CONTRIBUTION TO THE RESEARCH AND DEVELOPMENT OF RADIATION CHAMBERS IN STEAM REFORMING

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The mathematical model for investigation of combined heat transfer in the steam reforming radiation chamber with the application of zonal method, its development and final feature is discussed. The calculation results of the steam reforming radiation chamber unit generating syngas for the production of ammonia with the capacity of 1 000 t/day are confronted with the values measured on this unit. Also described is the effect of flue gas mixing on the characteristics of steam reforming process and application of the calculation method for the determination of life of reactor tubes in the field of creep.

In the steam reforming of methane, and/or hydrocarbon gas mixtures, the radiation chamber of primary reformer is the key technological equipment. The primary reformer furnace with the system of reactor tubes is, from the viewpoint of investments and operating exponses, rather extensive apparatus, that it is serviceable the mass of the tube system and even that of the furnace be minimized with the functional reliability maintaned.

The research activities were oriented on mastering the modelling process of steam reforming furnaces. The results of developmental activities is the elaboration of the set of calculation procedures that facilitated to obtain the data for the design of primary reformer furnace for the required process capacity and composition of reforming stock. The basic problem is the description of heat transfer in the furnace radiation part and the description of kinetics of reaction inside the reactor tubes.

The important path for the development of mathematical models and for making them more precise is their direct confrontation with experimental data. Analysing possible ways for obtaining experimental data we came to the conclusion that the behaviour of industrial reactor cannot be studied in the apparatus at atmospheric pressure. That is why the units generating syngas for the production of 1 000 t/day ammonia were measured in the primary reformer radiation chamber.

Confronting the measured and the calculated values, we selected as one of the main criteria the comparison of temperatures of outer surfaces of reaction tubes. These data affect, to a great extent, the designer's work in dimensioning the tubes.

Because of variance in measured and calculated course of temperatures of the reaction tubes outer surface it was necessary to verify the effect of selected parameters on the course of temperatures. Investigated were the effect of activation energy, initial velocity constants of chemical reaction, coefficients of heat transfer in the reaction tube catalytic space, effect of emissivity of reaction tubes surface, profile of fuel burning-up and length of flame of burners, namely, the quantities, whose values can generally be determined only approximately or from literary data. The results of simulation calculations were evaluated particularly with respect to the course and values of surface temperatures of tubes and in relation to the temperatures of the reaction mixture, output temperature of flue gases, degree of CH_4 conversion into CO and CO_2 and absorbed heat into the reaction tubes. The calculations based on models that consider plug flow of flue gases showed qualitative and quantitative discreppance in the calculated and measured profile of temperatures. The visualization of flue gases flow in the radiation chamber with the use of fume generators proved that the cause of discrepancy are deviations from the plug flow of flue gases. That is why mathematical model was formed for the calculation of heat transfer in the section of radiation chamber allowing to consider the mixing and recirculation of flue gases.

The relations used till now dimensioning the wall thickness of reaction tubes do not correspond with the conditions in elasticly plastic zone. That is why it was necessary, owing to the complex approach to the designing the radiation chamber of primary reformer, the mathematical model be worked up for the calculation of reaction tubes life giving a true picture of actual condition of material. The core of model is the calculation method for the determination of reaction tubes life in the field of creep based on expanded Lepin's constitutional equation of creep.

Mathematical Model for Simulation of Thermal-Chemical Phenomena

The mathematical model described below can be applied to the calculation of radiation chambers of reforming furnaces of shaft type that can differ each other by main dimensions and number of tubes, burners and their rows but having the furnace of the same geometry. In Fig. 1 is the diagram of radiation chamber of primary reforming unit of syngas for the production of ammonia (1 000 t/day) on which measurement was performed. The radiation chamber is of rectangular cross section with approximate dimension 15 × 11 m and length about 18 m. The reaction tubes are located vertically in 6 rows per 46 tubes. The preheated reaction mixture of hydrocarbon gas and water vapour enters the tubes from top at the pressure of about 3 MPa. The tube rows are heated from both sides by flue gases from the burners located in the furnace ceiling in seven rows per 15 burners; as a fuel the mixture of natural gas and relief gas from the ammonia synthesis was used. Both the working substances, namely, flue gases in the space of radiation chamber, and the reaction mixture in tubes proceed from top down in co-current flow. In the furnace bottom are the exhaust ducts of rectangular cross section, through which flue gases are led to the furnace convection section. The furnace walls are lined with refractory material lining. The reaction tubes with 145 mm o.d. and 17·5 mm wall thickness are centrifugally cast of high-alloy material. Filled are with catalyst in the form of Raschig rings 15 × 15 mm in size.

For the calculation of thermal fields and distribution of heat fluxes in radiation chambers a number of methods have already been developed, the principal survey of which is shown for example in ref.[1]. Based on the valuation of available materials on the calculation methods of radiation chambers, the zonal method seems to be most convenient. Its principle is described in ref.[2]. This method allows to construct models for the investigation of local thermal characteristics on the side of flue gases. The complete mathematical model originated through the amalgamation of the combustion space model and that of kinetic course of hydrocarbon mixture reforming with water vapour.

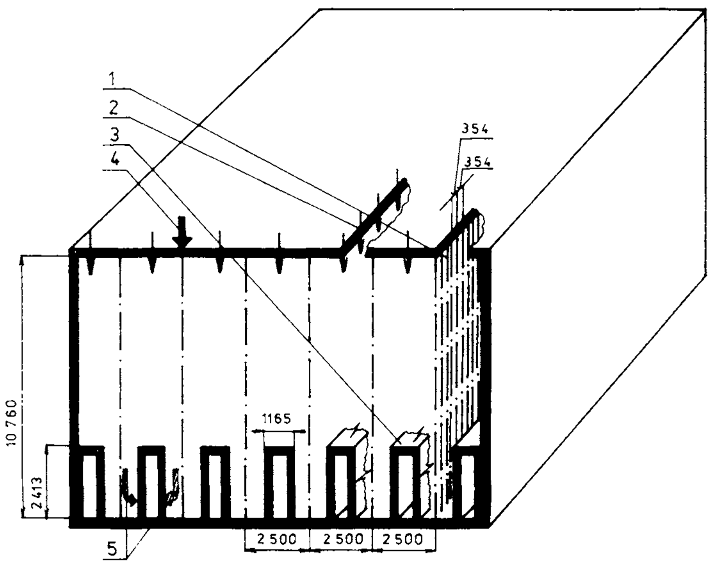

FIG. 1

Diagram of radiation chamber of furnace of primary reformer unit with 1 000 t of NH_3/day capacity. 1 Reaction tubes (6 rows/46 tubes); 2 burners (7 rows/15 burners); 3 exhaust ducts of flue gases; 4 inlet of reaction mixture; 5 outflow of flue gases

Model of Reforming Furnace Combustion Space

The zonal method enables to determine the distribution of temperatures and heat fluxes in gaseous volume (flue gases) even on the surface of reaction tubes and refractory and respects heterogeneity of thermal fields and real radiation properties (non-gray character) of flue gases. For the application of zonal method the space of flue gases, heat transfer surface and the radiation chamber refractory walls are divided into certain number of elements (zones) so that each zone could be taken for isothermic one with constant properties. For individual zones it is necessary to construct balance equations describing the thermal balance in zones (under steady state) conditions, whose solutions allow to obtain the unknown temperatures and heat fluxes in the given system. To obtain members of balance equations, it is necessary to construct gradually the matrices of direct exchange surfaces (characterizing the furnace geometry and effect of gray environment absorptivity), total exchange areas (comprising the effect of multiple reflection of radiation from the walls) and oriented exchange areas (respecting the presence of real non-gray gas). Also determined are to be heating conditions in the furnace and combustion conditions, coefficients of heat transfer by convection, and/or to select the flow field of flue gases.

The direct exchange areas (DEA) are the initial transfer factors featuring the basic significance for the whole thermal calculation by zonal method. Depending on correct determination of its values for concrete system is predominantly also the accuracy of final results. Designed and applied for mathematical model was the approximate method for determination of direct exchange areas based on mean geometric beam length. This method stems solely from derived analytic relations, which leads to considerable reduction of computation time for DEA calculation. The accuracy of method was verified by comparing it with precise values determined by numerical integration (based on Gauss integration formula for multiple integrals).

Giving a true picture of radiation properties of gaseous environment for the purpose of technical calculation with the aid of zonal method is the numerical method for calculation the coefficients of additive model presented in ref.[3].

Simplified Assumptions

To master complicated phenomena in the reforming furnace some simplified assumptions were accepted for mathematical model to investigate the heat transfer on the side of flue gases.

1) All the thermal and geometric parameters in the direction of the furnace length do not change; then, envisaged as heat transfer is investigated in one cross section of the radiation chamber as a two-dimensional problem. For an approximate verification of the assumption fightfulness the simplified calculation model for the investigation of heat transfer in the heat transfer space roughly corresponding with the section of radiation chamber was built up. According to the principles of zonal method we performed the calculation of temperatures of walls and density of heat flux removal at various lengths of chamber L_p. The dependences calculated for final length L_p differ from values for $L_p \to \infty$ significantly about for $L_p < 5$. With the length of actual reforming furnace the deviations are negligible.

2) Each row of tubes is substituted by equivalent, called specled wall, and by the ratio of heat transfer and free surfaces corresponding with the ratio of actual irradiated surface of tubes and the areas of gaps between tubes. The assumption is, because of determination of value of direct exchanging areas, indispensable. The ratio of heat exchange surface S_Q to the total surface S_C of equivalent tube wall is approximated by coefficient X depending on o.d. of reaction tubes $D_{E,T}$ and their spacing Z_T by the following relation

$$X = S_Q/S_C = 1 - \sqrt{[1 - (D_{E,T}/Z_T^2)]} + D_{E,T}/Z_T \operatorname{arctg} \sqrt{[(Z_T^2/D_{E,T}) - 1]} \,. \qquad (1)$$

Coefficient X is thus numerically coincident with currently used value of view factor between infinite full wall and the row of tubes located in parallel with it. The ratio of free surface S_0 to total surface of equivalent tube wall S_C is then given by the relation

$$Y = S_0/S_C = 1 - X \,. \qquad (2)$$

Model of Chemical Reaction

In the course of development of mathematical model of primary reformer even the method of description of chemical reactions inside catalytic bed was gradually making more precise. In the process of methane steam reforming, above all, the below reactions assert themselves.

$$CH_4 + H_2O = CO + 3H_2 \qquad (A)$$

$$CO + H_2O = CO_2 + H_2 \qquad (B)$$

First we started from simplified assumption that reaction (B) takes place much more faster than the first one, thus being practically in balance. The cracking reaction of methane with steam is generally taken for the first order reaction with respect to methane. On the basis of critical evaluation of papers published in literature engaged in kinetic course of steam reforming, the one-dimensional mathematical model was formed describing chemical phenomena and consumption of heat inside the reaction tube. The model is based on the solution of differential equations for the calculation of reaction mixture temperature, concentration of CH_4 and CO_2 and heat flux into individual zones of reaction tube, on the equations for the calculations of kinetics of reactions and on the relations for the calculation of heat transfer coefficient. The basic objective of this model is to find the heat flux into the tube in given zone for estimated or calculated temperature of the tube outer wall. Besides this, the temperature, pressure and concentration profile along the reaction tube are calculated from the given input data by this program. We assume constant values of main quantities, constant physical properties of reaction mixture and coefficient of heat transfer in individual zones.

Development Stages of the Mathematical Model Concept

The mathematical model concept for the simulation of thermal-chemical reactions in the reforming furnace radiation chamber has passed through several developmental

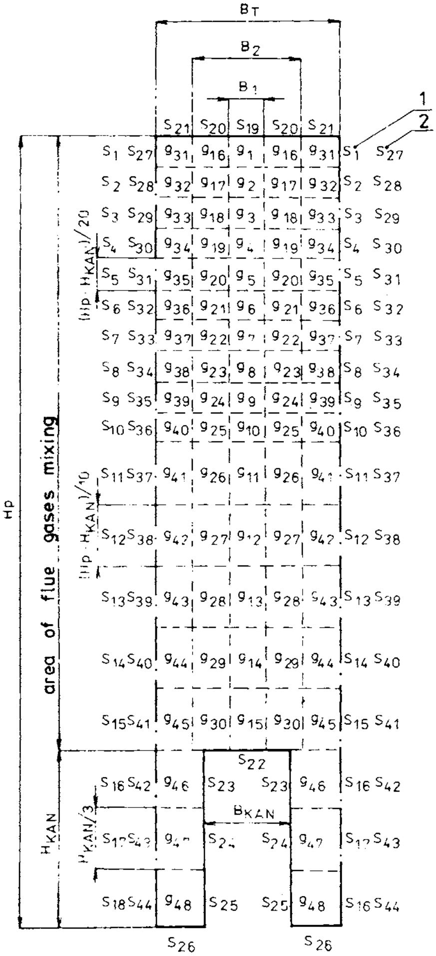

FIG. 2

Section of radiation chamber cross section and method of zoning. s Surface zones; g volume zones; 1 zones of tubes (heat exchange surface); 2 zones of gaps (adiabatic wall). Basic selectable dimensions (input data): $H_p(m)$, $B_T(m)$, $H_{KAN}(m)$, $B_{KAN}(m)$, $B_1(m)$, $B_2(m)$

stages with variations in the model of combustion space and the model of kinetic course of hydrocarbon mixture reforming.

The simulation calculations allowed to compare the model for heat transfer in the whole cross section of the radiation chamber with that considering only a section of radiation chamber cross section limited by two rows of reaction tubes. The courses and values of main characteristic quantities differed only slightly, thus, for further calculations, it was possible to use only the model that calculates the processes in the radiation chamber section.

The calculations, however, led to the determination of thermal profile of the reaction tube surface temperature with expressive maximum in the upper quarter of the tube length from the ceiling. The value of maximum surface temperature of the tube was unrealisticly high and also the character of calculated temperature profile did not correspond, in the main, with continuous course observed in process measurement (Fig. 5). With the aid of analysis we concluded that the cause of these deviations is the assumption of plug flow of flue gases from the burners to exhaust ducts. As available experimental possibility for the analysis of the radiation chamber aerodynamics we selected the visualization of flue gases flow in the furnace with the aid of smoke generator with blue smoke being sufficiently contrast against radiating walls[4]. The knowledge from the visualization was utilized in the simplified procedure for the description of flow field of flue gases. The main characteristics of recirculation field of flue gases can be determined by Thring–Newby's theory[5] based on simple assumptions about physical behaviour of free flows and flows in constrained space.

The way of zoning of the radiation chamber section is shown in Fig. 2. The tube wall is divided into surface zones, of which one half relates to the wall heat transfer surface representing the irradiated surface of tubes and one half is the free surface substituting the area of gaps between tubes. These zones are, during calculation, taken for adiabatic and as perfectly reflecting with radiance $\varepsilon_w = 0$. Simulated by this approximation is the fact that, in the space of radiation chamber, the intensity of flue gases radiation impinging on the tube wall from one and other side is approximately the same and the resulting heat flux in the gaps between tubes is zero.

Complete Mathematical Model for the Solution of Combined Heat Transfer

The total mathematical model results from combining the calculation procedures outside and inside the reaction tubes. The temperatures of reaction tube outer wall assessed or calculated on the model of combustion space are transferred as an input into the model of steam cracking in the reaction tube, from where we obtain the values of heat flux into individual surface zones of tubes that appear in balance equations of surface zones. Simple block diagram of complete mathematical model in Fig. 3. To determine unknown temperatures in the radiation chamber, it is necessary balance equations describing thermal equilibrium in zones to be constructed for individual surface and volume zones.

The thermal equilibrium in i^{th} surface zone being in contact with k^{th} volume zone can be described by the relation

$$\sum_{j=1}^{n}((S_i \leftarrow S_j)\,E_{w,j} - (S_j \leftarrow S_i)\,E_{w,i}) + \sum_{j=1}^{m}((S_i \leftarrow G_j)\,E_{g,j} - (G_j \leftarrow S_i)\,E_{w,i}) + \\ + \alpha_{k,i}S_i(t_{g,k} - t_{w,i}) - Q'_{w,i} = 0\,. \quad (3)$$

The flow field of flue gases in the mathematical model is alocated through relative mass flows of flue gases. The flow of flue gases from burners to the furnace bottom is

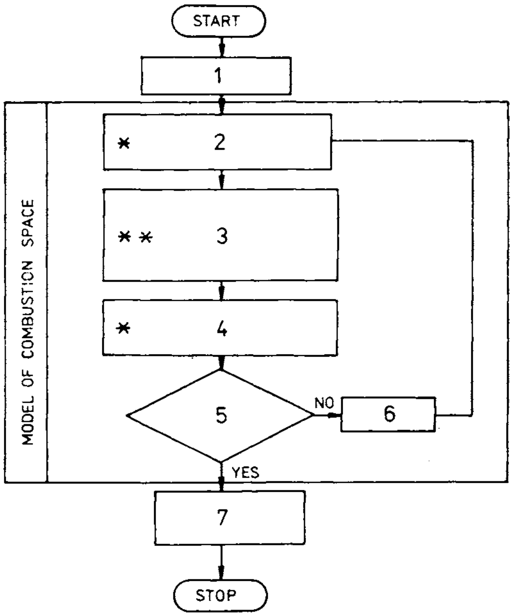

FIG. 3

Simplified flow chart of complete mathematical model for examination of heat transfer in radiation chamber. 1 Reading of input data and preparatory calculations; 2 iterative calculation of temperatures of volume zones and surface zones of refractory wall; 3 Model of chemical reaction – iterative calculation of heat fluxes into reaction tubes from estimated temperature their surfaces; 4 iterative calculation of new temperatures of surface zones of reaction tubes; 5 does the newly calculated temperature agree with original value? 6 new estimation of temperature; 7 calculation of resulting values and print of results. * Iterative calculation with respect to associated temperatures calculated from nonlinear algebraic equations (simultaneously with each newly calculated temperature the attendant value of oriented exchange areas are corrected); ** iterative calculation with respect to heat flux to reaction tube calculated from differential equation characterized by direct vertical flow, while the flow in opposite direction by recirculation vertical flow. The exchange of thermal energy of flue gases between the volume zones in horizontal direction is characterized also by direct and recirculation mass flows of flue gases. The balance of mass flow in volume zone (i, j) is shown in Fig. 4. And is generally given by relations

$$(P_{i,j} - R_{i,j}) + (V_{i,j} - U_{i,j}) = (P_{i+1,j} - R_{i+1,j}) + (V_{i,j+1} - U_{i,j+1}), \qquad (4)$$

where P is direct vertical flow, R is the recirculation vertical flow, U is direct horizontal flow and V is recirculation horizontal flow.

Then, it is assumed that the balance of mass flow of flue gases in i^{th} horizontal section is maintained:

$$\sum_{j=1}^{3} (P_{i,j} - R_{i,j}) = 100\,. \qquad (5)$$

(In horizontal direction are 3 volume zones, see Fig. 2.)

By multipling relative mass flows of flue gases by mass flow of flue gases and by corresponding mean specific thermal capacity, we obtain the thermal capacity of mass flow of flue gases from j^{th} to i^{th} volume zone $W_{g,j \to i}$ and/or conversely $W_{g,i \to j}$. The equation of thermal equilibrium for i^{th} volume zone lying in the area of flue gases mixing and being in contact with l surface and generally q volume zones is then given by the relation

$$\sum_{j=1}^{n} ((G_i \leftarrow S_j)\, E_{w,j} - (S_j \leftarrow G_i)\, E_{g,i}) + \sum_{j=1}^{m} ((G_i \leftarrow G_j)\, E_{g,j} - (G_j \leftarrow G_i)\, E_{g,i}) +$$
$$+ \sum_{j=1}^{l} \alpha_{i,j} S_j (t_{w,j} - t_{g,i}) + \sum_{j=1}^{q} (W_{g,j \to i} t_{g,j} - W_{g,i \to j} t_{g,i}) + Q'_{sp,i} = 0\,. \qquad (6a)$$

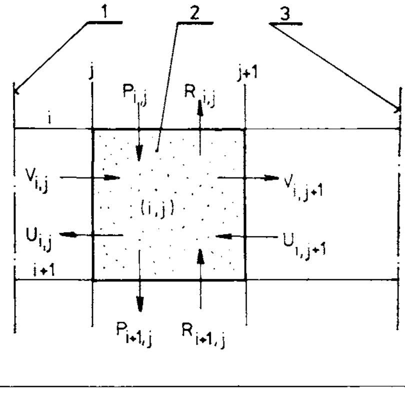

FIG. 4

Flue gases mixing between volume zones. 1 Axis of radiation chamber section (= axis of burners); 2 balanced volume zone; 3 tube wall; i, i + 1 horizontal cross sections; j, j + 1 vertical cross sections

In the field of plug flow of flue gases the thermal equilibrium is described by the relation

$$\sum_{j=1}^{n}((G_i \leftarrow S_j)\, E_{w,j} - (S_j \leftarrow G_i)\, E_{g,i}) + \sum_{j=1}^{m}((G_i \leftarrow G_j)\, E_{g,j} - (G_j \leftarrow G_i)\, E_{g,i}) +$$
$$+ W^{(1)}_{g,i} t^{(1)}_{g,i} - W^{(2)}_{g,i} t^{(2)}_{g,i} + \sum_{j=1}^{l} \alpha_{i,j} S_j (t_{w,j} - t_{g,i}) + Q'_{sp,i} = 0\,, \qquad (6b)$$

where $W^{(1)}_{g,i}$, $W^{(2)}_{g,i}$ is thermal capacity of mass flow of flue gases at the inlet, and/or outlet from i^{th} volume zone. The linkage between the input temperature of flue gases $t^{(1)}_{g,i}$, output temperature $t^{(2)}_{g,i}$ and that of flue gases $t_{g,i}$ in i^{th} volume zone is assumed in the form

$$T^4_{g,i} = \{[T^{(1)}_{g,i}]^4 + [T^{(2)}_{g,i}]^4\}/2\,.$$

Member $Q'_{sp,i}$ in Eqs (6) represents the quantity of heat that originated in fuel burning in burners. As the problem of burning is complicated by itself, the generation of heat in the flames of burners is involved approximately through selectible profiles of fuel burning including the Roesler's profile[6]. The calculation of oriented exchange areas determining in Eqs (3) and (6) the heat transfer by radiation between couples of surface and volume zones with real properties of flue gases respected is based on the additive model of real gas ("3 + 1" model is used[7], namely, the real radiation properties are substituted by the effect of three gray and one diathermal gas) and on the utilization of values of direct exchanging areas.

By writing out the balance relations (3) and (6) for all surface and volume zones the system of nonlinear algebraic equations is obtained

$$\begin{aligned} A_{w,i}T^4_{w,i} + B_{w,i}T_{w,i} + C_{w,i} &= 0 \qquad i = 1, 2, \ldots, n \\ A_{g,i}T^4_{g,i} + B_{g,i}T_{g,i} + C_{g,i} &= 0 \qquad i = 1, 2, \ldots, m \end{aligned} \qquad (7)$$

with the solution of which (by iterative procedure) the temperatures of all surface and volume zones can be determined. In the solution it was possible to use to advantage for example the iterative method utilizing the combination of Gauss–Seidel and Newton–Raphson's method that secures relatively fast convergency of calculation.

EXPERIMENTAL

The process measurement was performed on above described radiation chamber of primary reforming unit with the capacity of 1 000 t NH_3/day. Processed in the reaction furnace was the hydrocarbon stock in which methane was the dominant component at molar ratio of water vapour to methane 4·1. The reaction mixture entered the tubes with catalyst pre-heated to 485°C at 3·39 MPa pressure. The delivery of heat into the primary reformer was provided by burning fuel gas with calorific of 26 828 kJ m^{-3} with pre-heated air to 322°C at mean excess air 1·075. By fuel burning about 111 MW was liberated.

The objective of process measurement was to determine heat and mass balance of radiation chamber at the side of flue gases and reaction mixture, determination of surface temperatures of reaction tubes and refractory and visualization of flue gases flow in the radiation chamber.

Installed in the bottoms of exhaust ducts are bushes for exhausted thermocouples with Ni–CrNi sensor allowing to determine temperature of flue gases going out of the radiation chamber into the furnace convection part.

On one reaction tube, on two places, the reference contact was installed for the purpose of comparing the values of surface temperatures measured by contactless pyrometer Raynger R2HT. The device works on the basis of reception of infrared radiation in the field of so called spectral windows of radiation of three-atom gases (2·1 through 2·3 μm). Followed in the same way were the surface temperatures of the refractory inner wall.

By using the evacuated thermocouple from English company LAND with platinum sensor the possibility to measure the temperature of flue gases expanded by the own space of furnace with temperature of flue gases above 1 000°C.

RESULTS AND DISCUSSION

Confrontation of Calculations with Measuring Results

The mathematical model allows to obtain a notion about the distribution and course of temperature of flue gases, outer and inner surface of reaction tubes, reaction mixture, temperatures of refractory wall on the ceiling and on the bottom of radiation chamber, heat flux into tubes and their densities, pressures inside the tube, reaction velocities, stages of conversion and further quantities needed for the description of the steam reforming process along the length of reaction tube.
Table I shows a comparison of characteristic quantities calculated by the application of the mathematical model and the values measured on the process plant.

The temperature of entering reaction mixture could not be measured in the process unit with adequate accuracy. Based on the analysis of dry sample of production mixture it was found out that the total conversion of methane in the primary reformer during measurement was 68·8%. The calculation led to 67·2% conversion at 792°C of outlet temperature, which corresponds with temperature approximation to the equilibrium of 14·4 K, which is quite real.

On the basis of measurement of temperature of flue gases, going through individual exhaust duct out of the radiation chamber into the convection part of furnace the mean temperature of flue gases 964°C was determined, and this value was in good agreement with the data calculated from the mathematical model. Assuming that the calculated temperature 792°C was taken as the reaction mixture outlet temperature, very good agreement was achieved in the radiation chamber heat balance and the heat absorbed was 69 – 70 MW.

The mean thermal load of inner surface of reaction tubes was thus, on the basis of calculations and the measurement as well, determined with very small deviation and was about 68 kW m^{-2}.

TABLE I

Comparison of characteristic quantities calculated by mathematical model and measured on process plant

Quantity		Unit	Calculation	Measurement	Absolute difference	Relative difference
Outlet temperature of reaction mixture		°C	792	—[a]	—[a]	—[a]
Stage of CH_4 conversion to $CO + CO_2$		—	0·672	0·688	0·016	2·4
	H_2	vol. %	37·35	38·56	1·21	3·14
	CH_4	vol. %	5·04	4·82	0·22	4·56
Composition of	N_2	vol. %	0·43	0·43	0	0
reaction mixture	CO_2	vol. %	6·08	6·34	0·26	4·1
at the outlet	CO	vol. %	4·46	4·52	0·06	1·33
	H_2O	vol. %	46·64	45·33	1·31	2·89
Max. temperature of tube outer surface		°C	918·2	915–925	—	—
Outlet temperature of flue gases		°C	963·5	964	0·5	0
Mean heat load of tube outer surface		$kW m^{-2}$	51·68	51·42	0·26	0·5
Mean heat load of tube inner surface		$kW m^{-2}$	68·12	67·79	0·33	0·5
Absorbed heat		MW	68·91	69·576	0·34	0·5

[a] Measurement of outlet temperature of reaction mixture on process plant is not reliable.

When confronting the measured and calculated values, we consider the comparison of temperatures of outer surface of reaction tubes as one of important criteria, since these data affect to a great extent the designer's work in dimensioning wall thickness of reaction tubes. The measurement was performed on the process unit with above mentioned Raynger R2HT apparatus and about 4 000 readings of surface temperatures on 36% of tubes of furnace radiation chamber.

By processing these data we obtained the average course of temperature of tube outer wall versus longitudinal coordinate going from the furnace ceiling. This course is shown in Fig. 5. The maximum temperature of tubes was about within the range from 915 to 925°C. The mathematical model, which is, from the viewpoint of temperature calculation of reaction tube outer surface, very sensitive to the method of calculation of heat transfer coefficient inside the catalytic bed, provided, in the present case, maximum temperature of the tube outer surface 918·2°C, while, even from the viewpoint of quality, the calculated course of surface temperature was relatively in good agreement with the course of temperature of "mean" tube obtained by measurement.

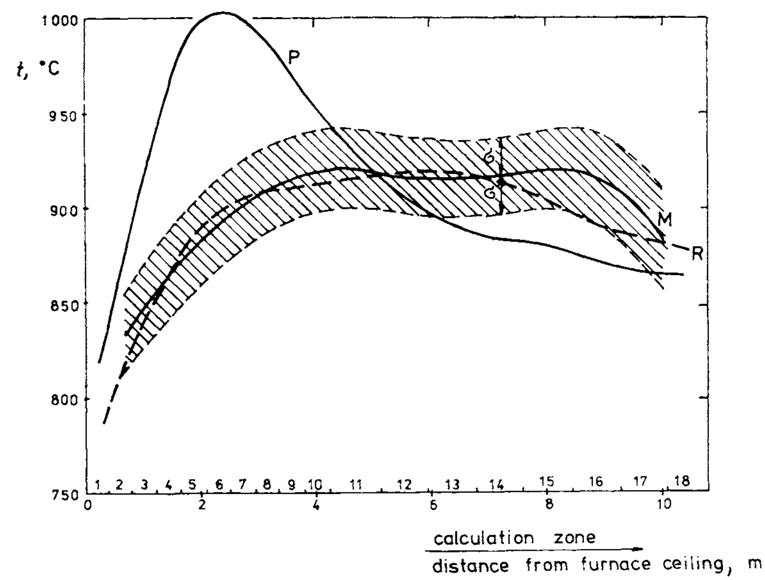

FIG. 5

Courses of temperatures on reaction tube outer surface along its length. M curve plotted from measured values; P model value, use of plug flow of flue gases; R model values, model comprising flow field of flue gases

The measurements performed until now did not allow responsible comparison of observed data with calculation results from the furnace ceniling. The orientation measurement of flue gases temperature at three height levels from the furnace ceiling indicate the right to choose the mathematical model with mixing gases flue which provides the flat profile of average temperature of fle gases from the furnace ceiling.

Mathematical Model for the Calculation of Life of Reaction Tubes

The thermal characteristics obtained by calculation with the aid of the mathematical model for simulation of thermal-chemical phenomena can be utilized as input data for the calculation of life of tubes in creep deformation, and/or in dimensioning the tubes. Contrary to the relations for the calculation of wall thickness of the cylindrical jacket with inner positive pressure[8], the model stems from the equation for creep strain velocity having the form[9-11]

$$\dot{\varepsilon} = m\varepsilon^{1-n} \exp\left[\alpha\sigma_0(1 + k_1\varepsilon + K)\right], \tag{8}$$

where ε is the creep (plastic) strain, m is the coefficient (time measure), n is exponent of hardness, σ_0 initial stress, k_1 is the coefficient of effective stress growth due to

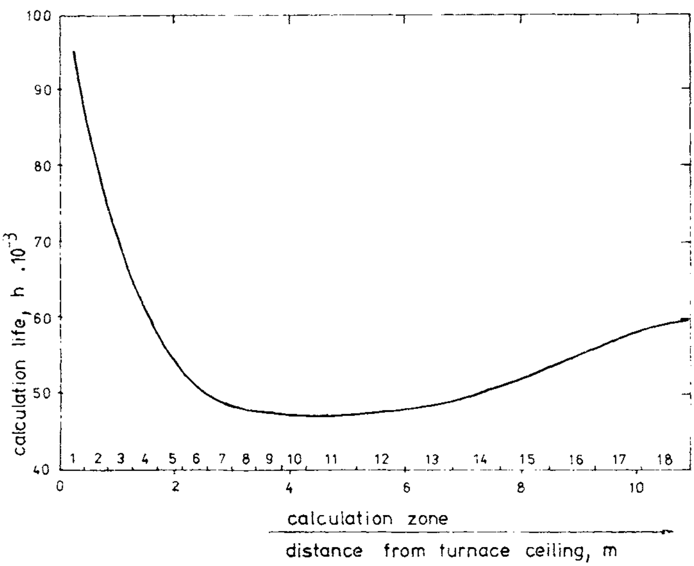

FIG. 6

Course of reaction tube life along its length. $\mu = 1{\cdot}3$ (safety), $\varepsilon_{tot} = 1\%$ (total strain) material transversal contraction ($k_1 = 1$), and for failure K the below relation applies

$$K = \int_0^\tau k_2 \, d\varepsilon + \int_0^\varepsilon k_3 \sigma_0 \, d\tau \,, \tag{9}$$

where τ is time, k_2 is the strain coefficient of damage and k_3 is time damage coefficient.

Coefficients $k_1, k_2, k_3, m, n, \alpha$ in Eqs (*8*), (*9*) – parameters of mathematical model for creep – are the functions of temperature and were obtained on the basis of creep tests performed at constant temperature for the tube material Cr24Ni24Nb (ref.[12]) and apply within the range of temperatures from 700 to 950°C.

Provided that the initial stress is constant, the system of Eqs (*8*), (*9*) can be integrated in closed form, thereby obtaining

$$\tau = 1/\alpha\sigma_0^2 k_3 \ln \{[\sigma_0 k_3 \Gamma(n; \alpha\sigma_0 k \varepsilon_{cr})]/[m \exp(\alpha\sigma_0)(\alpha\sigma_0)^{n-1} k^n] + 1\} \tag{10}$$

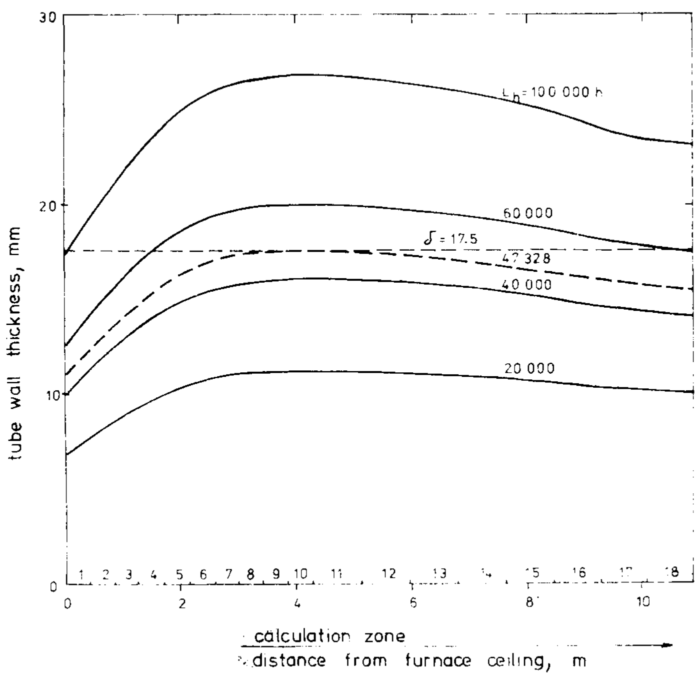

FIG. 7

Course of tube wall thickness along its length vs life. L_h calculation life, h; $\delta = 17{\cdot}5$ mm, reaction tube wall thickness for reforming furnace calculated. Note: Life 47 328 hours is the lowest calculation life in tube critical spot (calculation zone No. 10) where $k = k_1 + k_2$ and Γ is incomplete gamma function. Equation (*10*) allows to calculate the time to reach the selected (functionally admissible) creep strain.

The mathematical model that calculates the time to reach the calculation life of reaction tube takes over, from the model simulating the thermal-chemical processes, the courses of reaction tube temperatures (Fig. 5), pressure inside the tube, dimensions of tube and respects the distribution of reaction tube into surface zones needed for the application of zonal method. Allocated further on is the safety and admissible total strain ε_{tot}, for which the calculation life L_h is calculated. The course of reaction tube life vs its length is plotted in Fig. 6. From the dependence it is clear that the lowest life of tube is achieved in calculation zone No. 10 about 4 m far from the furnace ceiling (critical zone).

For the calculation of tube wall thickness the calculation method of life determination is comprised in the iterative algorithm and the mathematical model for the tube dimensioning calculates the tube wall thicknesses in individual zones for the allocated calculation service life. The results of calculation for lives of 20, 40, 60 and 100

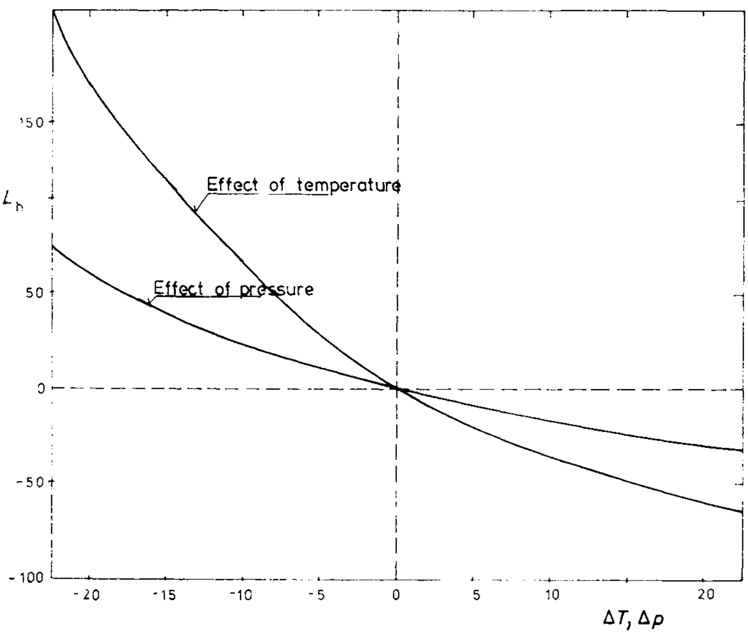

FIG. 8

Grafical representation of the dependence of life change on temperature of the tube wall and/or internal pressure. ΔT shift of temperature course in tube wall, %; ΔL_h change in life, %; Δp change in pressure, %

thousands hours are graphically represented in Fig. 7. Also on the graph is the course of staggered tube wall thickness when considering the minimum time value to achieve the calculation life for the critical zone (47 328 hours).

From the simulation calculations with creep model it has been established that the pressure and, above all, the temperature exert significant effect on the change in service life of the reforming funace reaction tubes (Fig. 8).

LIST OF SYMBOLS

A	coefficient of non-linear equation
B	coefficient of non-linear equation
C	coefficient of non-linear equation
$D_{E.T}$	outer diameter of reaction tube, m
E	density of radiation flux of black body with temperature T ($E = 5{\cdot}67 \,.\, 10^{-8}\, T^4$), $W\,m^{-2}$
$(G_i \leftarrow G_j)$	oriented exchange area for radiation flow originating from j^{th} volume zone and absorbed by i^{th} volume zone, m^2
$(G_i \leftarrow S_j)$	oriented exchange area for radiation flow originating from j^{th} surface zone and absorbed by i^{th} volume zone, m^2
k_1	coefficient of growth of effective stress due to transversal contraction of material
k_2	deformation coefficient of damage
k_3	time coefficient of damage, $MPa^{-1}\, s^{-1}$
K	coefficient of damage
L_h	calculation life, h
m	number of volume zones
	coefficient (time measure)
n	number of surface zones
	coefficient of hardening
P	direct vertical flow
Q'	heat flux, W
R	recirculation vertical flow
S	surface area, m^2
t	temperature, °C
T	temperature, K
U	direct horizontal flow
V	recirculation horizontal flow
W	thermal capacity of mass flow, $W\,K^{-1}$
X	relative part of heat exchange area of equivalent tube wall
Y	relative part of free area of equivalent tube wall
Z_T	spacing of radiation tubes, m
α	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
	coefficient of strain velocity sensitivity to stress
$\Gamma(n; x)$	incomplete gamma function
δ	thickness of tube wall, m
ε	emissivity
	creep plastic strain
$\dot{\varepsilon}$	strain rate, s^{-1}

φ	angular coefficient
μ	safety factor
σ	stress, MPa
τ	time, s

Subscripts

C	total area
cr	creep
g	gas, volume zone
$i \to j$	from i^{th} to j^{th} zone
0	free area
Q	heat exchange area
sp	combustion
tot	total
w	surface, surface zone

Superscripts

(1)	inlet value
(2)	outlet value

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