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

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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 5020E 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 transfered by radiation, convection and flow effect. Various temperatures and emissivities are employed for each wall. An emissive power is defined by

$$\left.\begin{array}{ll} E_f=(1-e^{-K_f \ell})\sigma T^4 & \text{for flame} \\ E_g=(1-e^{-K_g \ell})\sigma T^4 F(T) & \text{for gas} \\ E_w=\varepsilon_w \sigma T^4 & \text{for wall} \end{array}\right\} \quad (1)$$

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

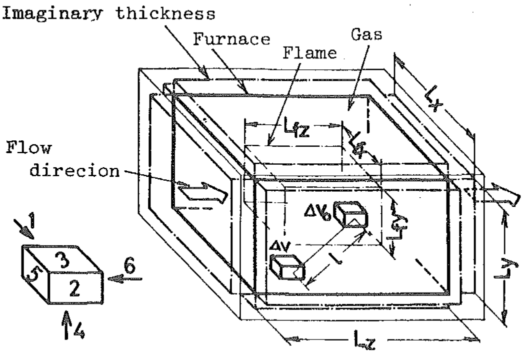


Fig.1

σ : Stefan-Boltzmann's constant

$$F(T)=\frac{C_1\int_{\lambda_1}^{\lambda_2}\frac{d\lambda}{\lambda^5\{\exp(C_2/\lambda T)-1\}}}{\sigma T^4}\doteqdot\exp\{\sum A_i(\log_e\lambda_2 T)^i$$

$$-\sum A_i(\log_e\lambda_1 T)^i\}$$: correction factor

for region of wave length λ_1 to λ_2[3]

The following Eq. is obtained for small volume ΔV_0 in Fig.1.

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

where H_e : emissive power H_q : heat generation

H_r : heat transfered by radiation

H_c : heat transfered by convection and flow effect

Then, the following Eq. is obtained for ΔV_w .

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

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[(8)~(5)] 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 rflected 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

$$J=C_f Q_f F(T)/N+C_f Q_f\{1-F(T)\}/N \qquad (4)$$

where N : number of bundles

Q_f : heat generating rate

$C_f=(H_q+H_r+H_c)/(H_q+H_r)$: 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

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

Transforming the above to normal coordinates

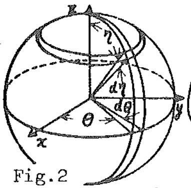


Fig.2
Flame or Gas

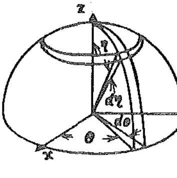


Fig.3
Wall

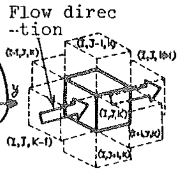


Fig.4

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

where R_x, R_y, R_z : emitting probability in each axis

Then, an intensity J of bundle from ΔV_w is obtained by

$$J=\varepsilon_w\sigma T_w^4 F(T)\Delta A_w/N+\varepsilon_w\sigma T_w^4\{1-F(T)\}\Delta A_w/N \qquad (7)$$

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

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

Transforming the above

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

An absorbing probability R_l is applied for bundle absorbed at distance

$$R_l=1-e^{-\sum K_i\Delta l},\ U=\sum K_i\Delta l=-\log_e(1-R_l) \qquad (10)$$

where K_i : K_f or K_g U : optical thickness

When the bundle reaches boundary of imaginary thickness, a passing probability R_ε is obtained by

$$R_\varepsilon=\varepsilon_w \qquad (11)$$

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

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

Thus, in order to simulate the heat transfer, a passage of energy bundle should be determined by the following procedure. At first, C_f 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_0 is obtained by

$$C_f H_r=\sum\sum\sum\{C_f Q_f R_{ff} F(T)\Delta V+C_f Q_f R_{ffr}\{1-F(T)\}\Delta V\}$$
$$+\sum\sum\{\varepsilon_w\sigma T_w^4 R_{wf} F(T)\Delta A_w+\varepsilon_w\sigma T_w^4 R_{wfr}\{1-F(T)\}\Delta A_w\}$$

for flame (13a)

$$C_fH_r=\sum\sum\sum C_fQ_fR_{fg}F(T)\Delta V+\sum\sum\varepsilon_w\sigma T_w^4R_{wg}F(T)\Delta A_w$$

for gas (13b)

$$H_r=\sum\sum\sum\left[C_fQ_fR_{fw}F(T)\Delta V+C_fQR_{fwr}\{1-F(T)\}\Delta V\right]$$
$$+\sum\sum\left[\varepsilon_w\sigma T_w^4R_{ww}F(T)\Delta V+\varepsilon_w\sigma T_w^4R_{wwr}\{1-F(T)\}\Delta V\right]$$

for wall (14)

where R_{ff}, R_{fg}, R_{fw}, R_{wf}, R_{wg}, R_{ww} : absorbing probability for region of wave length λ_1 to λ_2. R_{ffr}, R_{wfr}, R_{fwr}, R_{wwr}: absorbing probability for region exept λ_1 to λ_2

An equivalent heat generation of ΔV_0 in Fig.1 is obtained by

$C_fH_q=C_fQ_f\Delta V_0$ for flame, $C_fH_q=0$ for gas (15)

$H_w=\varepsilon_w\sigma T_w^4\Delta A_w$ 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.

$$H_c=P_{tf}\left(\frac{T_{i-1,j,k}-T_{i,j,k}}{\Delta L_x}\Delta L_y\Delta L_z+\frac{T_{i+1,j,k}-T_{i,j,k}}{\Delta L_x}\Delta L_y\Delta L_z\right.$$
$$\left.+\frac{T_{i,j-1,k}-T_{i,j,k}}{\Delta L_y}\Delta L_x\Delta L_z+\frac{T_{i,j+1,k}-T_{i,j,k}}{\Delta L_y}\Delta L_x\Delta L_y\right)$$
$$+WC_p\frac{T_{i,j,k-1}-T_{i,j,k}}{\Delta L_z}\Delta V$$

for flame (17a)

$$H_c=P_{tg}\left(\frac{T_{i-1,j,k}-T_{i,j,k}}{\Delta L_x}\Delta L_y\Delta L_z+\frac{T_{i+1,j,k}-T_{i,j,k}}{\Delta L_x}\Delta L_y\Delta L_z\right.$$
$$\left.+\frac{T_{i,j-1,k}-T_{i,j,k}}{\Delta L_y}\Delta L_x\Delta L_z+\frac{T_{i,j+1,k}-T_{i,j,k}}{\Delta L_y}\Delta L_x\Delta L_y\right)$$
$$+WC_p\frac{T_{i,j,k-1}-T_{i,j,k}}{\Delta L_z}\Delta V$$

for gas (17b)

$H_c=\alpha\Delta T\Delta A_w$ for wall (18)

where P_{tf}, 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_f is decided by the above value.

Then, a total emissive power of ΔV_0 is defined by

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

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

$Q_m=\dfrac{\sum\sum\sum Q_f\Delta V+\sum\sum\varepsilon_w\sigma T^4\Delta A_w}{V_t}$: mean heat generating rate

$V_t=\sum\sum\sum\Delta V+\sum\sum\Delta A_w\Delta L$: imaginary total volume

An addition of Eqs.(13) and (15) makes

$C_fH_r+C_fH_q=\dfrac{H_q+H_r+H_c}{H_q+H_r}(H_q+H_r)=H_e$ equal to (2)

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

$H_w-(H_r+H_c)=H_a$ 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_f 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(5),(6) (generation of random number, direction of energy bundle, absorbing length for region of R1 to R2, absorbing length except R1 to R2, 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) MFX,MFY,MFZ : number of meshes of flame
MZ1,MZ0 : position of flame and air intake
(3) AKF,AKG : absorption coefficient m^{-1}
R1, R2 : wave length μ
(4) ALX,ALY,ALZ : furnace dimension m
QF : heat generating rate in flame Kcal/m^3h
(5) CP : specific heat Kcal/Kg °K
W : mass velocity Kg/m^2h
PRF,PRG : equivalent thermal conductivity kcal/mh°K
HC, H0 : convective heat transfer rate Kcal/m^2h°K
(6) E1~E6 : emissivity of wall
T1~T6 : temperature of wall °K
TOF,TOG : temperature of air and recirculating gas °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

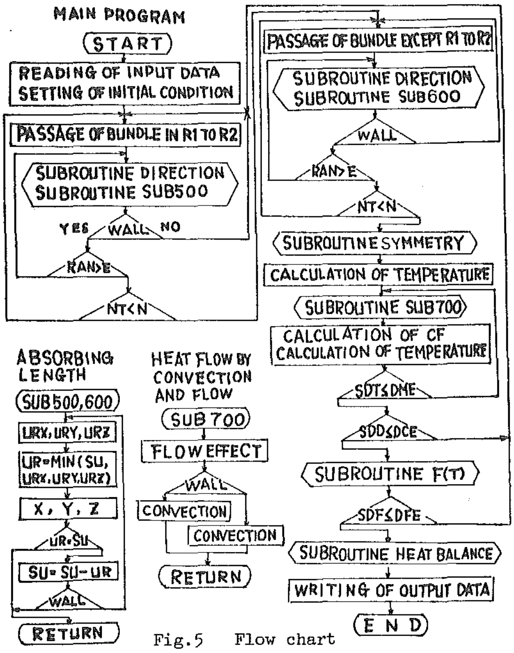


Fig.5 Flow chart

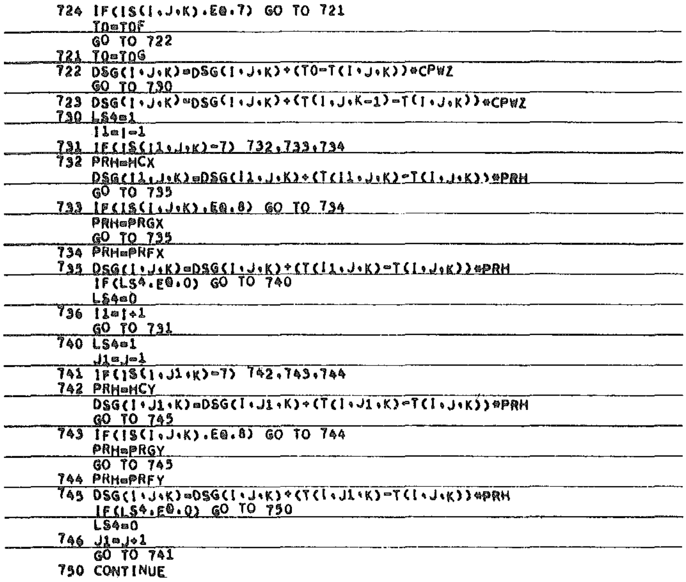
```
 34 DO 60 IT=1,MX
    DO 60 JT=1,MY
    DO 60 KT=1,MZ
    NT=0
 40 I=IT
    J=JT
    K=KT
    SQ=(Q(I,J,K)-QR(I,J,K))*DUM(I,J,K)
    IF(SQ.EQ.0.) GO TO 60
    NT=NT+1
    X=DLX*(FLOAT(I)-0.5)
    Y=DLY*(FLOAT(J)-0.5)
    Z=DLZ*(FLOAT(K)-0.5)
    IS1=IS(I,J,K)
 41 SG(I,J,K)=SG(I,J,K)+SQ
    CALL SUB900(NRAN,RAN)
    SU=-ALOG(RAN)
 42 CALL SUB400(NRAN,PAI,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
    SQ=SQ*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)-SQ
    IF(NT.LT.N) GO TO 40
 44 NT=0
 50 I=IT
    J=JT
    K=KT
    SQR=QR(I,J,K)*DUM(I,J,K)
    IF(SQR.EQ.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)+SQR
    CALL SUB900(NRAN,RAN)
    AL=-ALOG(RAN)/AKF
 52 CALL SUB400(NRAN,PAI,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
 55 SQR=SQR*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)-SQR
    IF(NT.LT.N ) GO TO 50
 54 NTT=NTT+N
```

```
   60 CONTINUE
C     FINAL POINT OF INNER LOOP OF CALCULATION
   57 AN=N
      IF(IXY.EQ.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.EQ.0.) GO TO 63
      IF(IS(I,J,K).EQ.7) GO TO 64
   63 T(I,J,K)=(SG(I,J,K)*QM/(4.*AKP(I,J,K)*S))**0.25
      GO TO 70
   64 IF(F(I,J,K).EQ.0.) GO TO 70
   62 T(I,J,K)=(SG(I,J,K)*QM/(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).EQ.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.EQ.0) GO TO 71
      LS1=0
      GO TO 90
   71 IF(DME.EQ.0.) GO TO 80
      P=0.5
   72 CALL SUB700(P,T,IS,MX,MY,MZ,MZO,DLX,DLY,DLZ,TOG,TOF,QM,CP,W,
     1           PRG,PRF,PRO,HC,HO,DSG)
      DO 77 I=2,MX-1
      DO 77 J=2,MY-1
      DO 77 K=2,MZ-1
      IF(SG(I,J,K).EQ.0.) GO TO 59
      IF((SG(I,J,K)-DSG(I,J,K)).EQ.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-MZO) 77,65,67
   65 IF(IS(I,J,K).EQ.7) GO TO 66
      T(I,J,K)=(T(I,J,K)+TOF)/2.
      GO TO 77
   66 T(I,J,K)=(T(I,J,K)+TOG)/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.EQ.0.) GO TO 75
      IF(IS(I,J,K).EQ.7) GO TO 74
   75 T(I,J,K)=(SG(I,J,K)*DUM(I,J,K)/DUMS(I,J,K)*QM/(4.*AKP(I,J,K)*S))
     1          **0.25
      GO TO 77
   74 IF(F(I,J,K).EQ.0.) GO TO 77
   76 T(I,J,K)=(SG(I,J,K)*DUM(I,J,K)/DUMS(I,J,K)*QM/(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).EQ.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).EQ.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,Q,T,MX,MY,MZ,MFX,MFY,ALX,ALY,TOG,TOF,QM,CP,W,QSG,
     1           QT,TM,QTG,DQT,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).EQ.0.) GO TO 84
      SDD=SDD+ABS((DUM(I,J,K)-DUMS(I,J,K))/DUM(I,J,K))
```

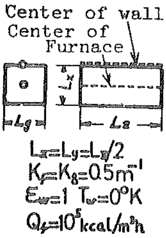
```
 84 CONTINUE
    SDD=SDD/FLOAT((MX-2)*(MY-2)*(MZ-2))
    IF(SDD.LE.DCE) GO TO 290
    IF((QSG+DQT).GE.0.) GO TO 280
    DO 83 I=2,MX-1
    DO 83 J=2,MY-1
    DO 83 K=2,MZ-1
    DUM(I,J,K)=DUM(I,J,K)*(0.5-PD/2.)+DUMS(I,J,K)*(0.5+PD/2.)
 83 CONTINUE
    PM=PM/3.
    GO TO 32
280 IF(PD.GT.0.1) GO TO 310
290 IF(ABS((QSG+DQT)/DQT).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+DQT)/DQT/2.)
    PD=PD*0.5
    GO TO 32
 80 IF(DFE.EQ.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).EQ.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 QR(I,J,K)=Q(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
    URX=-(X-DLX*FLOAT(I-1))*AKP1/RX
    GO TO 511
510 URX=(DLX*FLOAT(I)-X)*AKP1/RX
511 IF(RY.GE.0.) GO TO 512
    URY=-(Y-DLY*FLOAT(J-1))*AKP1/RY
    GO TO 513
512 URY=(DLY*FLOAT(J)-Y)*AKP1/RY
513 IF(RZ.GE.0.) GO TO 514
    URZ=-(Z-DLZ*FLOAT(K-1))*AKP1/RZ
    GO TO 515
514 URZ=(DLZ*FLOAT(K)-Z)*AKP1/RZ
515 UR=AMIN1(SU,URX,URY,URZ)
    X=X+UR*RX/AKP1
    Y=Y+UR*RY/AKP1
    Z=Z+UR*RZ/AKP1
    IF(UR.EQ.URX) GO TO 520
    IF(UR.EQ.URY) GO TO 522
    IF(UR.EQ.URZ) 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
    TO=TOF
    GO TO 722
721 TO=TOG
722 DSG(I,J,K)=DSG(I,J,K)+(TO-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=HCX
    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



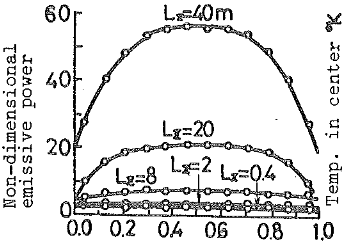


Fig.7 Non-dimensional height

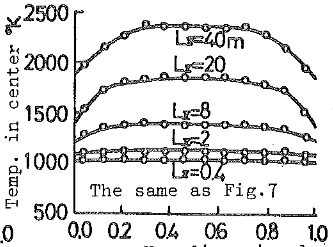


Fig.8 Non-dimensional height

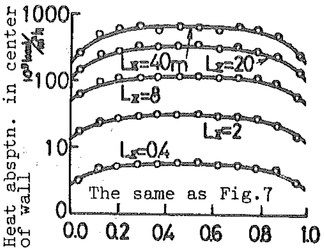


Fig.9 Non-dimensional height

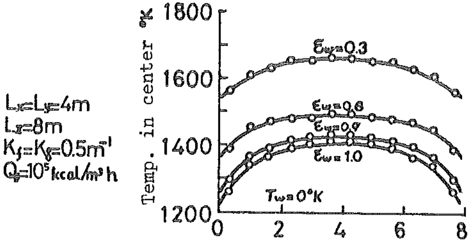


Fig.10 Height L_z m

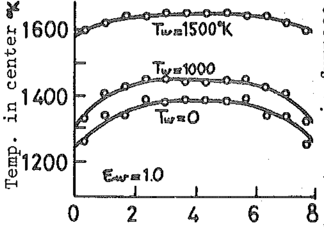


Fig.11 Height L_z m

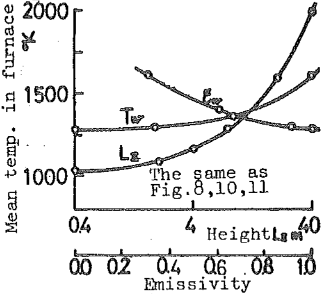
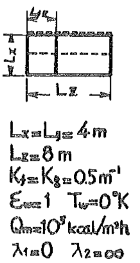


Fig.12



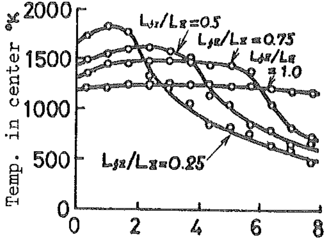


Fig.13 Height L_z m

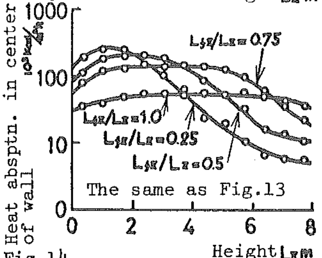


Fig.14 Height L_z m

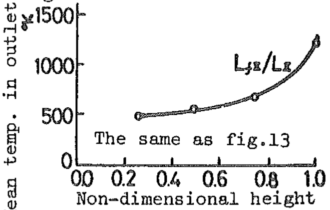
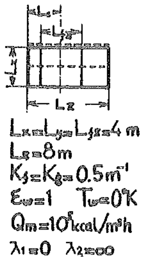


Fig.15



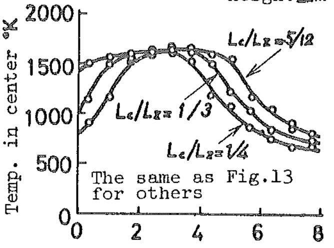


Fig.16 Height L_z m

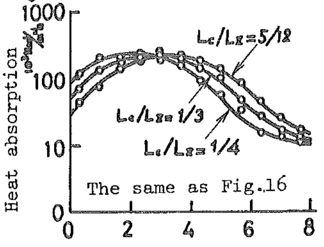


Fig.17 Height L_z m

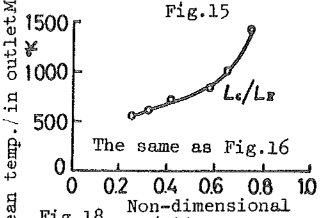


Fig.18 Non-dimensional height

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 z axis by flow effect gives some considerable influence for this temperature, but heat flow in x and y 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.

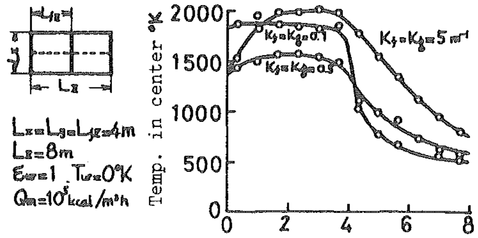


Fig.19

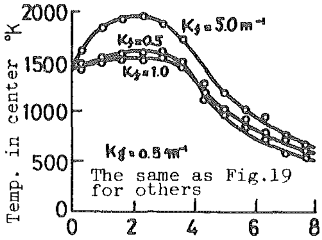


Fig.20

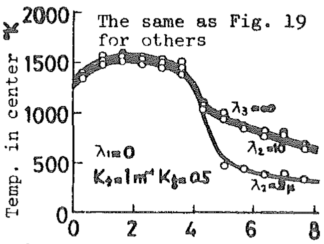


Fig.21

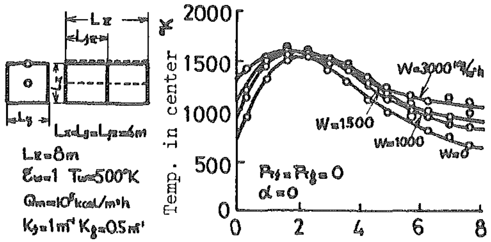


Fig.22

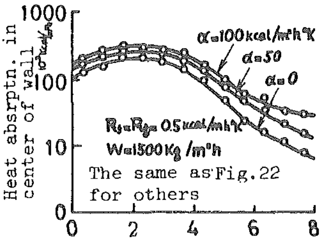


Fig.23

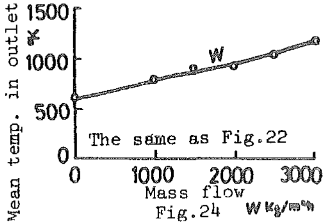


Fig.24

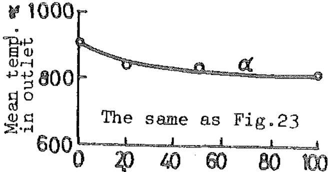


Fig.25

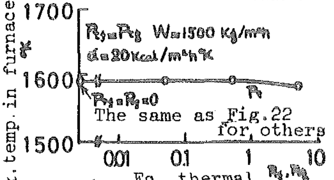


Fig.26

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.

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