408 Transaction of the Korean Society of Mechanical Engineers, Vol. 10, No. 3, pp. 408~418, 1986.

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Prediction of Temperature Distribution for Heat Treatment of 2.5% C-15% Cr Sleeve Casting Roll for Coke Briquette

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(Received February 21, 1986)

2.5% C-15% Cr 성형탄 슬리이브 캐스팅로울의 열처리에 대한 온도 분포예측

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Key Words: Heat Treatment(열처리), Unsteady Conductive Heat Transfer(비정상 전도 열전달), Gas Radiative Heat Transfer(기체 복사 열전달), Finite Difference Method(유한 차분법), Zone Method(Zone 방법)

초 록

표면은 단단하고 내면은 강인한 조직을 얻기위하여 대형 성형탄 로울에 대하여 노에서의 급속가열 및 대기 상태에서의 자연냉각의 열처리가 수행되어진다. 급속가열 및 냉각시 성형탄 로울 내부의 온도 분포 예측을 위하여 대류 및 복사 열전달 경계조건을 가지는 1차원 비정상 열전도 방정식이 유한 차분법을 사용하여 해석되어졌다. 여기서 급속가열시 연소가스로 부터 기체복사에 의하여 성형탄 로울의 바깥표면을 통하여 흡수되는 열량은 "Zone 방법"을 사용하여 구하였으며 화염의 총괄복사율이나 흡수율은 "F_E Operator"를 사용하여 회색기체들의 가중치 합으로 나타내었다. "F_E Operator" 값으로써 1.3을 사용하여 급속가열 및 자연냉각의 열처리에 대하여 수행한 계산결과는 실지크기에 대하여 수행된 측정치를 아주 잘 나타내어 주었다.

Nomenclature

a_i', a_i : Weighting factor, dimensionless
A_i, B_i, C_i, D_i : Coefficients of finite difference equation
C : Specific heat, Ws/m °K
F_E : F_E Operator
GS : Direct gas to surface exchange area
$\overline{GS}$: Total gas to surface exchange area
h : Heat transfer coefficient, W/m^2 °K
k : Thermal conductivity, W/m °K
K_i : Absorption coefficient ft^{-1} or m^{-1}
L : Pathlength, ft or m
Nu : Nusselt number, dimensionless
r : Radius, m
R : Radius, dimensionless
SS : Direct surface to surface exchange area
$\overline{SS}$: Total surface to surface exchange area
t : Time, sec
T : Temperature, °K
θ : Temperature, dimensionless
τ : Time, dimensionless
ρ : Density, kg/m^3
ε : Total emissivity, dimensionless
$\mathscr{L}$: Total absorptivity, dimensionless

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σ : Stefan Boltzmann constant, 1.798×10^{-8} W/m^2 K^4

Subscript

1 : Outer surface of supporting shaft
2 : Inner surface of sleeve roll for coke briquette
3 : Outer surface of sleeve roll for coke briquette
avg : Average
c : Convective heat transfer
cond : Conduction
conv : Convection
$c+w$: CO_2—H_2O gas mixture
in : Initial temperature
ref : Reference temperature
r : Radiative heat transfer
t : CO_2—H_2O-transient species-soot gas mixture

1. Introduction

A wear mechanism of the outer surface of sleeve roll coke briquette is occurred by a combined abrasion wear of both sliding and rolling friction. To improve this kind of abrasion wear resistance, it is required to have a hard outer layer in the surface with fine and uniform distribution of carbide (M_7C_3) under the base structure of martensite, and a tough pearlite tissue in the sublayer of the sleeve roll to resist a shock(1).

These different properties in the outer and inner layers of the roll could be obtained by differential heat treatment with a rapid heating in the surface since the hard or tough properties of the material are dependent on a heating and cooling rate. Therefore, it is very important to predict the temperature distribution in the sleeve roll during heating and cooling to satisfy the required specification. An assembly for the production of the sleeve roll is heated rapidly in the furnace to raise only the temperature of outer surface layer, and then, this assembly is cooled down at the atmosphere without air blowing to prevent cracking due to the thermal stress. In addition, the sleeve roll is rotated slowly to achieve uniform properties through the roll circumference during both heating and cooling.

The combined heat transfer problem of gas radiation and heat conduction in the sleeve roll is solved by the numerical integration of finite difference method. The net heat flux to be absorbed through the outer surface of the roll from the combustion gas in the furnace is calculated by utilizing the "Zone Method" where the total emissivity and absorptivity is expressed with the weighted sum of gray gases. Here, F_E Operator is used to represent the radiation characteristics of real combustion gas. The calculated results were compared with the experimental data obtained from the heat treatment of the prototype. In both cases of heating and cooling, the predicted results showed a good agreement with the measured data. The convection effect of rotating speed of the roll on cooling rate was also examined.

Using these results, we can establish the optimal heat treatment condition of real large diameter roll which will be manufactured(2~5).

2. Experimental Procedure

A series of procedure given in Fig. 1 was taken as an intended heat treatment cycle for the rapid heating in furnace and air cooling in the atmosphere. The temperature in Fig. 1 represents the temperature value in the targeted

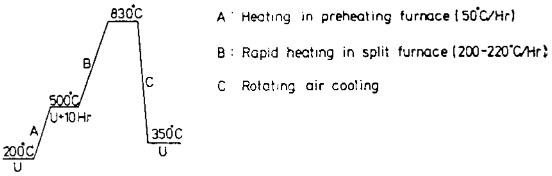


Fig. 1 Differential heat treatment operational cycle

Table 1 Chemical composition of supporting shaft and sleeve roll

Comp.	C	Si	Mn	P	S	Cr	Ni	Mo	Al	Cu
Sleeve	2.47	0.54	0.89	0.023	0.012	14.8	1.22	0.73	—	—
Shaft	0.32	0.24	0.80	0.011	0.012	1.76	0.82	0.21	0.004	0.22

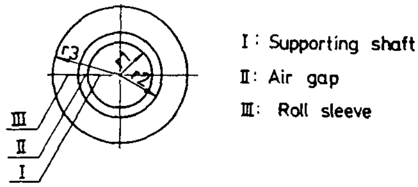
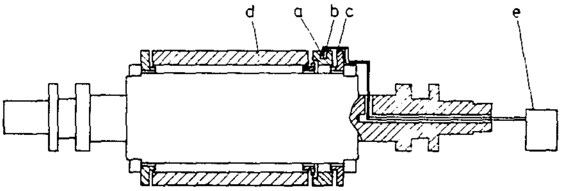
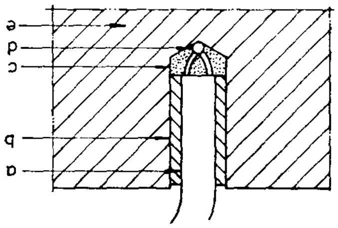


Fig. 2 A cross section of assembly for heat treatment of sleeve roll for coke briquette



a: hot junction b: thermocouple metal Ⅰ(chromel)
c: thermocouple metal Ⅱ(alumel) d: roll body
e: indicator

Fig. 3 An outline diagram of temperature measurement equipment in roll



a : Thermocouple protecting tube
b : Fireproof mortar or fiber
c : Copper powder
d : Junction
e : Body

Fig. 4 A measurement point of temperature in roll

surface hardness depth (in the present case, about 60 mm).

An assembly for the production of roll for coke briquette is shown in Fig. 2, where a chemical composition for an inner supporting shaft and an outer sleeve roll is listed in Table 1 and an air gap fills between them. In Fig. 2, $r1(=0.4035\,\mathrm{m})$, $r2(=0.447\,\mathrm{m})$ and $r3(=0.603\,\mathrm{m})$ are radius of the supporting shaft, the inner and outer radius of the sleeve roll respectively. The more detailed explanation for this assembly is given in ref. (2).

A measurement of temperature distribution of roll was performed by constructing the equipment shown in Fig. 3 using the ring and brush. Here, a chromel-alumel sheathed thermocouple was used for the high temperature part in the furnace. As shown in Fig. 4, copper powder was filled for the good contact between a measuring point and the hot junction of thermocouple. The temperature of combustion gas by firing the municipal propane gas was controlled in the main control box connected with the split furnace.

According to the heat treatment condition in Fig. 1, an assembly in Fig. 2 is heated rapidly in furnace and, then, if the temperature of the outer surface of sleeve roll reaches the required value (in the present case, about 910°C), this assembly is taken out from the furnace and cooled down at the atmosphere; and this assembly is rotated with very slow speed for the purpose of maintaining the uniform circumferential temperature in both cases of rapid heating and cooling.

3. Prediction of Temperature for Rapid Heating and Cooling

To predict the temperature distribution for this assembly, the 1 dimensional unsteady heat conduction equation was solved by using the finite difference method based on the control volume and the simulation results were compared with the experimental ones performed for the real sleeve roll.

3.1 Governing Equation and Non-Dimensionalization

1-dimensional unsteady heat conduction equation for the infinitely long cylinder in which the thermal property varies according to the temperature takes the following form;

$$\rho(T)C(T)\partial T/\partial t=(1/r)(\partial/\partial r)[rk(T)(\partial T/\partial r)] \qquad (1)$$

where $\rho(T)$, $C(T)$ and $k(T)$ represent respectively a density, specific heat and thermal conductivity as a function of temperature.

The values of thermal conductivity k and specific heat C of supporting shaft and sleeve roll having the chemical composition shown in Table 1 used the following temperature polynomial expression obtained by the linear regression method for the data in ref. (6) and (7). The polynomial expression of thermal conductivity and specific heat for the supporting shaft becomes

$$k=15.8581+0.817327\times10^{-1}T-0.162445\times10^{-3}T^2+0.858248\times10^{-7}T^3 \qquad (2)$$

$$C=96.1065+1.02906\,T \qquad (2\text{-}1)$$

Similarly, the polynomial expression for sleeve roll is

$$k=22.3933+0.109955\times10^{-1}T-0.8116337\times10^{-5}T^2+0.192662\times10^{-8}T^3 \qquad (3)$$

$$C=7104.77-33.3131\,T-0.58904\times10^{-1}T^2-0.42721\times10^{-4}T^3+0.108901\times10^{-7}T^4 \qquad (3\text{-}1)$$

And, the expression for density used the following one for both shaft and roll.

$$\rho=7710/[1.+16.7\times10^{-6}(T-298)]^3 \quad \text{at } 298\,K\leq T\leq 973\,K \qquad (4)$$

$$\rho=8070/[1.+16.2\times10^{-6}(T-1093)]^3 \quad \text{at } T\geq 1093\,K \qquad (4\text{-}1)$$

Here, 16.7×10^{-6} and 16.2×10^{-6} represent respectively linear thermal expansion coefficient at the specified temperature range and are the measured values using a dilatometer in KHIC. As a temperature exists between 973°K and 1093°K, the linear thermal expansion coefficient can't be exactly measured due to the phase transformation and the medium value is used for density(2,3).

We choose the nondimensional variables as follows;

$$R=r/r_3$$

$$\theta=(T-T_\infty)/(T_{in}-T_\infty) \qquad (5)$$

$$\tau=\mathscr{L}_0 t/(r_3)^2$$

where

$$\mathscr{L}_0=k(T_{in})/\rho(T_{in})C(T_{in}) \qquad (5\text{-}1)$$

Here, T_{in} is an initial temperature of roll; and T_∞ represents an ambient temperature at the atmosphere. Then, the 1 dimensional dimensionless unsteady heat conduction equation becomes

$$\mathscr{L}_0\rho(T)C(T)\partial\theta/\partial\tau=(1/R)(\partial/\partial R)[Rk(T)(\partial\theta/\partial R)] \qquad (6)$$

3.2 Initial and Boundary Condition

(1) Initial condition

For $0\leq r\leq r_3$,

$$T(0,r)=f(r) \qquad (7)$$

where $f(r)$ represents the temperature profile in the assembly of Fig. 2 at the initial simulation time; and as an initial condition was used the uniform preheating temperature (in the present case, the measured value is about 450°C) before heating rapidly in the split furnace.

(2) Boundary condition

(i) Inner shaft ($0\leq r\leq r_1$)

From the symmetry condition, at $r=0$

$$\partial T/\partial r=0 \tag{8}$$

At $r=r_1$,

$$-k\partial T/\partial r=h_{c1}(T_1-T_{avg})+h_{r1}(T_1-T_2) \tag{9}$$

where

$$T_{avg}=(T_1+T_2)/2 \tag{9-1}$$

In equation (9), h_{c1} represents a heat transfer coefficient for the natural convection of air gap between an inner shaft and outer sleeve roll and the following value from Goldstein and Kuehn was used(8).

$$h_{c1}=(k_{air}/2r_1)[(Nu_{cond})^{15}+(Nu_{conv})^{15}]^{1/15} \tag{9-2}$$

where, k_{air} means the thermal conductivity of air gap.

And h_{r1} represents a heat transfer coefficient due to the radiative heat transfer between an outer surface of inner shaft and an inner one of outer roll.

$$h_{r1}=\frac{\sigma(T_1^3+T_1^2T_2+T_1T_2^2+T_2^3)}{1/\varepsilon_1+(r_1/r_2)(1/\varepsilon_2-1)} \tag{9-3}$$

where ε_1 and ε_2 represent respectively the emissivity of outer surface of shaft and inner one of sleeve roll; T_1 and T_2 represent respectively the dimensional temperature of outer surface of shaft and of inner one of roll.

(ii) Outer roll for coke briquette ($r_2 \leq r \leq r_3$)

Like the outer surface of steel shaft,

at $r=r_2$

$$-k\partial T/\partial r=h_{c2}(T_2-T_{avg})+h_{r2}(T_2-T_1) \tag{10}$$

where

$$h_{c2}=(k_{air}/2r_2)[(Nu_{cond})^{15}+(Nu_{conv})^{15}]^{1/15} \tag{10-1}$$

$$h_{r2}=\frac{\sigma(T_2^3+T_2^2T_1+T_2T_1^2+T_1^3)}{1/\varepsilon_1+(r_1/r_2)(1/\varepsilon_2-1)} \tag{10-2}$$

The boundary condition of the outer surface of roll surface ($r=r_3$) can be expressed as follows;

$$-k\partial T/\partial r=h_{c3}(T_3-T_{ref})+h_{r3}(T_3-T_{ref}) \tag{11}$$

Here, T_3 is the temperature of outer surface of sleeve roll; T_{ref} is the temperature of combustion gas in rapid heating and of ambient atmosphere in cooling. In rapid heating, because the effect of convective heat transfer was very small compared to the radiative one, the first term of equation (11) was neglected in rapid heating; and the evaluation of the radiative heat transfer, h_{r3} of equation (11), in the furnace will be explained in details in section 3.3. After taking out the sleeve roll from the heating furnace, the sleeve is cooled down at atmosphere without air blowing. During cooling process, it is considered that there exists radiative heat transfer between hot surface of the roll and surrounding room temperature and convective heat transfer due to the rotation of the sleeve roll and the movement of heated surrounding air. Therefore, the following expression of h_{c3} and h_{r3} in cooling are used in this study;

$$h_{c3}=0.095(0.5\,Re^2+Gr)^{0.35}\,r_3/k_f \tag{12}$$

where

$$Re=2\,w(r_3)/\nu \tag{12-1}$$

$$Gr=g\beta(T_3-T_{ref})(2\,r_3)^3/\nu^2 \tag{12-2}$$

and,

$$h_{r3}=\varepsilon_3\sigma(T_3^3+T_3^2T_{ref}+T_3T^2_{ref}+T^3_{ref}) \tag{13}$$

Equation (12) is the correlation by Carmi(9); Re and Gr represent respectively the Reynolds and Grashopf number calculated at the film temperature; w is the angular velocity of sleeve roll; ε_3 and T_3 of equation (13) represent respectively the total emissivity and the temperature of the outer surface of sleeve roll.

3.3 Calculation of Radiative Heat Transfer Coefficient h_{r3} in Heating Furnace

The radiative heat transfer coefficient h_{r3} of equation (11) in heating in furnace is expressed as follows;

$$-k\partial T/\partial r=h_{r3}(T_3-T_{ref})=Q_3/A_3 \tag{14}$$

where, A_3 is a surface area of sleeve roll; Q_3 represents the net heat flux to be absorbed through the outer surface of sleeve roll. Using zone method[10], Q_3 can be expressed as follows;

$$Q_3=\sum_{u,i} a_i'(T_u)(\overline{G_uS_3})_i\sigma T_u^4 + \sum_{r,i} a_i(T_r)(\overline{S_rS_3})_i\sigma T_r^4 - A_3\varepsilon_3\sigma T_3^4 \qquad (15)$$

where

$(\overline{G_uS_3})_i$: The total exchange area between a gas volume u and a surface zone 3 for a gray gas i

$(\overline{S_rS_3})_i$: The total exchange area between a surface zone r and a surface zone 3 for a gray gas i

a_i' : Weighting factor for various gray gases contributing to the emissivity of real gas

a_i : Weighting factor for various gray gases contributing to the absorptivity of real gas

To calculate Q_3 using the zone method of equation (15), the following items should be determined first;

(i) Calculation of absorption coefficients and weighting factors to represent the total emissivity and absorptivity of real combustion gas.

(ii) Calculation of total exchange area.

(1) Calculation of absorption coefficients and weighting factors

If the fossil fuel is combusted and ideally converted to CO_2 and H_2O gas mixture, the total emissivity ε_{c+w} and absorptivity $\mathscr{L}_{c+w}$ for the CO_2—H_2O gas mixture can be expressed with the weighted sum of gray gases as follows;[11]

$$\varepsilon_{c+w}(T_g)=\sum_{i=1}^{M}(a_i')_{c+w}(1-e^{-K_iL}) \qquad (16)$$

where

$$(a_i')_{c+w}=\sum_{k=1}^{N}(b_{ik}')_{c+w}T^{k-1}_g \qquad (16\text{-}1)$$

and.

$$\mathscr{L}_{c+w}(T_s)=\sum_{i=1}^{M}(a_i)_{c+w}(1-e^{-K_iL}) \qquad (17)$$

where

$$(a_i)_{c+w}=\sum_{k=1}^{N}(b_{ik})_{c+w}T^{k-1}_s \qquad (17\text{-}1)$$

K_i in equation (16) and (17) means the absorption coefficient; $(a_i')_{c+w}$ and $(a_i)_{c+w}$ represent the weighting factor corresponding to the absorption coefficient K_i for CO_2—H_2O gas mixture; M and N represent respectively the total number of gray gases and maximum polynomial degree to show the functional relationship with temperature; T_g and T_s are respectively the temperature of combustion gas and of surface surrounding the combustion gas.

However, to calculate the total emissivity of real combustion gas to be produced in furnace or combustor, the contribution of transient species and soot in addition to the CO_2—H_2O gas mixture should be considered.

The total emissivity $\varepsilon_t(T_g)$ and absorptivity $\mathscr{L}_t(T_s)$ of CO_2—H_2O-transient species-soot gas mixture can be expressed as follows using "F_E Operator" which implies the influence of transient species and soot;[11,12]

$$\varepsilon_t(T_g)=[F_E-1+\varepsilon_{c+w}(T_g)]/F_E \qquad (18)$$

$$\mathscr{L}_t(T_s)=[F_E-1+\mathscr{L}_{c+w}(T_s)]/F_E \qquad (19)$$

Using equations (18), (19) and the procedure explained in ref. (11), the total emissivity $\varepsilon_t(T_g)$ and absorptivity $\mathscr{L}_t(T_s)$ of CO_2—H_2O-transient species-soot gas mixtures can be expressed with the weighted sum of gray gases as follows;

$$\varepsilon_t(T_g)=\sum_{i=1}^{M+1}(a_i')_t(1-e^{-K_iL}) \qquad (20)$$

where

$$(a_i')_t=\sum_{k=1}^{N}(b_{ik}')_tT^{k-1}_g \qquad (20\text{-}1)$$

and,

$$\mathscr{L}_t(T_s)=\sum_{i=1}^{M+1}(a_i)_t(1-e^{-K_iL}) \qquad (21)$$

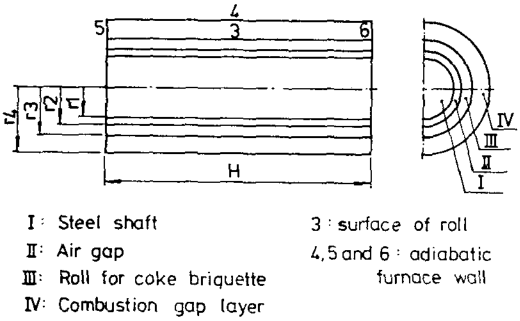


Fig. 5 Geometry for rapid heating

where

$$(a_i)_t=\sum_{k=1}^{N}(b_{ik})_t T^{k-1}{}_s \qquad (21\text{-}1)$$

Here, the weighting factors $(a_i')_t$ and $(a_i)_t$ and absorption coefficients K_i are the values calculated according to the solution procedure of ref. (11). These values are used as weighting factors a_i' and a_i of equation (15).

(2) Calculation of total exchange area

In order to calculate the total exchange area during rapid heating, the surfaces were divided into 4 zones (Zone 3; the outer surface of sleeve roll, Zone 4, 5 and 6; adiabatic furnace wall); and combustion gas was considered to be one zone.

The quantity of net heat transfer to be absorbed through the outer surface of sleeve roll by the radiative heat transfer is made up of the sum of direct heat transfer from the combustion gas and of reflected one from the adiabatic wall surrounding the combustion gas for the geometry shown in Fig. 5 for the rapid heating of the present sleeve roll. The direct surface to surface exchange area corresponding to the absorption coefficient K_i for the boundary surfaces surrounding the combustion gas becomes

$$S_iS_j=\int_{A_i}\int_{A_j}\frac{e^{-K_i r}\cos\theta_i\cos\theta_j}{r^2}dA_i dA_j \qquad (22)$$

The above equation (22) was integrated by the composite Gaussian Legendre numerical method. The direct gas to surface exchange area G_iS_j is obtained by using the above S_iS_j corresponding to the respective gray gas K_i and the following equation (23);

$$\sum_j G_jS_i+\sum_k S_kS_i=A_i \qquad (23)$$

The total gas to surface exchange area $\overline{G_iS_j}$ and surface to surface exchange area $\overline{S_iS_j}$ are derived by using the above direct exchange area and the explicit matrix expression by Noble(13).

4. Method of Solution

A solution of equation (1) satisfying the given initial and boundary condition is obtained from the integration over the control volume shown in Fig. 6 and a finite difference equation integrated over the control volume becomes;(14)

$$A_i\theta_{i-1}{}^{\nu+1}+B_i\theta_i{}^{\nu+1}+C_i\theta_{i+1}{}^{\nu+1}=D_i \qquad (24)$$

where

$$A_i=\frac{R_{i-1/2}}{(R_i-R_{i-1})}\;\frac{k_{i-1/2}^{\nu+1}}{(\rho_i^{\nu+1}\;C_i^{\nu+1}\mathscr{L}_0)}$$

$$C_i=\frac{R_{i+1/2}}{(R_{i+1}-R_i)}\;\frac{k_{i+1/2}^{\nu+1}}{(\rho_i^{\nu+1}\;C_i^{\nu+1}\mathscr{L}_0)}$$

$$B_i=-A_i-C_i-\frac{R_i(R_{i+1/2}-R_{i-1/2})}{\Delta\tau}$$

$$D_i=-\frac{R_i(R_{i+1/2}-R_{i-1/2})}{\Delta\tau}\theta_i{}^{\nu} \qquad (24\text{-}1)$$

Here, we used a fully implicit scheme for time and calculated the thermal property (thermal conductivity, specific heat and density) in a forward time step ($\nu+1$). A consideration of the boundary condition is given from the solution of heat balance over a half control volume shown in Fig. 6 and this can be categorized as follows;

(i) Given boundary temperature.

(ii) Given boundary heat flux.

(iii) Boundary heat flux specified via a heat transfer coefficient and the temperature of the

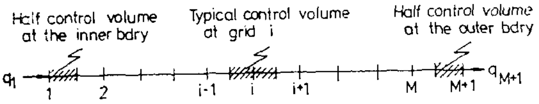


Fig. 6 Grid schematic

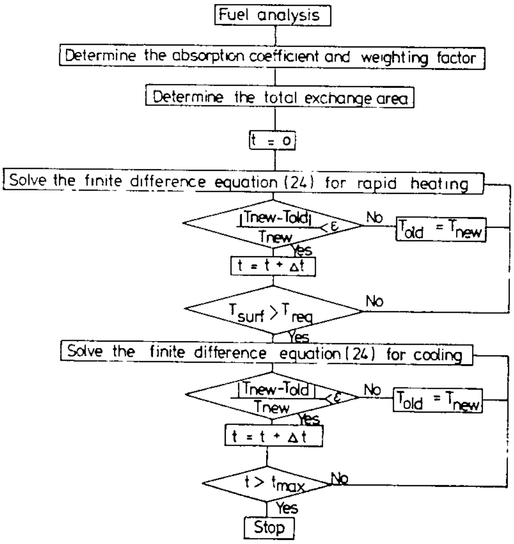


Fig. 7 Flow chart

surrounding temperature.

A solution of the above finite difference equation (24) was obtained through the execution of the program developed according to the flow chart shown in Fig. 7.

5. Results and Discussion

The number of grid used to obtain the solution of the finite difference equation (24) was 40 and the accuracy of results didn't have any variations compared to those of the larger number of grid; the dimensionless time interval were increased by 0.0002; the convergence criteria of this nonlinear equation was within the value of 0.0001.

For the calculations of radiation heat transfer from the combustion gas, the following parameters were evaluated. A fuel to be used for rapid heating in the combustion furnace is a municipal propane gas which is made up of the following chemical composition;

CH_4 : 0.001%
C_2H_6 : 2.29%
C_3H_8 : 94.85%
C_4H_{10} : 2.82%

The total emissivity $\varepsilon_t(T_g)$ and absorptivity $\mathscr{L}_t(T_s)$ produced by combusting this fuel was expressed with the weighted sum of the six gray gases by adding the infinitely large absorption coefficient ($K\to\infty$) corresponding to the optically thick limit in addition to the absorption coefficients of CO_2—H_2O gas mixture. The absorption coefficients and weighting factors calculated for the present fuel are listed in Table 2.

For the data in the Table 2, 1.3 as the value of F_E Operator in equations (18) and (19) is used since it predicts very well the measured temperature distribution in the sleeve roll during heating; and the temperature polynomial expression for the weighting factors used the third degree. The total exchange area $\overline{GS}$ and $\overline{SS}$ corresponding to the respective gray gas to be calculated for the geometry ($H=1.7$ m, $r_3=0.603$ m, $r_4=1.35$ m) shown in Fig. 5 are listed in Table 3. For total surface emissivities, 0.8 was used for the surface of sleeve roll and 0 for the remaining adiabatic surface of furnace. Therefore, the remaining total exchange area values except $\overline{G_1S_3}$ and $\overline{S_3S_3}$ result in 0 from the explicit matrix relation by Noble(13).

As a temperature of combustion gas for the evaluation of the above parameters was used the surrounding average temperature measured by thermocouples in the furnace. The measured and calculated temperature distribution for the heat treatment of sleeve roll is shown in Fig. 8. In Fig. 8, the highest temperature line from start is the measured temperature of combustion-gas in the furnace in which temperature is raised from about 900°C to about 1050°C for an hour, and then, the constant temperature of 1050°C is kept until heating is finished. The solid line and marked points in the right side of Fig. 8 represent the measured and predicted tempe-

Table 2 Values of the coefficients K_M and b_{MN} to express the total emissivity and absorptivity of the municipal propane gas; $P_C=0.116$ atm.; $P_W=0.154$ atm; $P_{tot}=1$ atm; $F_E=1.3$

	M	K_M	b_{M1}	$b_{M2}\times10^4$	$b_{M3}\times10^7$	$b_{M4}\times10^{11}$
ε	1	0	0.42313	−3.4027	1.6499	−1.9968
	2	0.00485	−0.05939	2.4155	−0.98924	1.3325
	3	0.03366	0.24761	1.6379	−0.58753	0.35619
	4	0.32257	0.12025	0.48773	−0.41847	0.65226
	5	3.64058	0.14146	−0.11357	−0.14961	0.25453
	6	∞	0.23077	0	0	0
$\mathscr{L}$	1	0	0.03511	−2.2005	1.8930	−2.5683
	2	0.00485	−0.10640	5.8218	−2.8617	3.6736
	3	0.03366	0.91554	−5.1133	1.5829	−1.8845
	4	0.32257	−0.00374	2.5085	−1.1478	1.4437
	5	3.64058	0.14896	−0.35642	−0.03424	0.10590
	6	∞	0.23007	0	0	0

Table 3 Values of total surface to surface exchange area $\overline{S_3S_3}$ and gas to surface exchange area $\overline{G_1S_3}$ for the gray gas in Table 2 [Unit : m^2]

M	1	2	3	4	5	6
$\overline{S_3S_3}$	4.95190	4.51990	2.88530	0.29149	0.00127	0.0
$\overline{G_1S_3}$	0.0	0.30426	1.54990	4.38960	5.19470	5.15270

rature profiles in the locations of 0, 30, 60, 90 and 140 mm depth from the outer surface of sleeve roll, and the outer surface of supporting shaft during rapid heating. As we used 1.3 as a value of F_E Operator, the simulation results of heating curves show a good agreement with the measured temperature curves. When the temperature of the outer surface of sleeve roll reaches the required value, the assembly of the sleeve roll is picked out of the furnace and cooled down at the atmosphere room temperature.

In cooling, the simulation results calculated by using the equation (12) and (13) as a boundary condition are compared with the experimental values in the left side of Fig. 8 for the temperature distribution of 0, 30, 60, 90 and 120 mm depth from the outer surface of sleeve roll, and the outer surface of supporting shaft. The predicted results agree well with the measured ones like the rapid heating.

As seen in Fig. 8, the temperature of the outer surface of sleeve roll is decreased very rapidly just after taking out the assembly from the furnace due to the radiative heat transfer of high surface temperature. About 15 minutes later from the start cooling, the cooling rate by radiative heat transfer of surface temperature becomes smaller as the temperature of outer surface becomes decreased. The prediction of

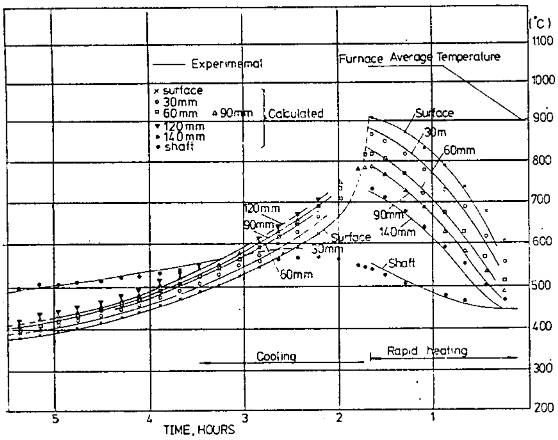


Fig. 8 Calculated and experimental heating and cooling curves of assembly for the production of sleeve roll for coke briquette; $F_E=1.3$

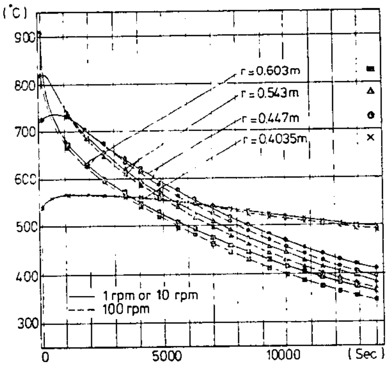


Fig. 9 Variation of cooling curve according to the variation of angular velocity; $F_E=1.3$

outer surface temperature of the supporting shaft, which were increased and decreased very slowly in both rapid heating and cooling due to the influence of the air gap, is also good agreement with the measured temperature.

As the temperature of the outer surface becomes lower after long time from the start of cooling, a convective heat transfer has gradual effect on the cooling characteristics compared to the radiative one.

In order to know the cooling characteristics according to the variations of angular velocity of this assembly, the cooling curves at the outer surface of sleeve roll, 60 mm from the outer surface of sleeve roll, the inner surface of sleeve roll and the outer surface of supporting shaft are shown in Fig. 9. As seen in Fig. 9, there are no differences between curves for angular velocities of 1 and 10 rpm. When the angular velocity is increased to 100 rpm, there are a little differences which mean that the effect of rotating speed does not have much influences on the heat transfer of the sleeve roll. Therefore, it can be concluded that it is enough to select the angular velocity to maintain circumferential temperature for the operational condition of the roll production.

6. Conclusions

The solutions of unsteady heat conduction equation with boundary conditions of radiation and convection for both heating and cooling were sufficient to predict the temperature profile for the heat treatment of the large diameter sleeve roll. We have reached the following conclusions from the comparisions of the predicted results with the measured ones for both rapid heating and cooling curves;

(1) 1 dimensional unsteady heat conduction equation with convective and radiative boundary condition was solved by the numerical simulation using the finite difference method based on the control volume and a corresponding computer program was developed.

(2) The "Zone Method" was used to calculate a radiative heat transfer by a combustion gas produced by firing the municipal propane fuel in furnace in case of rapid heating and 1.3 among the values of "F_E Operator" used to represent the radiative property (total emissivity and absorptivity) of this flame predicted very well the experimental results.

(3) In cooling, the predicted results using

equation (12) and (13) as a boundary conditions for the convective and radiative cooing at the atmosphere were well in accord with the measured valus for the natural cooling at the atmosphere.

Because the variation of angular velocity of sleeve roll doesn't have much effect on the cooling characteristics, it is required to select the angular velocity to maintain the uniform circumferential temperature of the sleeve roll.

(4) Consequently, it is expected that the temperature profiles can be controlled in the sleeve roll to obtain the better material properties since the prediction of the temperature distribution during the heat treatment is very well performed.

Acknowledgement

We would like to express our heartfelt thanks to Mr. J.H. Choi and J.D. Kim in KMIC who gave us a beneficial discussion for a metallurgical problem.

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