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COMPUTER MODELING OF THE CONTINUOUS ANNEALING FURNACE

Sung Ho Jeong*, Joon Jeong Yi*, Jong Keun Kim* and Man Yeong Ha**

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A computer program to calculate the strip temperature heated in the continuous annealing furnace was developed, using the zone method for radiative heat transfer analysis with the measured gas temperature in the furnace. Using the F_E Operator, the present study considered the effects of soot and transient species in addition to the H_2O-CO_2 gas mixture on the gas radiative heat transfer. The predicted strip temperature distribution for $F_E=1.05$ represented well the measured data. The maximum difference in the heat flux transfered to the strip from the combustion gas for $F_E=1.0$(without soot and transient species gas radiation) and 1.05(with soot and transient species gas radiation) was about 15%. The present study also investigated the effects of line speed and thickness variations on the strip temperature, establishing the bases for the on-line computer model.

Key Words : Continuous Annealing Furnace, F_E Operator, Gas Radiation, Strip Heating, Zone Method

NOMENCLATURE

a'_i, a_i : Weighting factor, dimensionless
A : Area, m^2
b', b : Coefficients for temperature polynomial Eqs. (2) and (4)
c_p : Specific heat, W-s/kg-K
D : Strip thickness, m
F_E : F_E Operator, dimensionless
gs : Direct gas to surface exchange area, m^2
GS : Total gas to surface exchange area, m^2
h : Heat transfer coefficient, W/m^2-K
k : Thermal Conductivity, W/m-K
K_i : Absorption coefficient, m^{-1}
L : Mean beam length, m
LS : Line speed, m/min
M : Number of gray gas component, dimensionless
N : Maximum temperature polynomial degree, dimensionless
NG : Total number of gas volume zones, dimensionless
NS : Total number of surface zones, dimensionless
N_u : Nusselt number, dimensionless
P_r : Prandtl number, dimensionless
r_{ij} : Distance between the ith and jth zone, m
R_e : Reynolds number, dimensionless
ss : Direct surface to surface exchange area, m^2
SS : Total surface to surface exchange area, m^2
T : Temperature, K
U : Overall heat transfer coefficient, W/m^2-K
v : Strip velocity, m/s
V : Volume of a gas volume zone, m^3
x : Moving direction of the strip, m
α : Total absorptivity, dimensionless
ε : Total emissivity, dimensionless
σ : Stefan Boltzmann constant, $5.6696\times10^{-8} W/m^2\text{-}K^4$

Subscripts

a : Atmosphere
in : Entry
f : Furnace
g : Gas
out : Exit
s : Surface
st : Strip
$c+w$: CO_2-H_2O gas mixture
t : CO_2-H_2O-transient species-soot gas mixture
w : Furnace wall

* The Research Institute of Industrial Science & Technology P. O. Box 135, Pohang 790-600, Korea
** Department of Mechanical and Production Engineering Pusan National University, Kumjung-Ku, Pusan 609-735, Korea

1. INTRODUCTION

A heating process in the continuous annealing furnace (CAF) is very crucial in order to obtain a stainless strip satisfying the required specifications (anti-corrosion, manufacturing ability, etc.) (Shimada et al., 1980). Thus, it is very important to control the strip temperature in the proper range in the furnace. The gas temperature in the furnace is set automatically according to the strip conditions heated in the furnace. Thermocouples are located in the longitudinal direction of the furnace and measure gas temperature continuously. If the measured gas temperature in a zone is lower than the set value, the supplied fuel and air are increased, whereas, if the gas temperature is higher than the set value, it is reversed. This results in establishing the stable gas temperature in the furnace. Based on the characteristics of the CAF in the POSCO (Pohang Steel Co.), the main purpose of the present study is to calculate the strip temperature according to the working conditions (line speed, strip thickness, etc.) and to establish an on-line computer model to control the strip temperature.

In order to achieve this purpose, the simplified model using the zone method (Hottel and Sarofim, 1967, Larsen and Howell, 1986 and Li et al., 1986) is employed in the present study to calculate the heat balance in the furnace. Since the gas temperature in the furnace is very high, the dominant mode of heat transfer is radiative one which is more than 90% of total heat transfer (Li et al., 1986). The values of exchange areas and the radiation properties of combustion gas are very crucial to the overall accuracy of the results using the zone method. The smoothing techniques of Larsen and Howell (1986) were used to improve the accuracy of direct exchange areas. The total emissivity and absorptivity of combustion gas were expressed with the weighted sum of gray gases (Farag and Allam, 1981, Felske and Charalam Populos, 1982, Ha and Hur, 1986, Nakara and Smith, 1977 and Sarofim et al., 1978). The major components for gas radiation are CO_2 and H_2O. However, it was reported that the heat flux to be absorbed through the surface was lower than the measured one when only two components CO_2 and H_2O were used for gas radiation, due to the contribution of soot and transient species of combustion gas (Bueters, 1974 and Bueters et al., 1974). In order to consider the contribution of soot and transient species for gas radiation, the Combustion Engineering (Bueters, 1974 and Bueters et al., 1974) employed the F_E Operator in the furnace design of industrial or utility boilers. Ha and Yoon (1990) also applied the F_E Operator for heat transfer analysis of the large size rotor in the furnace, with good results. The present study calculates the strip temperature along the distance of the CAF and compares the predicted results with the measured data. The effects of different F_E Operator on the strip temperature distribution is also investigated.

2. CAF SIMULATION MODEL

2.1 Furnace Modeling

A CAF is consisted of (convective and radiative) preheating sections and heating and equalizing section as shown in a schematic diagram of Fig. 1. Combustion gas formed in the heating and equalizing section heats the strip, passing through the pre-heating sections in order to pre-heat the strip. This results in saving energy and reducing the heat load in the heating and equalizing section. The heat balance equations in the heating and equalizing section is solved using the zone method with the following assumptions :

(1) The heating and equalizing section is divided by the equal eight gas and surface zones in the longitudinal direction, as shown in Fig. 2. Only the top part above the strip is solved using the symmetry condition. The roof and both side walls located at the same distance from the furnace entry are considered as a single surface zone (see Fig. 2). The entry location is modeled as an imaginary surface with $\varepsilon=1$. The gap between the strip and the side walls is modeled as an adiabatic wall with $\varepsilon=0$ (see Fig. 2). Thus eight gas volume and thirty four surface zones are used to model the heating and equalizing section for the zone method.

(2) The gas temperature distribution in the furnace is assumed to be known. Measured data are used for gas temperature at each gas zone and the temperature in a gas zone is assumed to be uniform.

(3) Since the thickness of the strip is very small (about 2~8 mm), the lumped model is used, giving the uniform temperature in the thickness direction.

(4) The convective heat transfer coefficients in each zone

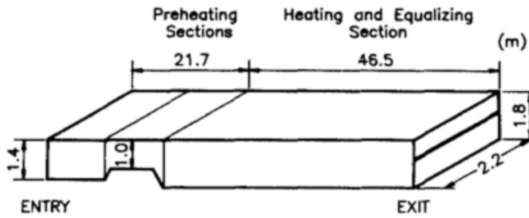

Fig. 1 A schematic diagram of a continuous annealing furnace

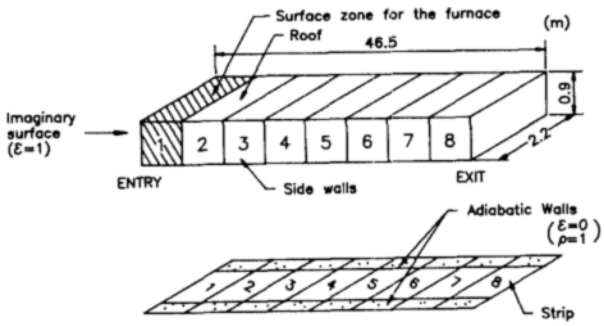

Fig. 2 Indexing of the CAF for the zone method

are expressed as a function of the gas velocity which is uniform at each volume zone using the plug flow assumption.

2.2 Modeling of Combustion Gas Radiation Properties

If the fossil fuel is fired and ideally converted into CO_2 and H_2O gas mixture, the total emissivity ε_{c+w} and absorptivity α_{c+w} for CO_2–H_2O gas mixture can be expressed with the weighted sum of those of gray gases as follows : (Farag and Allam, 1981, Felske and Charalam Populos, 1982, Ha and Hur, 1986, Nakara and Smith, 1977 and Sarofim et al., 1978).

$$\varepsilon_{c+w}(T_g)=\sum_{i=1}^{M}(a'_i)_{c+w}(1-e^{K_iL}) \tag{1}$$

where

$$(a'_i)_{c+w}=\sum_{k=1}^{N}(b'_{ik})_{c+w}T_g^{k-1}, \tag{2}$$

and

$$\alpha_{c+w}(T_s)=\sum_{i=1}^{M}(a_i)_{c+w}(1-e^{K_iL}) \tag{3}$$

where

$$(a_i)_{c+w}=\sum_{k=1}^{N}(b_{ik})_{c+w}T_g^{k-1}, \tag{4}$$

K_i in Eq.(1) and (3) means the absorption coefficients ; $(a'_i)_{c+w}$ and $(a_i)_{c+w}$ represent the weighting factors corresponding to the absorption coefficient K_i for CO_2-H_2O mixture ; M and N represent the total number of gray gases and maximum polynomial degree to show the functional relationship with temperature, respectively ; T_g and T_s are the temperature of combustion gas and surface surrounding the combustion gas.

However, the contribution of transient species and soot in addition to CO_2-H_2O gas mixture should be considered in order to calculate the total emissivity of real combustion gas to be produced in the furnace or combustor as shown by Bueters (1974) and Bueters et al. (1974). The total emissivity $\varepsilon_t(T_g)$ and absorptivity $\alpha_t(T_s)$ of CO_2-H_2O-transient species-soot gas mixture can be expressed as follows using the F_E Operator which implies the influence of transient species and soot (Ha and Hur, 1986 and Bueters, 1974) :

$$\varepsilon_t(T_g)=\frac{F_E-1+\varepsilon_{c+w}}{F_E}\quad 1\le F_E<\infty \tag{5}$$

$$\alpha_t(T_s)=\frac{F_E-1+\alpha_{c+w}}{F_E}\quad 1\le F_E<\infty \tag{6}$$

$F_E=1.0$ in Eq.(5) and (6) corresponds to the case of gas radiation of CO_2-H_2O gas mixture (Hottel radiator) without considering the contribution of transient species and soot, whereas $F_E\rightarrow\infty$ represents the black-body radiation where emissivity is independent of beam length, temperature, and pressure. Thus, the behavior of F_E is physically that we can obtain the gas radiation properties of CO_2-H_2O-transient species-soot mixture for a transition region from a Hottel radiator to the black-body limit. Using Eqs.(5) and (6) and the procedures given by Ha and Hur (1986), the total emissivity $\varepsilon_t(T_g)$ and absorptivity $\alpha_t(T_s)$ can be expressed as follows :

$$\varepsilon_t(T_g)=\sum_{i=1}^{M+1}(a_i')_t(1-e^{K_iL}) \tag{7}$$

where

$$(a_i')_t=\sum_{k=1}^{N}(b_{ik}')_tT_g^{k-1}, \tag{8}$$

and

$$\alpha_t(T_s)=\sum_{i=1}^{M+1}(a_i)_t(1-e^{K_iL}) \tag{9}$$

$$(a_i)_t=\sum_{k=1}^{N}(b_{ik})_tT_s^{k-1} \tag{10}$$

Here, the weighting factors $(a_i')_t$ and $(a_i)_t$ and absorption coefficient K_i are the values calculated according to the solution procedure by Ha and Hur (1986).

2.3 Energy Balance Equation

The heat transfered to the strip and the furnace wall from the combustion gas is governed by the following energy balance equation :

$$Q_i=\sum_{j}^{NS}\sum_{n=0}^{M+1}a_t(S_jS_i)_n\sigma T_{s,j}^4+\sum_{j}^{NG}\sum_{n=0}^{M+1}a_t'(G_jS_i)_n\sigma T_{g,j}^4 -\varepsilon_iA_i\sigma T_{s,i}^4+h_iA_i(T_{g,k}-T_{s,i}) \tag{11}$$

The (major) heat $Q_{st,i}$ transfered to the strip by radiative and convective heat transfer is used to heat the strip, and temperature distribution of the strip along the moving direction is determined form the following equation :

$$mC_pv\frac{dT}{dx}=Q_{st,i} \tag{12}$$

where v and x represent the line speed and the moving direction of the strip, respectively. The temperature variation in the thickness direction is neglected since the thickness is very small (~2.0~8.0mm). The heat loss $Q_{wall,i}$ through the furnace wall is expressed as

$$Q_{wall,i}=UA_i(T_{s,i}-T_a) \tag{13}$$

where U represents the overall heat transfer coeffcient through the furnace wall which is composed of glass wool, insulation fire brick and stainless steel plate. The heat transfer coefficient h_i in Eq.(11) is obtained from the following correlation given by Afgan and Beer (1974).

$$N_u=0.069R_e^{0.8}P_r^{0.4} \tag{14}$$

Weighting factors a_i' and a_i in Eq.(11) are given in Eqs.(8) and (10). SS and GS in Eqs.(11) represent the total surface-to-surface and gas-to-surface exchange areas, respectively, which are obtained using the wall reflectivity and the direct exchange areas (corresponding to the absorption coefficient K_n) expressed by :

$$s_is_j=\int_{Aj}\int_{Ai}\frac{e^{-K_nr}\cos\theta_i\cos\theta_j}{r_{ij}^2}dA_idA_j \tag{15}$$

$$g_is_j=\int_{Vi}\int_{Aj}\frac{K_ne^{-K_nr}\cos\theta_j}{r_{ij}^2}dA_jdV_i \tag{16}$$

The direct exchange areas obtained using numerical integration are difficult to satisfy the following criterion :

$$\sum_{j=1}^{NS}s_js_i+\sum_{j=1}^{NG}g_js_i=A_i \tag{17}$$

Thus, the least-square smoothing techniques by Larsen and Howell (1986) are used to improve the accuracy of the calculated exchange area.

3. RESULTS AND DISCUSSION

The fuel used in the CAF is a COG (coke oven gas) in which H_2 and CH_4 is about 85%. The burners are located at the both side walls in the heating and equalizing section. The capacity of the burners in the heating section is larger than that in the equalizing section. As shown in Fig. 1, the strip moves from the entry (heating section) to the exit (equalizing section) of the CAF. However the combustion gas of COG flows from the exit to the entry, resulting in different mass flow rates and heat transfer coefficients [governed by Eq. (14)] at each zone. The calculated overall heat transfer coefficient U given in Eq.(13) is 1.0 W/m^2-K for the structure of the furnace wall shown in Fig. 3. Since the surface of the strip is oxidized under the surrounding conditions of high temperature combustion gas, 0.7 was used as a value of the strip surface emissivity. 0.9 was taken as a value of furnace wall emissivity. The total emissivity ε_t and absorptivity α_t of combustion gas were expressed as a weighted sum of gray gases. The values of F_E operator were varied between 1.0 and 1.06 to consider the effects of soot and

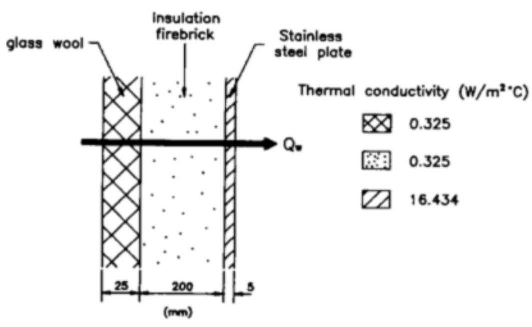

Fig. 3 Furnace wall structure

Table 1 Values of the coefficients of K_M and b_{MN} to express the total emissivity and absorptivity of combustion gas ; F_E =1.05

	M	K_M	b_{M1}	$b_{M2}\times 10^{-3}$	$b_{M3}\times 10^{-6}$	$b_{M4}\times 10^{-9}$
	1	0	0.84192	−1.69196	1.29807	−0.27362
	2	0.01572	−0.99390	2.33352	1.52632	0.31716
ε_t	3	0.12774	1.06659	−1.22448	0.76387	−0.16889
	4	1.08408	−0.31015	0.97043	0.70246	0.15297
	5	7.30485	0.35344	−0.30290	0.10194	−0.01395
	6	∞	0.04762	0	0	0
	1	0	1.37277	−3.62977	2.91931	−0.64970
	2	0.01572	−2.35068	5.80293	−4.07017	0.87561
α_t	3	0.12774	1.85630	−2.68254	1.64165	−0.34418
	4	1.08408	−0.27852	1.00280	−0.76817	0.17373
	5	7.30485	0.33150	−0.31193	0.13142	−0.02297
	6	∞	0.04762	0	0	0

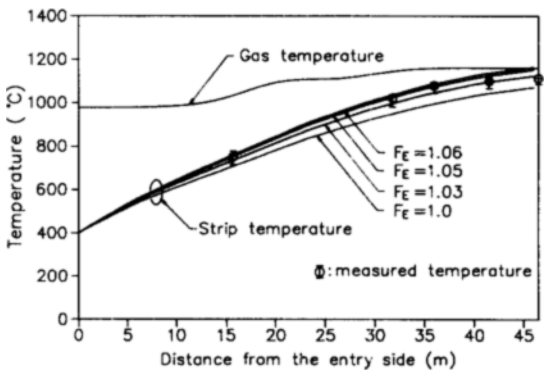

Fig. 4 Strip temperature as a function of the distance from the entry side along the moving direction and the F_E Operator (case 1)

transient species. Table 1 shows the absortion coefficients and their weighting factors for F_E=1.05. The third order expression as shown in Table 1 was used for temperature polynomial of weighting factors given in Eq.(8) and (10). The calculated direct exchange areas ss and gs using the numerical integration and the least-square smoothing techniques satisfy well the constraint Eq.(17), and correct total exchange areas SS and GS can be evaluated for the energy balance Eq.(11).

Figures 4, 5 and 6 represent the surrounding gas temperature and the strip temperature along the distance of the CAF corresponding to the cases 1, 2 and 3 of Table 2, respectively. The gas temperature is the measured value in the prototype CAF operated in the POSCO. The solid lines for the strip temperatures represent the predicted results while the circles being the measured value. The bar around the measured values show the data range. As shown in these figures, the strip temperature increases rapidly at the heating section due to the large temperature difference between the gas and the strip. As the strip approaches to the exit of the CAF, the increasing rate reduces since the strip temperature is getting close to the gas temperature. The strip temperature with F_E =1.0 is lower than the measured data since this corresponds

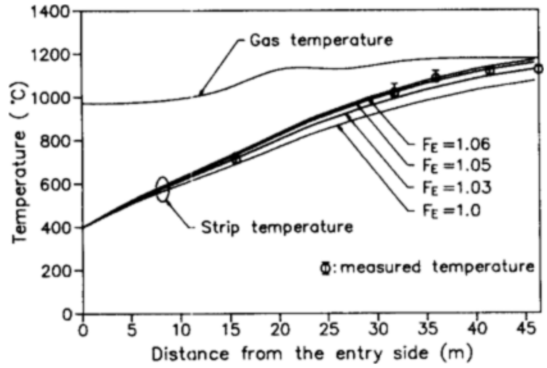

Fig. 5 Strip temperature as a function of the distance from the entry side along the moving direction and the F_E Operator (case 2)

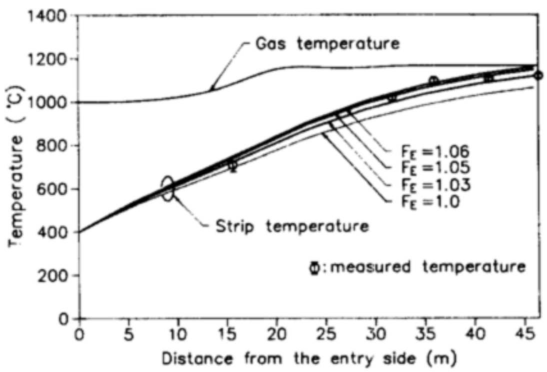

Fig. 6 Strip temperature as a function of the distance from the entry side along the moving direction and the F_E Operator (case 3)

Table 2 Simulation conditions used in Figs. 4, 5 and 6

	Case 1	Case 2	Case 3	
Strip thickness (mm)	3.2	4.0	3.0	
Line speed (m/min)	26.2	19.3	30,3	
Gas temperature (℃)	971	976	992	zone 1
	986	982	1015	zone 2
	1037	1016	1064	zone 3
	1128	1094	1152	zone 4
	1128	1110	1156	zone 5
	1160	1145	1165	zone 6
	1176	1160	1168	zone 7
	1176	1159	1167	zone 8

to the case with the mixture of CO_2 and H_2O only. When the F_E value increases to 1.03 and 1.05, the strip temperature increases since the heat flux to the strip by the gas radiation increased due to the formation of the soot and transient species and agrees with the measured data well. When F_E increases further to 1.06, the strip temperature at the exit of the CAF rises up to the gas temperature. Thus 1.06 is the upper limit value for the F_E Operator to compensate the effects of the soot and transient gas species in addition to the CO_2-H_2O gas radiation. From these results we can deduce

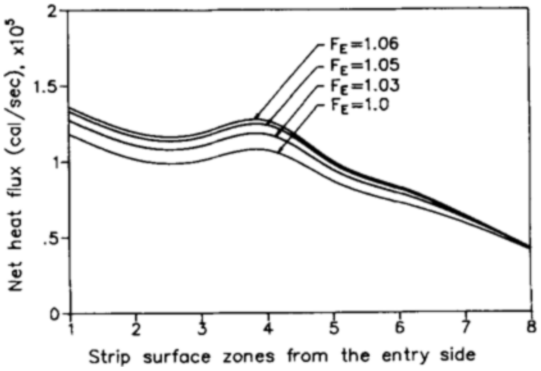

Fig. 7 Net heat flux transfered to the strip as a function of the distance from the entry side along the moving direction and the F_E Operator

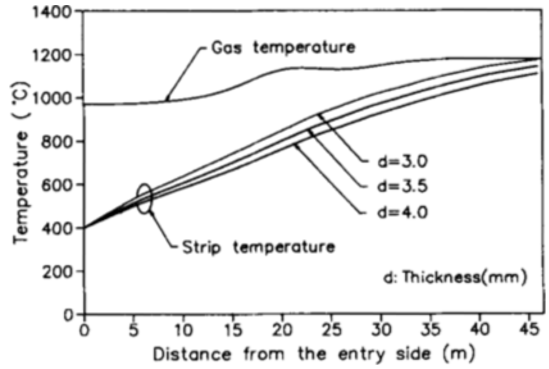

Fig. 9 Strip temperature as a function of the distance from the entry side along the moving direction and the strip thickness

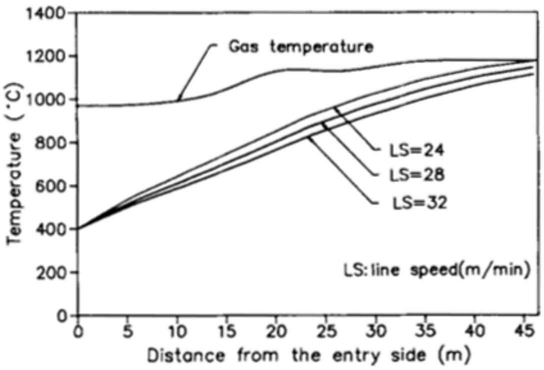

Fig. 8 Strip temperature as a function of the distance from the entry side along the moving direction and the line speed

that $F_E=1.05\sim1.06$ is the value to represents the gas radiation of CO_2-H_2O-soot-transient species gas mixture for the CAF of the POSCO.

Figure 7 represents the distribution of the net heat flux transfered to the strip surface along the moving direction for different F_E Operator values for the case 1 in Table 2. As F_E increases, the net heat flux increases due to the increases of soot and transient species, and results in the different strip temperature gradient as shown in Figures 4.5.6. The maximum difference in the net heat flux between $F_E=1.0$ and 1,05 is about 15 % at the fourth strip surface zone (around the center of the furnace). When the strip approaches to the exit of the CAF, the strip temperature is getting close to the gas temperature and differences in the net heat flux with different F_E Operator values decrease, such as about 3% difference for $F_E=1.0$ and 1.05.

Figures 8 and 9 show the effects of the line speed and thickness on the strip temperature distribution along the moving direction of the CAF. With the increases of the line speed and the thickness of the strip, the heating load of the furnace increases, resulting in the lower strip temperature. The strip temperature difference with the both effects increases as the strip approaches to the exit of the CAF.

The on-line computer model used in the industrial furnace should consider the variations of the line speed, strip thickness, gas temperature and inlet strip temperature in order to obtain the targetted strip temperature at the exit of the furnace. Another requirement for on-line computer models is the quick response to the changes of the governing variables. Thus the above results obtained from the off-line computer model should be expressed as a simplified equation as follows :

$$T_f=155.52+0.7T_{out}+11.36LS\times D +0.00071LS\times D\times T_{out}+2.0LS\times D\times T_{out}/T_{in} \quad (18)$$

The definition of variables in Eq.(18) is given in the nomenclature. This simplified equation can be applied to the on-line computer model with modifications obtained from the learning control of the CAF.

4. CONCLUSIONS

The followings are the main conclusions obtained numerically on the strip temperature along the longitudinal direction of the CAF operated in the POSCO :

(1) The zone method was used to calculate radiative heat transfer in the furnace and the F_E Operator was employed in order to represent the total emissivity and absorptivity of CO_2-H_2O-soot-transient species gas mixtures. The calculated strip temperature using $F_E=1.05$ agrees well with the measured data obtained from the CAF in POSCO. The net heat transfer to the strip for $F_E=1.05$ was 15% larger than that for $F_E=1.0$, at the center of the CAF.

(2) As the line speed and the thickness of the strip increases, the heating load of the furnace increases, resulting in the lower strip temperature at the exit of the CAF.

(3) A simple correlation to express the set value of the furnace temperature as functions of line speed, strip thickness and the strip exit temperature was suggested. This correlation can be applied to the on-line computer model with modifications using the learning control.

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