(I,J,K))/2.
87 BR(I,J,K)=0(I,J,K)*(1.-F(I,J,K))
GO TO 32

507 IS1=IS(I,J,K)
508 AKP1=AKP(I,J,K)
IF(RX.GE.0.) GO TO 510
UNX=(X-DLX*FLOAT(I-1))*AKP1/RX
GO TO 511
510 UNX=(ULX*FLOAT(I)-X)*AKP1/RX
511 IF(RY.GE.0.) GO TO 512
UNY=(Y-DLY*FLOAT(J-1))*AKP1/RX
GO TO 513
512 UNY=(ULY*FLOAT(J)-Y)*AKP1/RX
513 IF(RZ.GE.0.) GO TO 514
URZ=(Z-DLZ*FLOAT(K-1))*AKP1/RZ
GO TO 515
514 URZ=(ULZ*FLOAT(K)-Z)*AKP1/RZ
515 UN=AMIN1(SU,URX,UNY,URZ)
X=X+UR*RX/ACP1
Y=Y+UN*RY/ACP1
Z=Z+UN*RZ/ACP1
IF(UR.E0.UNX) GO TO 520
IF(UR.E0.UNY) GO TO 522
IF(UR.E0.UNZ) GO TO 524
GO TO 530
520 IF(RX.GE.0.) GO TO 521
I=I-1
GO TO 526
521 I=I+1
GO TO 526
522 IF(RY.GE.0.) GO TO 523
J=J-1
GO TO 526
523 J=J+1
GO TO 526
524 IF(RZ.GE.0.) GO TO 525
K=K-1
GO TO 526
525 K=K+1
526 SU=SU-UR
IS1=IS(I,J,K)
IF(IS1.GT.6) GO TO 506

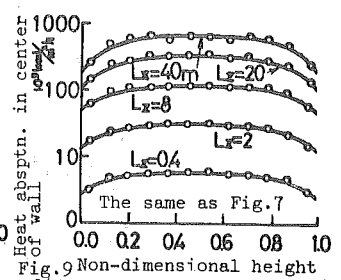
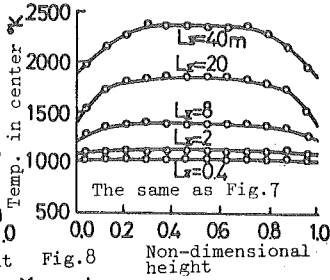
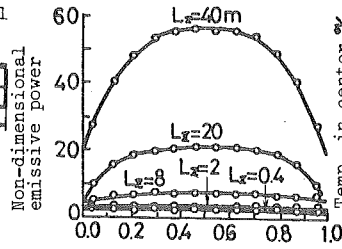
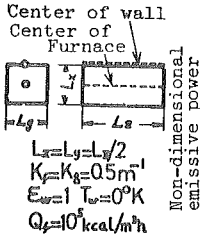
```

```

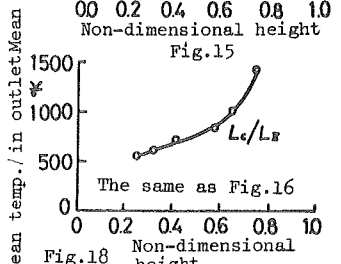
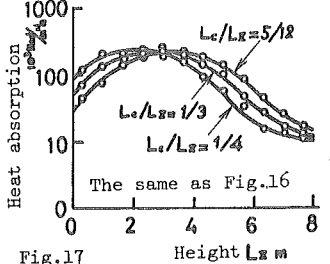
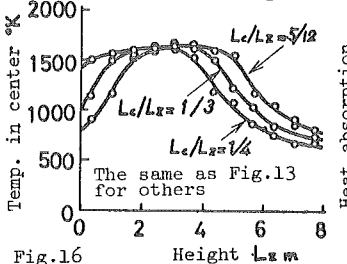
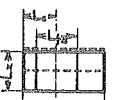
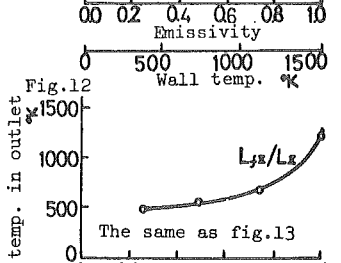
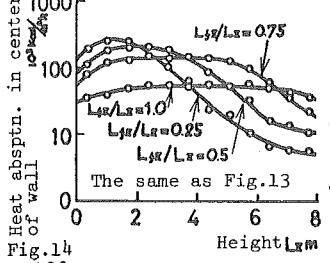
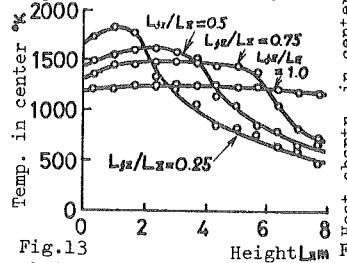
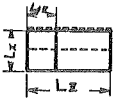
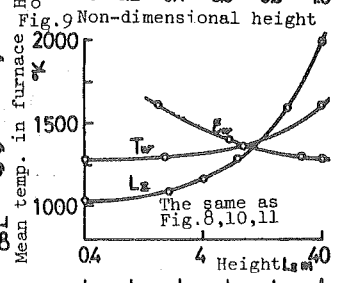
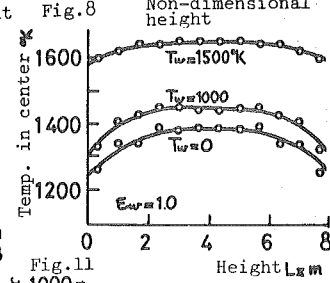
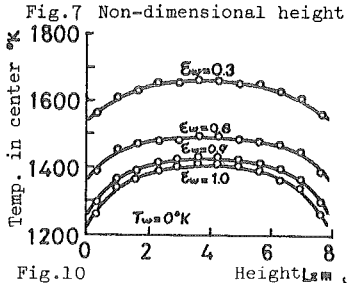
724 IF (IS(I,J,K).EQ.7) GO TO 721
      TQ=TQF
      GO TO 722
721 TQ=TQF
722 DSG(I,J,K)=DSG(I,J,K)+(TQ-T(I,J,K))*CPWZ
      GO TO 730
723 DSG(I,J,K)=DSG(I,J,K)+(T(I,J,K-1)-T(I,J,K))*CPWZ
730 LS4=1
      I1=I-1
731 IF (IS(I1,J,K)=7) 732,733,734
732 PRH=HGX
      DSG(I1,J,K)=DSG(I1,J,K)+(T(I1,J,K)-T(I,J,K))*PRH
      GO TO 735
733 IF (IS(I,J,K).EQ.8) GO TO 734
      PRH=PRGX
      GO TO 735
734 PRH=PRFX
735 DSG(I,J,K)=DSG(I,J,K)+(T(I1,J,K)-T(I,J,K))*PRH
      IF (LS4.EQ.0) GO TO 740
      LS4=0
736 I1=I+1
      GO TO 731
740 LS4=1
      J1=J-1
741 IF (IS(I,J1,K)=7) 742,743,744
742 PRH=HCY
      DSG(I,J1,K)=DSG(I,J1,K)+(T(I,J1,K)-T(I,J,K))*PRH
      GO TO 745
743 IF (IS(I,J,K).EQ.8) GO TO 744
      PRH=PRGY
      GO TO 745
744 PRH=PRFY
745 DSG(I,J,K)=DSG(I,J,K)+(T(I,J1,K)-T(I,J,K))*PRH
      IF (LS4.EQ.0) GO TO 750
      LS4=0
746 J1=J+1
      GO TO 741
750 CONTINUE

```

Fig.6 Main part of program



$L_x = L_y = 4 \text{ m}$
 $L_z = 8 \text{ m}$
 $K_f = K_g = 0.5 \text{ m}^{-1}$
 $Q_f = 10^5 \text{ kcal/m}^2 \text{h}$



size. And, Figs. 10 and 11 show the same item under influence of emissivity and temperature of wall. A level of mean temperature in furnace has tendency, in Fig. 12, to increase with size and wall temperature, but decrease with emissivity.

In order to check the other influences of flame shape, absorption coefficient and region of wave length, calculations are also performed in case of the same furnace which contains flame and gas and has no convection and flow effect. Then, Figs. 13 to 18 show distributions of temperature and heat absorption under influence of shape and position of flame. And, Figs. 19 to 21 show the same item under influence of absorption coefficient and region of wave length.

Next, the authors study influences of convection and flow effect in case of the same furnace which contains flame and gas with convection and flow effect. Then, Fig. 22 shows distribution of temperature under influence of flow effect, and Fig. 23 shows distribution of heat absorption under influence of convection between media and wall. A level of mean temperature in furnace outlet has tendency, in Figs. 24 to 26, to increase with mass flow, but decrease with convection. It is recognized that heat flow in x axis by flow effect gives some considerable influence for this temperature, but heat flow in y and z axis by convection gives smaller influence for it. And, it is recognized that influence of equivalent thermal conductivity can be scarcely found in case of 100 times thermal conductivity.

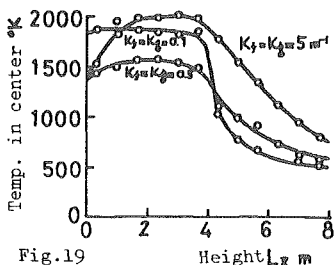
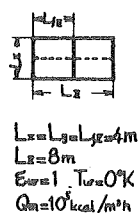


Fig.19

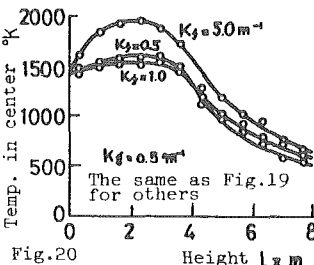


Fig.20

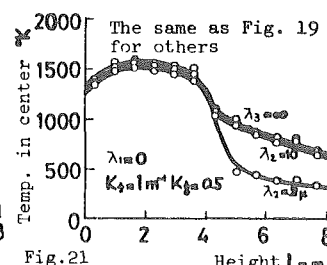


Fig.21

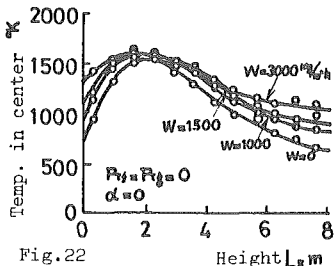
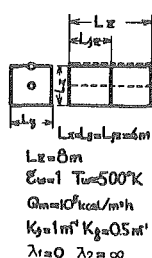


Fig.22

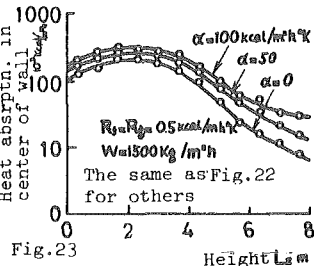


Fig.23

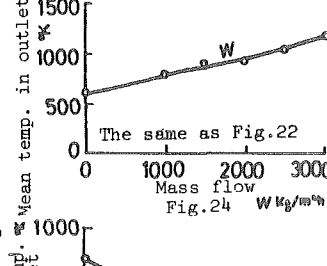


Fig.24

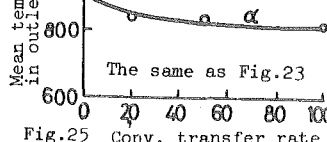


Fig.25

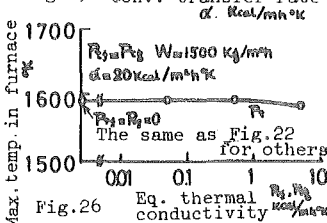


Fig.26

From the above-mentioned studies, it is recognized that some influences of furnace size, emissivity and temperature of wall, flame shape and position are most important factors, influence of flow effect is next factor and the other influences of region of wave length and convection are relatively small. Then, considering combustion condition and outlet temperature in furnace, each influence should be checked by tendency as shown in Figs.12,15,24,25 and 26.

4. CONCLUSIONS

(1) The authors make an attempt to analyze radiative and convective heat transfer in a three dimensional furnace through digital simulating method.

(2) The calculation is conducted by Monte Carlo method for radiation and finite-difference method for convection and flow effect. A program of the above is coded by FORTRAN IV and its main parts are shown in this paper.

(3) Some calculated results are shown in this paper. In view of these results, it is recognized that influences of furnace size, emissivity and temperature of wall, flame shape and position are most important factors, influence of flow effect is next important factor and the other influences of region of wave length and convection are relatively small.

(4) Considering combustion condition and outlet temperature in furnace, each influence may be checked by tendency from calculated results.

(5) As possible to simulate heat transfer in furnace under various conditions, some effects in actual operation would be understood by this study.

ACKNOWLEDGEMENT

The authors appreciate generous instruction given by Professor T. Saito and are indebted to Computer Center in University of Tokyo and Hokkaido University and also indebted to Graduate Student K. Taniguchi for his cooperation.

REFERENCES

- (1) J. R. Howell and M. Perlmuter: Trans. ASME, Ser.C, Vol.86, No.1, Feb., 1964, p.116.
- (2) J. R. Howell: ASME paper, 65-WA/HT-54, Nov., 1965, p.1.
- (3) H. Taniguchi: Trans. Japan Soc. Mech. Engrs., Vol.33, No.247, Mar., 1967, p.406
- (4) H. Taniguchi: ibid., Vol.34, No.261, May, 1968, p.897.
- (5) H. Taniguchi and M. Funazu: ibid., Vol.13, No.66, Dec., 1970, p.1458.
- (6) H. Taniguchi: Library Program of Computer Center, Univ. Of Tokyo (DI/TC/SFMO, F3/TC/SYCO).