MODELLING OF ROTARY KILN BASED

DIRECT REDUCTION

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INTRODUCTION

Direct Reduction (DR) is the process by which iron ore, as oxide, is reduced by a reductant, viz., coal or natural gas to the product called sponge iron or Direct Reduced Iron (DRI). Coal based DR is carried out in a rotary kiln reactor where iron ore is reduced usually by noncoking coal. The kiln temperature is maintained at around 1000°C towards the discharge end, the rotational speed is usually kept in the range of 0.4 to 0.7 r.p.m. While the inclination of the kiln is fixed in the range of 1.5° to 2.5°. The kiln rotational speed, coupled with the inclination, imparts a forward motion to the charge bed of the kiln, thus aiding it to travel towards the discharge end. The charge consisting of iron ore and coal, while traversing the kiln length at high temperature, undergoes two simultaneous reactions, viz., gasification of the coal and reduction of the oxide ore. The oxide ore thus gradually gets converted to the lower oxides and finally, to the metallised poduct, DRI (90 - 95% metallised). However, the hot product from the kiln also contains coal char and ash and these being nonmagnetic, are separated from the product DRI (magnetic) by magnetic separation. Before magnetic separation, the hot kiln-discharge product is cooled to about 100°C, usually in a rotary cooler, indirectly cooled by water (Schematic diagram of the process appears in Fig.1).

To understand the process conditions inside the rotary kiln, as well as for scaling-up purpose, and to make adjustments in feed proportioning, kiln rotation and distribution of coal from both ends of the kiln process modelling is necessary.

The R&D Division of Tata Steel put up a pilot plant for DR in early 1970s. Parallel to the running of the pilot plant of 10 tpd capacity, modelling work was also undertaken on DR. All these concerted efforts led to the development of TISCO Direct Reduction (TDR) process, since commercially exploited in IPITATA Sponge Iron Ltd.'s plant - 300 tpd capacity.

This paper highlights the various areas of modelling.

Background of Modelling: Scope of modelling such processes like DR essentially involves the following areas:

i) Evaluation of the physical situation arising out of the movement of the solid charge bed

- calling for physical modelling.

ii) Evaluation of process conditions influenced by heat transfer and kinetics

- calling for mathematical modelling.

Physical Modelling: Physical modelling was undertaken to understand the influence of various operational variables/parameters viz., kiln inclination, rotational speed, kiln geometry (L/D ratio), blockage of the kiln diameter at the discharge end as well as to simulate the phenomenon of accretion build up in a DR kiln. The investigation was carried out with room temperature models in which cylindrical vessels, representing rotary kilns, were used. The model kilns were made from steel plates and also from 'perspex' sheets. 'Scaled down' sized iron ore was used as the charge material - the details of the study have been published elsewhere(1). The dimensions of the various model kilns and the circular and conical dams appear in Table-I. Figure 2 shows a schematic view of the experimental set up.

The functional form of the correlation for the retention time of the charge inside the rotary kiln was taken as:

$$T = \frac{KL^3}{F} \left(\frac{R}{\theta}\right)^a \left(\frac{F}{L^3 N}\right)^b \left(\frac{L}{D}\right)^c \quad \ldots.(1)$$

after dimensional analysis of the variables involved represented as:

$$T = f\,(L,\ F,\ R,\ \theta,\ S,\ N,\ D\ )$$

Expression (1) above incorporates three dimensionless group, and one dimensional constant, and regression analysis of the data generated by about 1000 experimentations in a span of about three years, yielded the following correlation:-

$$T \ = \ \frac{0.1026\ L^3}{F} \left(\frac{R}{\theta}\right)^{1.054} \left(\frac{F}{L^3 N}\right)^{0.981} \left(\frac{L}{D}\right)^{1.10} \ldots(3)$$

Equation (3) could be reduced to:

$$T = \frac{0.1026\ RL}{DN\theta} \quad \ldots\ldots\ (4)$$

where F, the feed rate, does not appear. This influence of F, the feed rate had earlier been reported to be negligible(2,3,4,5) but this work revealed that the feed rate had an effect on the retention time of the charge and although the effect may be small, it cannot be neglected.

Fig.3 compares the predicted values of retention times for various experimentations by several investigators including this work, and the validity of the model developed is well observed. Fig.4 shows a comparison of the prediction by this model with the experimental observations made during this study.

The major conclusions drawn from the exhaustive study were:

(a) Kiln inclination of around 1.5°, kiln rotational speed of around 0.5 rpm and a reductionof discharge end kiln diameter by 30 - 40% by providing circular dams - give the optimised flat filling degree profile of 15 - 18% throughout the kiln length which is desired for most efficient operation of a DR kiln.

(b) During the travel through the rotary kiln, radial segregation occurs across the depth of the charge bed - the factors responsible for this are the difference in bulk density, size and angle of repose - of ore and coal. However, axial segregation along the kiln length is absent.

(c) A build up covering over 30% of kiln diameter at 60 - 70% distance from kiln inlet end, makes kiln operations almost impossible, because of marked increase in the residence time of the charge and very high back spillage of the charge through the inlet end itself. A rotational speed of 0.5 r.p.m. becomes critical in such a case and further increase does not help in anyway.

Mathematical Modelling: Any rotary kiln for Direct Reduction is basically a moving bed reactor and thus, process analysis through mathematical modelling, involves consideration of various modes of heat transfer in the rotary kiln, the kinetics of the reactions taking place viz., gasification of the coal (carbon) and reduction of the oxide ore to lower oxides, and, the traverse of the charge bed from the kiln inlet end towards the discharge end.

As a first step, the following assumptions were made:

(i) Steady state model was to be developed - this is very logical as a DR kiln is under unsteady state only during plant start up or when there has been some major breakdown in the feeding system, etc. - which are only occasional.

(ii) All modes of heat transfer, viz., conductive, convective and radiative are present.

(iii) The solid charge bed is well mixed - this is possible under idealised kiln operating conditions, where around 15% of the filling degree helps in attaining this condition.

(iv) The freeboard gas, moving countercurrent to the charge bed, is well mixed.

(v) The flame length at the kiln discharge end is less than the kiln diameter, hence it is neglected.

(vi) The rotational speed (around 0.5 r.p.m.) and inclination (1.5° to 2.0°) do not make any significant contribution on natural convective heat transfer.

(vii) The kiln was divided into two zones - preheating zone (no reaction) and reduction zone.

The following modes of heat transfer were considered:

Conductive : (i) From the charge - covered part of the refractory lining to the charge bed.
(ii) From the inner surface of the refractory lining to the outer shell.

Convective : (i) From the freeboard gas to the charge bed - forced convection.
(ii) From the freeboard gas to the refractory - forced convection.
(iii) From the outer shell of the kiln to the surroundings - natural convection.

Radiative : (i) From the freeboard gas to the charge.
(ii) From the freeboard gas to the refractoory lining.
(iii) From the outer shell of the kiln to the surroundings.

The heat transfer equations, reduction equation and overall heat balance equations appear elsewhere(6).

Finally, four sets of nonlinear equations were generated and this required a numerical solution approach using the Newton - Raphson iteractive technique.

A. Burroughs 6800 mainframe computer was used with FORTRAN IV as the language.

As the total amount of carbon (coal) to be used was unknown at the start (it depends on the kiln length, L/D ratio, ore reducibility/coal reactivity) - the reducing gas quantity was thus unknown. To get around this situation, a trial input parameter 'C' was incorporated - 'C', depending on the mass rate of the reducing gas, was varied for each run, keeping other parameters constant. This so called variable parameter 'C', thus helped in the solution.

Some typical results are shown in Figures 5 to 10. The major conclusions arrived at from this modelling work ~~have~~ were:

(a) The higher is the amount of countercurrent coal for injection, the lower is the radiative transfer.

(b) Increase in exit gas temperature (through the kiln inlet end), lowers the kiln length and hence L/D ratio for fixed diameter.

(c) To process 10 -12 tpd of sponge iron, a kiln of length about 22 metres, having an internal diameter of 1.2 metre, is required. This was verified in the TDR pilot plant.

To process 300 tpd of sponge iron, the kiln should be 70 - 75 metres long with internal diameter of about 3.5 metres. This formed the basis of the kiln design for IPITATA.

CONCLUSIONS

The above described work has shown how a complicated situation can be well tackled through mathematical and physical modelling studies and verifying the results of such modelling studies with the aid of pilot plant experimentation. The work has also highlighted as to how modelling can help in scale-up exercises.

D	inside diameter of kiln, metre
F	volumetric feed rate metre^3/minute
K	constant of proportionality
L	kiln length, metre
N	rotational speed, r.p.m.
R	angle of repose, degrees
T	residence time of charge, minutes
θ	slope of the kiln, degrees

TABLE - I : DETAILS OF DAMS IN THE KILN

(a) Circular dams

Type of dam	% dameter covered	% area covered
A	0 (No dam)	0
B	10	19
C	20	36
D	30	51
E	40	64
F	50	75

(b) Conical dams

Type of dam	% diameter covered at 66% kiln length
C_o	0
C_1	15
C_2	30
C_3	45
C_4	60
C_5	75

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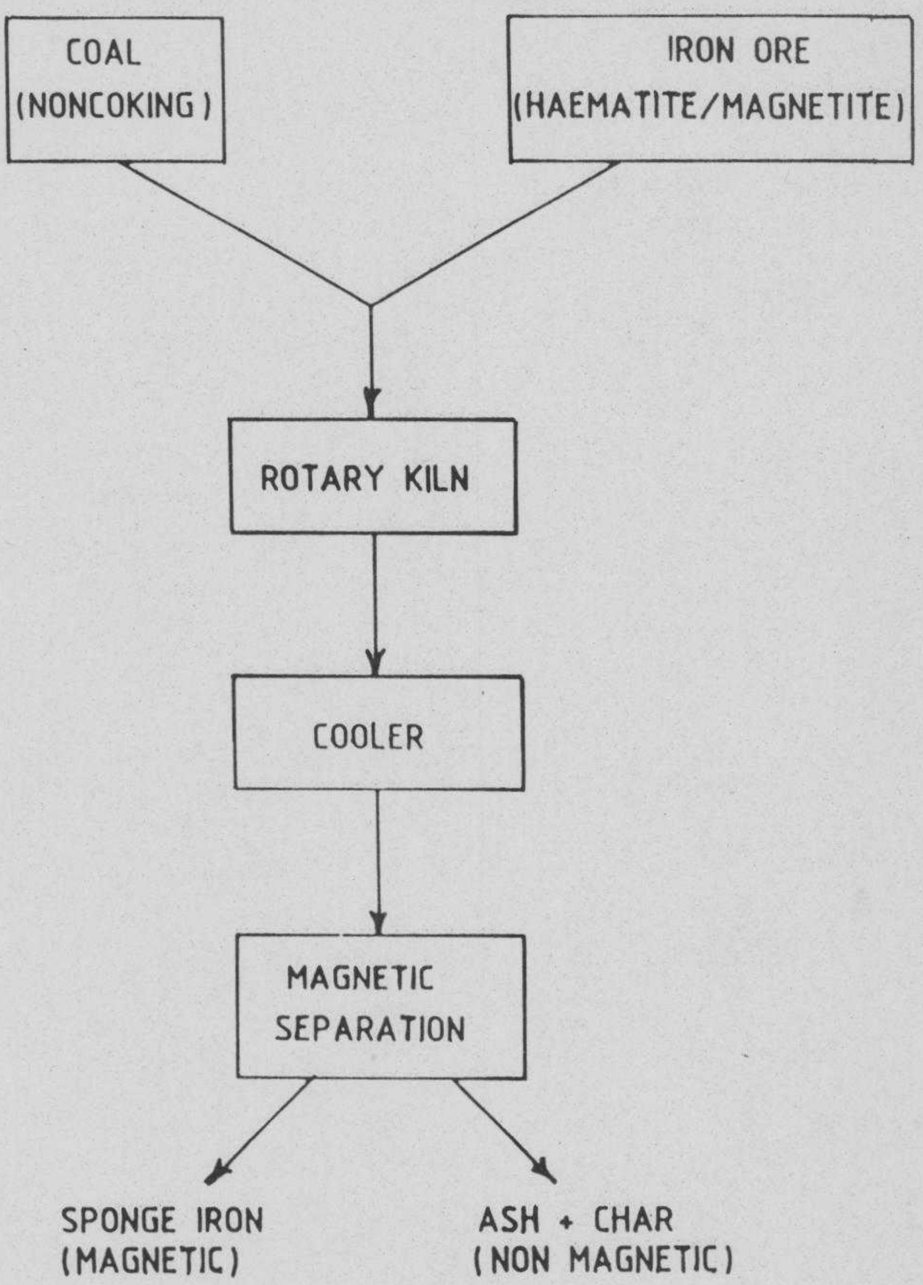

FIG. 1: ROTARY KILN BASED DR.

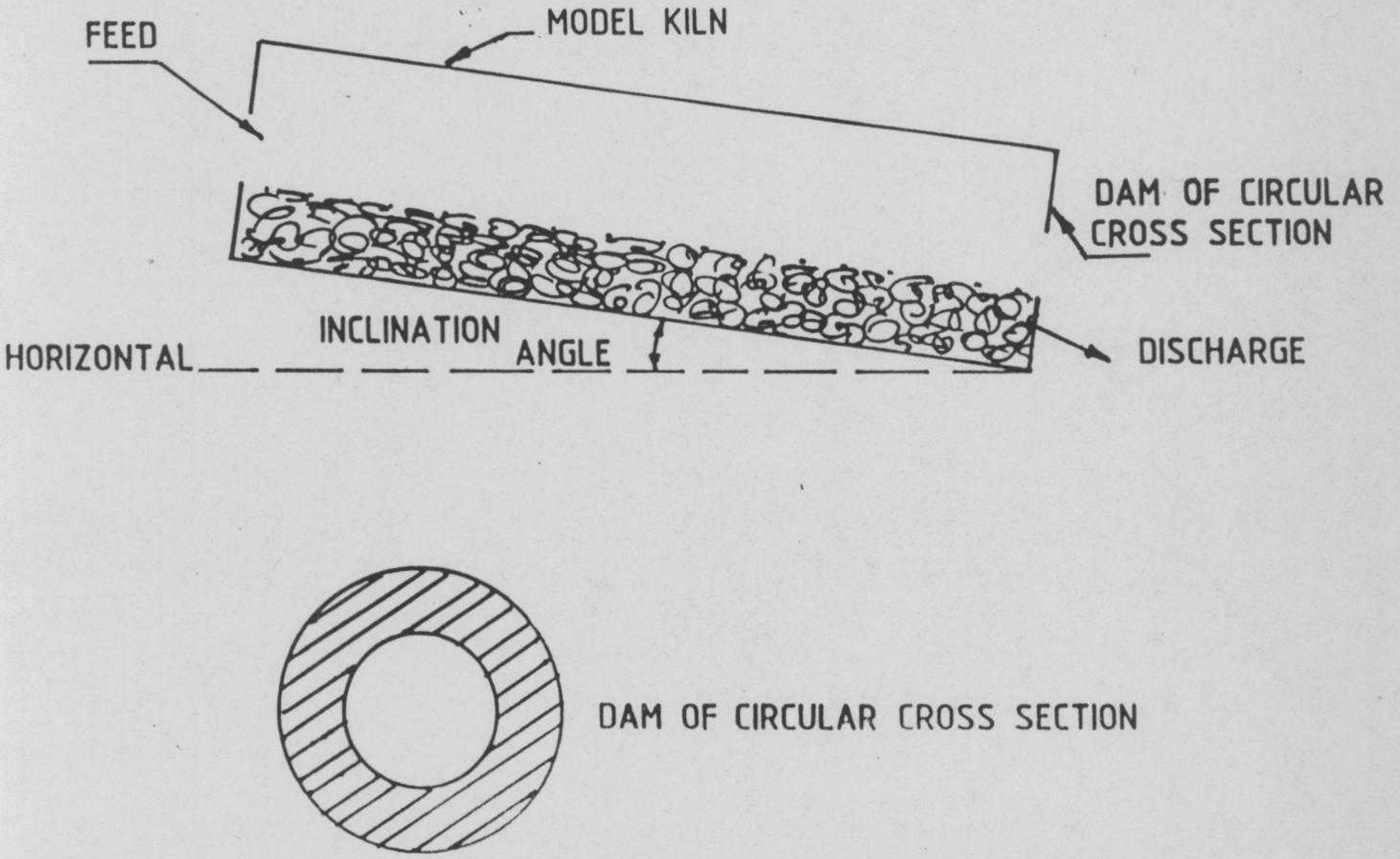

FIG. 2 : SCHEMATIC OF THE EXPERIMENTAL SET UP FOR PHYSICAL MODELLING.

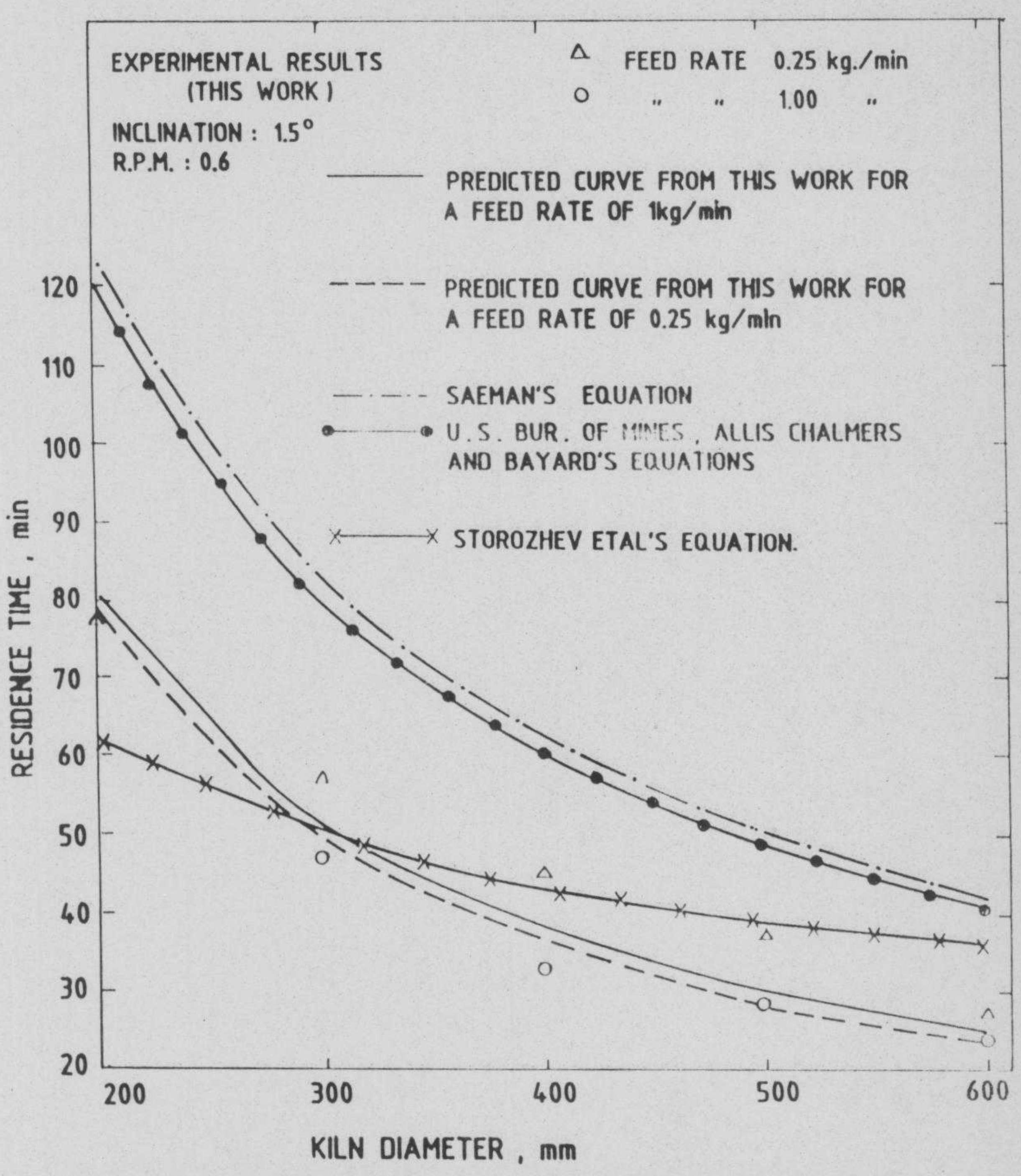

FIG. 3: COMPARISON OF RESULTS OF THE PRESENT WORK WITH OTHER AVAILABLE FORMULAS.

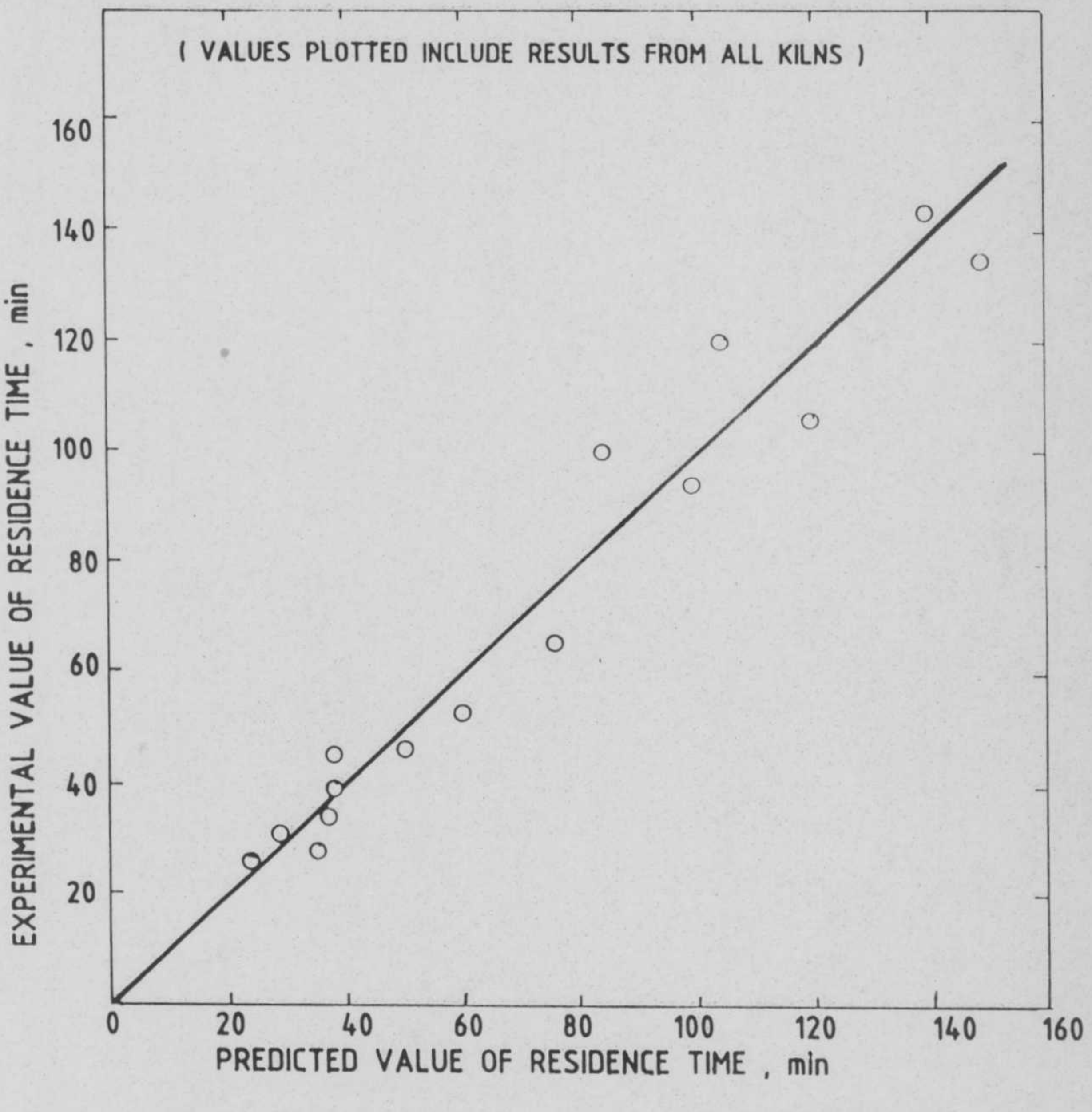

FIG. 4 : COMPARISON OF PREDICTED VALUE OF RESIDENCE TIME AND THE EXPERIMENTALLY MEASURED VALUE.

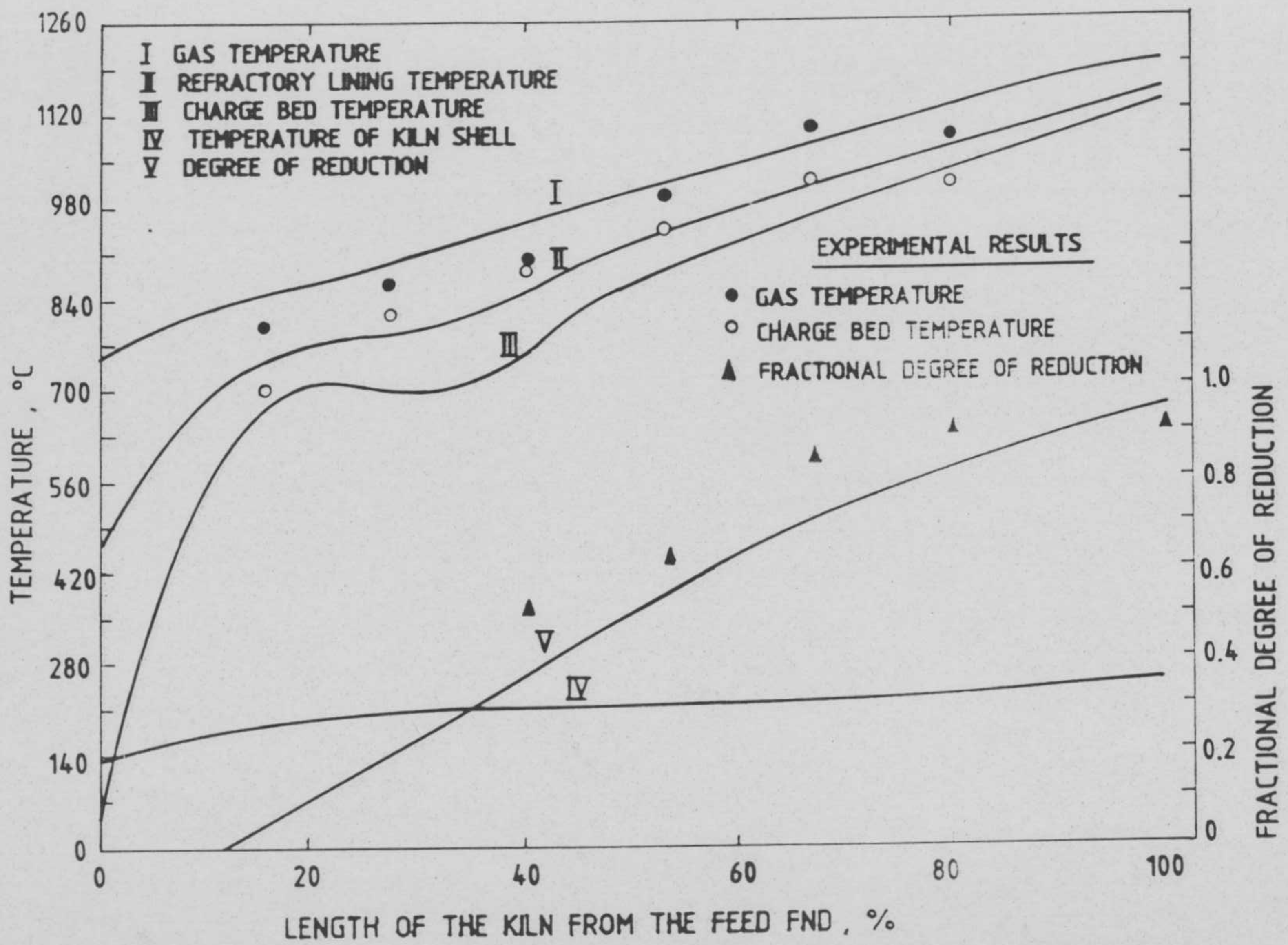

FIG. 5 : TEMPERATURE AND REDUCTION PROFILES ALONG THE LENGTH OF THE KILN

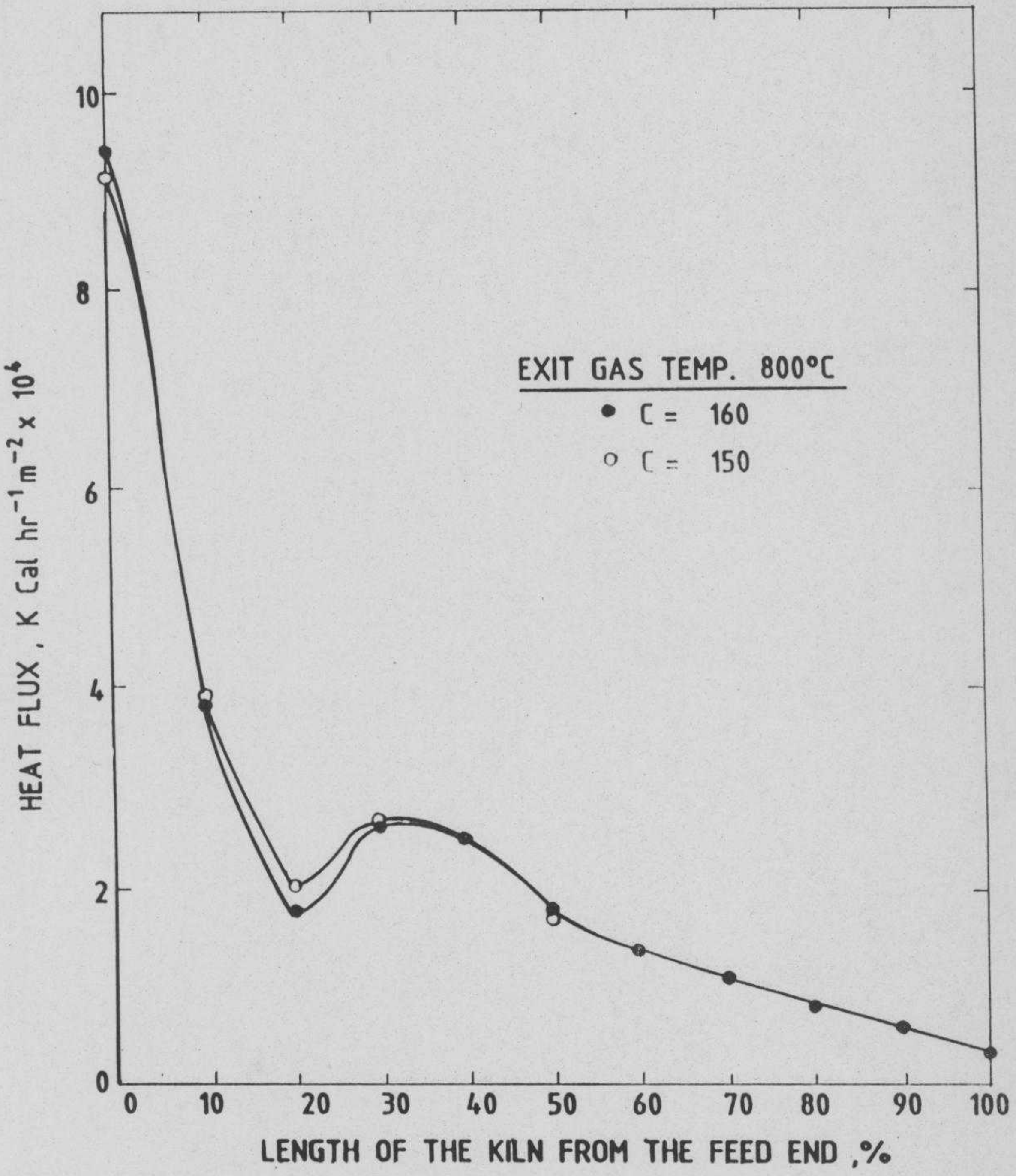

FIG. 6 CONDUCTIVE HEAT FLUX FROM THE LINING TO THE CHARGE AS A FUNCTION OF 'C'.

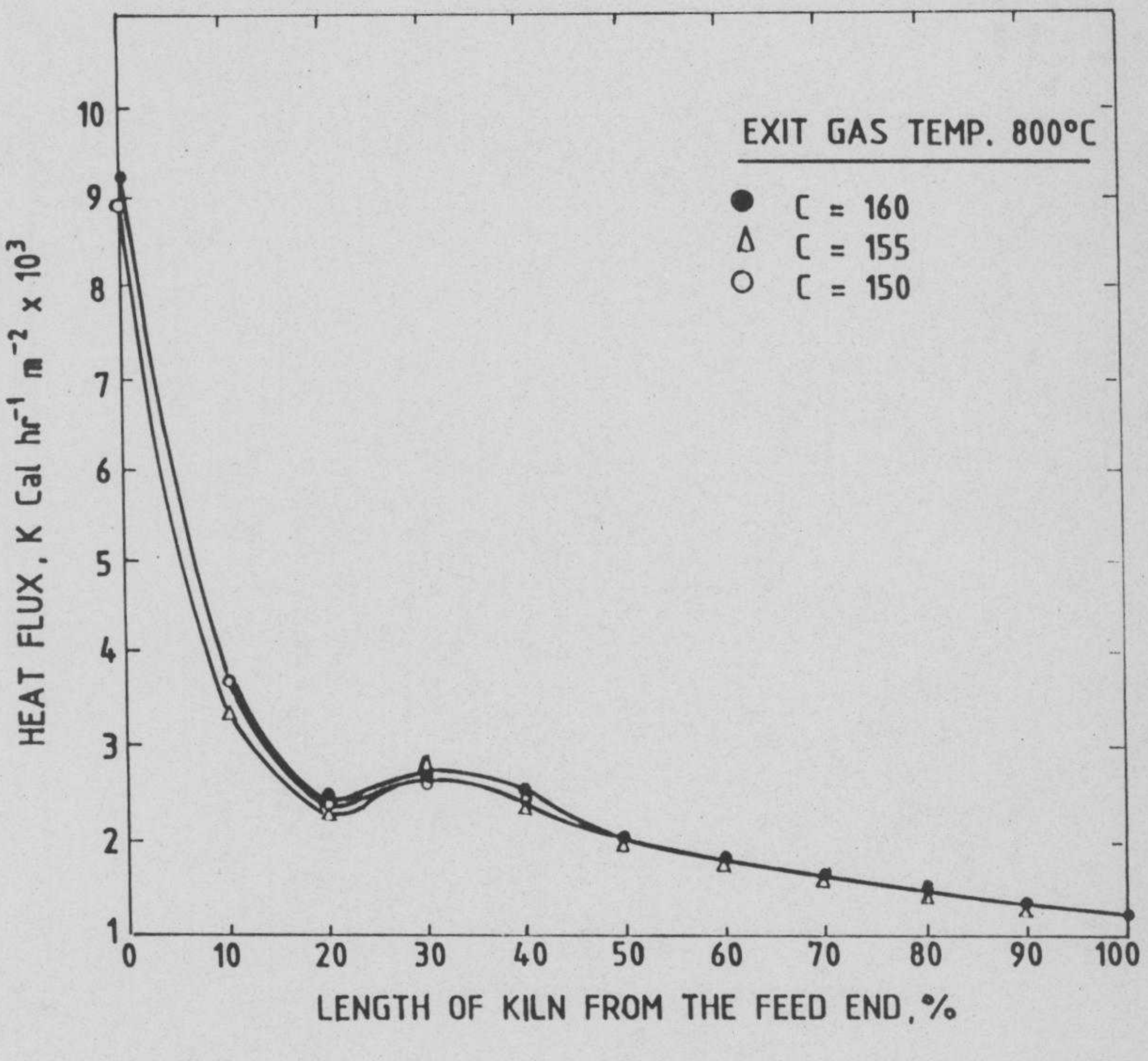

FIG.7 :CONVECTIVE HEAT FLUX FROM THE GAS TO THE KILN LINING AS A FUNCTION OF 'C'.

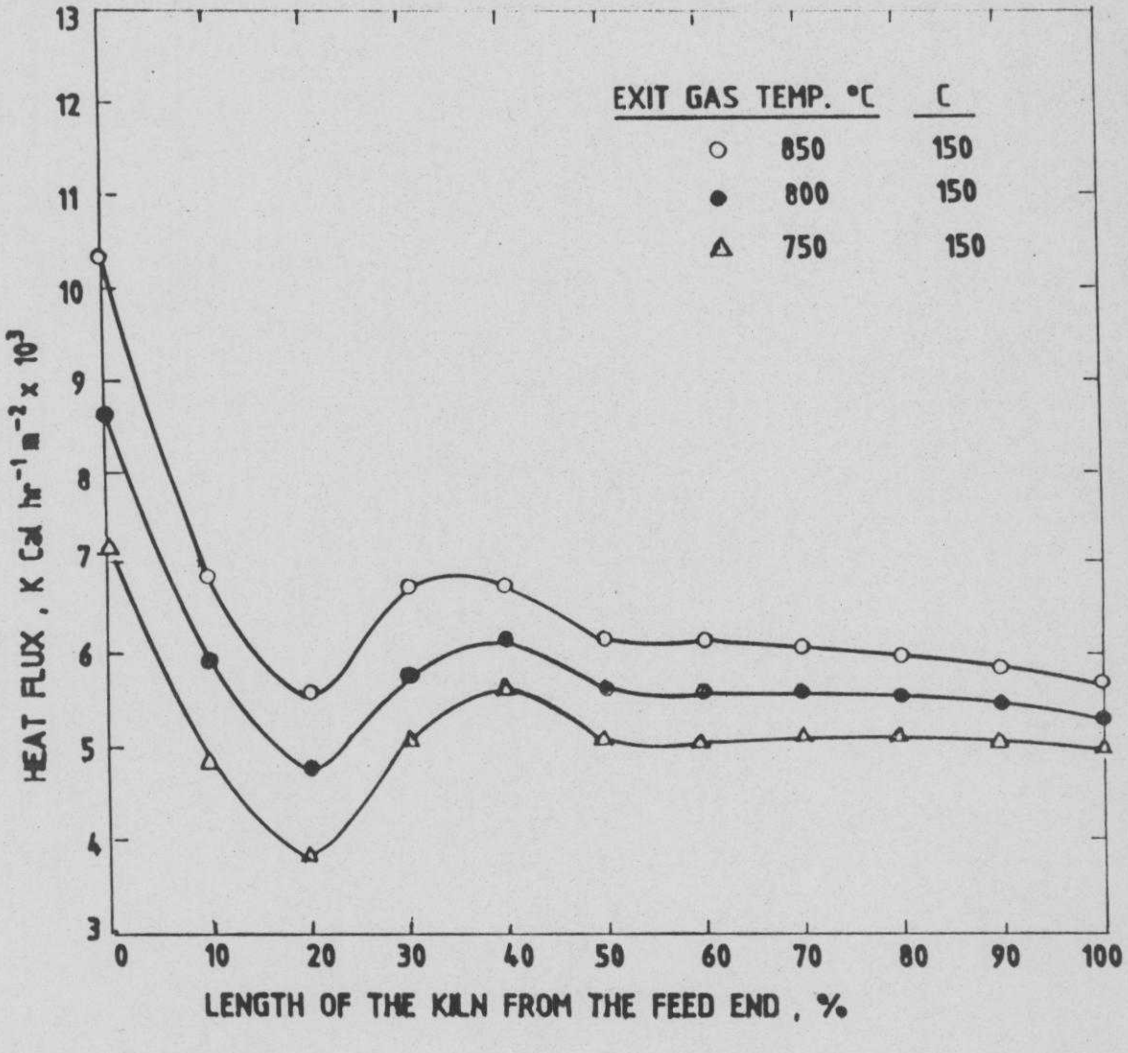

FIG. 8 : RADIATIVE HEAT FLUX FROM THE GAS TO THE KILN LINING AS A FUNCTION OF THE EXIT GAS TEMPERATURE.

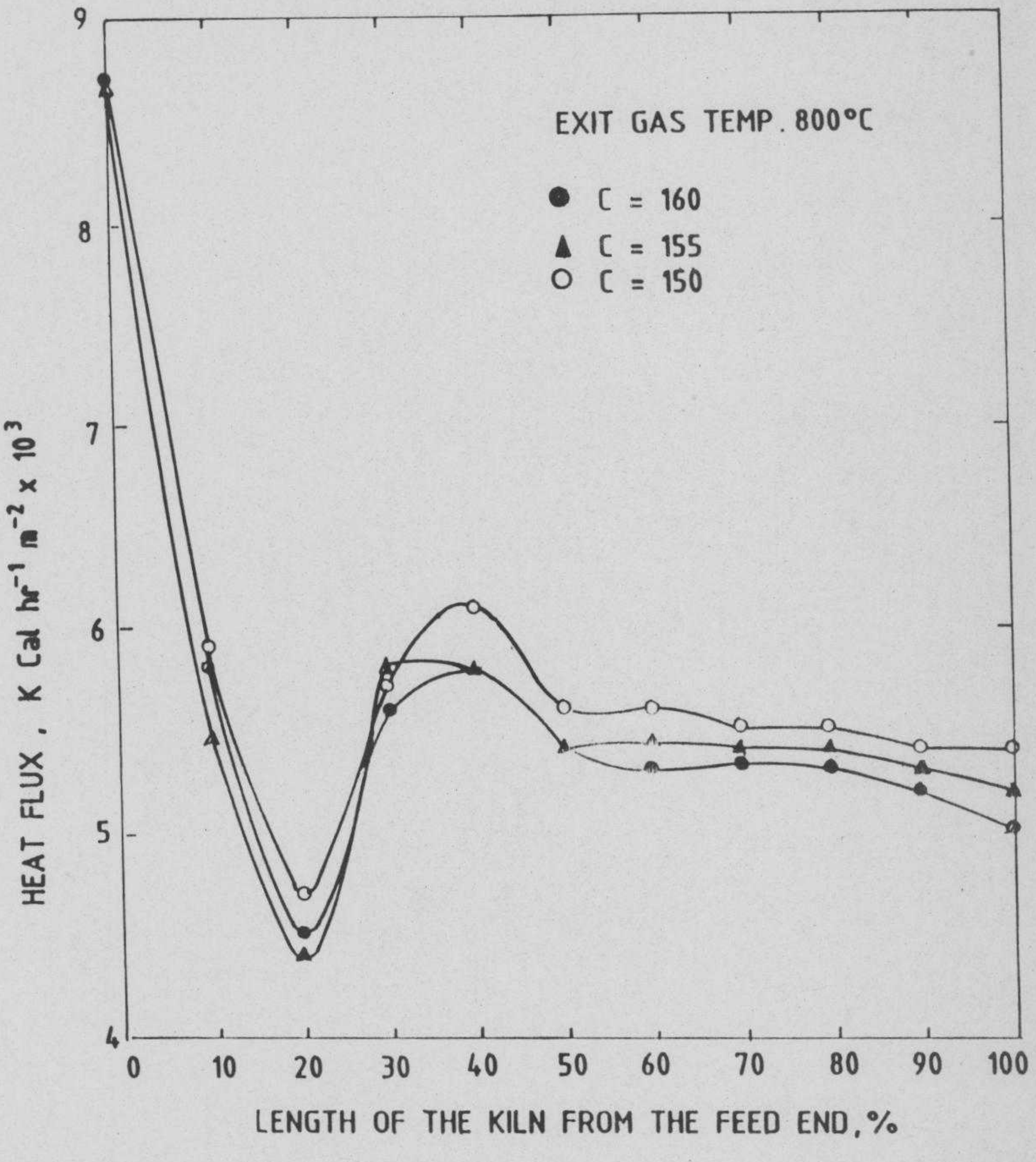

FIG.9 : RADIATIVE HEAT FLUX FROM THE GAS TO THE KILN LINING AS A FUNCTION OF 'C'.

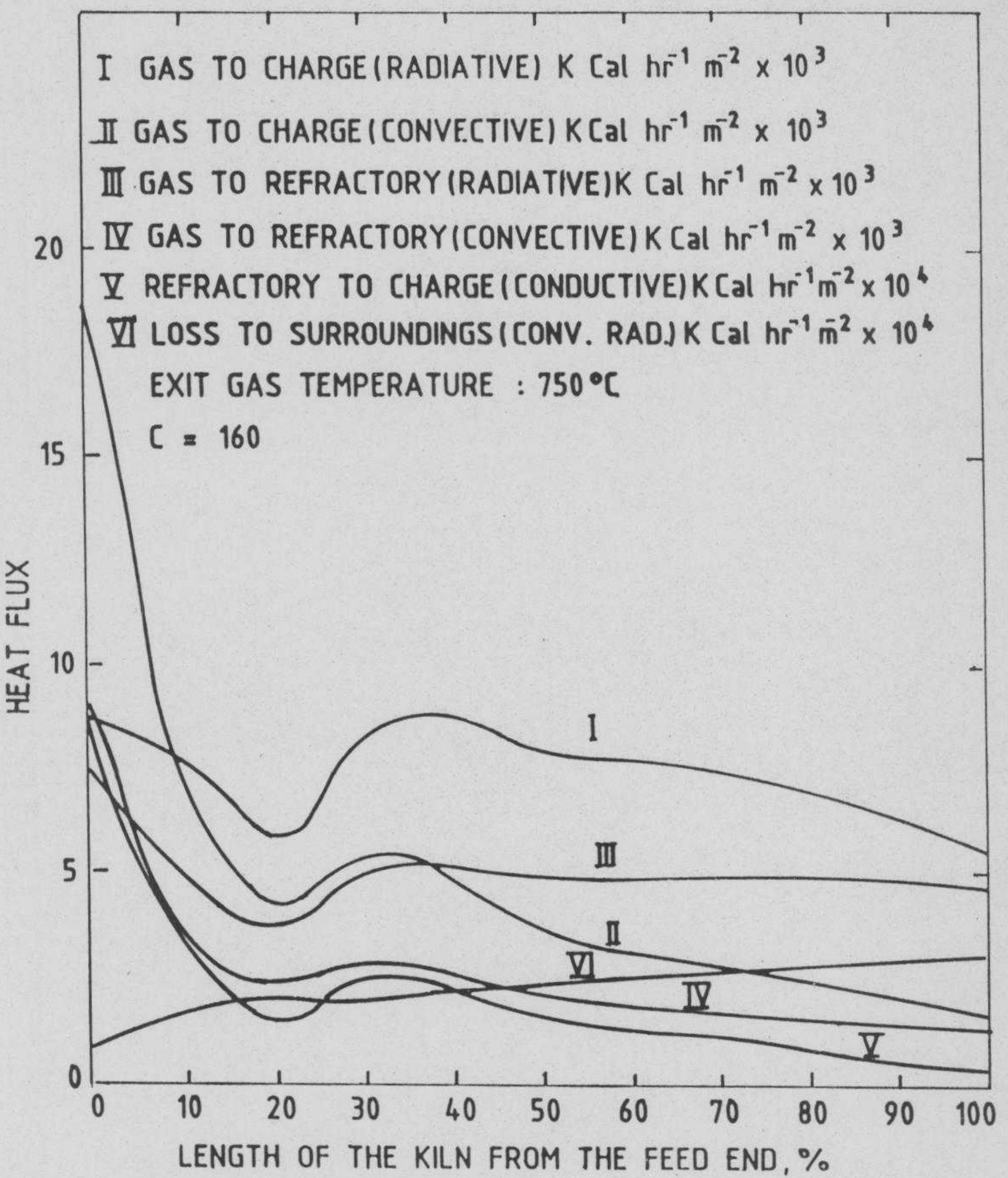

FIG. 10 : CONTRIBUTION OF VARIOUS HEAT FLUXES TO THE OVERALL HEAT TRANSFER.