MATHEMATICAL ASSUMPTIONS FOR THE CALCULATION OF CLEAN WALL TEMPERATURES AND THE THICKNESS OF CRUSTS ON THE HAIRPINS OF COAL PASTE PREHEATERS.

Experience with paste preheaters shows that with increasing on-stream time the pressure drop on the product side increases steadily under constant operating conditions; this results in higher recycle heating-gas temperatures for the same quantity of heat transferred which in turn leads to an increase in the wall temperature of the hairpin tubes. On the basis of actual physical inspection this phenomenon is explained by the formation of crusts on the inside of the hairpin tubes; during continued operation the thickness of these crusts of low heat conductivity increases slowly. The following method of calculation has been worked out by Dr. Wilde, I. G. Oppau, and is to be used for the evaluation of data on paste preheaters collected from all hydrogenation plants.

1) Temperature of the clean outside wall. The heat transfer coefficient for the clean outside wall for preheaters of the same design and operating conditions are designated as α_a. The temperature flow in the preheater must, of course, be known. The temperatures are best taken from the log-books of the corresponding plant units and are evaluated according to experience. The heat losses of the preheaters (3.10^5-4.10^6 kg.-cal./hour) must be reasonably distributed over the preheater sections and the calculated mixing temperature for paste and gas should be used. The following values are used for the average spec. heat:

recycle heating gas: 0.32 kg. cal./standard m^3
hydrogen: 0.34 kg. cal./standard m^3
coal paste: 0.55 kg. cal./kg.

The value 0.55 which includes flushing oil is, according to the I. G., valid over the entire temperature region 250-450°C. at an average content of solid matter of about 48%. If the concentration deviates much from this value the specific heat value changes within narrow limits as shown in fig. 1. Of course, the various qualities of material flowing in the paste and mixture section and also the quenching gas for the hot separator must be taken into consideration. Finally, the efficiency of the preheater, which should be around 70%, should be checked since it indicates whether the assumption of the quantity of recycle heating gas has been reasonable.

The value for α_a has been obtained by using the simple case of a single hairpin tube for gas. A heat transfer coefficient of K = 10-12 kg. cal./m^2/hour is calculated for the finned surface in this case. The internal surface of the hairpin is generally F_i = 8 m^2, the entire outer surface is F_a = 200 m^2 for the narrow 14 mm fin spacing and F_w = 150 m^2 for the wide 20 mm spacing. The heat transfer coefficient assumed for the internal surface can be generally expressed as follows:

$$K_i = K \frac{F_a, w}{F_i} \text{ , assuming } \frac{F_a}{F_i} = 25 \text{ or } \frac{F_w}{F_i} = 18.7.$$

For the more important narrow fin spacing it follows that:

$$K_i = (10-12) \ 25 = 250 - 300 \text{ kg. cal./}m^2\text{/hour.}$$

For a cylindrical tube without fins fabricated from a material of the heat conductivity λ_R the following equations can be written:

$$\frac{1}{K_1\,D_1} = \frac{1}{\measuredangle_1\,D_1} + \frac{\ln\frac{D_a}{D_1}}{2\,\lambda_R} + \frac{1}{\measuredangle_a\,D_a}$$

$$\frac{1}{K_1} = \frac{1}{\measuredangle_1} + \frac{D_1\,\ln\frac{D_a}{D_1}}{2\,\lambda_R} + \frac{1}{\measuredangle_a}\,\frac{D_1}{D_a}$$

If λ_R is taken as 30 kg. cal./m/hour/°C. and $D = 0.171$ m and $D_1 = 0.090$ m, the following equation results:

$$\frac{1}{K_1} = \frac{1}{\measuredangle_1} + 0.00096 + \frac{1}{\measuredangle_a}\quad 0.526$$

$$\frac{1}{\measuredangle_a} = \frac{\frac{1}{K_1} - \frac{1}{\measuredangle_1} - 0.00096}{0.526}$$

For pure hydrogen at high pressure $\measuredangle_1$ must assume a large value. The lower limit lies at about 2000, the upper one at ∞.

	$\measuredangle_1 = 2000$		$\measuredangle_1 = \infty$	
	$K_1 = 250$	$K_1 = 300$	$K_1 = 250$	$K_1 = 300$
$\frac{1}{\measuredangle_a}$	$\frac{0.00400-0.00146}{0.526}$ = 0.00480	$\frac{0.00300-0.00146}{0.526}$ = 0.00355	$\frac{0.00400-0.00096}{0.526}$ = 0.00580	$\frac{0.00333-0.00096}{0.526}$ = 0.00450
$\measuredangle_a$	208	282	172	222
	average 245		average 197	

Since $\measuredangle_a$ is used for calculating the external and internal wall temperatures from the temperatures of the recycle heating gas and the product it is recommended to use

$$\measuredangle_a = 250 \text{ kg. cal./m}^2\text{/hour/°C.}$$

to ensure that high calculated values are obtained. The temperature flow diagram for the preheater indicates the average heat transfer K from the distribution of hairpin tubes in each section and the initial and end temperature differentials T' and T''. K must then be converted to K_1. The exact logarithmic average for the temperature differential $\frac{T'-T''}{\ln\frac{T'}{T''}}$ is only required if the ratio $\frac{T'}{T''}$ deviates strongly from 1 since otherwise the arimethic average $\frac{T'+T''}{2}$ is satisfactory.

Table 1

$\frac{T'}{T''}$	1.0	1.5	2	2.5	3
$\frac{T \text{ av. arithm.}}{T \text{ av. logarithm.}}$	1.00	1.01	1.04	1.07	1.10

The wall temperatures to be found are those of the recycle heating gas temperature t of the corresponding location lowered by a definite fraction of the momentary temperature differential, independent, mathematically speaking, from the corresponding value α_1. If t_p is the corresponding product temperature it follows that $T = t_2 - t_p$ and by using the auxiliary value K_1 the external wall temperature is found as follows:

$$t_a = t_2 - (t_2 - t_p)\frac{\frac{1}{\alpha_a}\frac{Di}{Da}}{\frac{1}{K_1}}$$

$$t_a = t_2 - (t_2 - t_p)\frac{K_1}{\alpha_a\frac{Da}{Di}}$$

$$t_a = t_2 - (t_2 - t_p)\frac{K_1}{475}$$

The internal wall temperature is found correspondingly:

$$t_1 = t_2 - (t_2 - t_p)\frac{\frac{1}{\alpha_a}\frac{Di}{Da} + \frac{Di}{2\lambda_R}\ln\frac{Da}{Di}}{\frac{1}{K_1}}$$

$$t_1 = t_2 - (t_2 - t_p)\frac{K_1}{375}$$

Some of the temperatures found in this way can be compared with measured values which permits an estimation of the unavoidable discrepancies.

Using the constant value for α_a it is possible by using K_1 to obtain the mathematically required heat transfer coefficient α_1. This coefficient should be valid for the internal wall of the paste hairpin provided this is free from deposits. If a value for the actual heat transfer coefficient for wall-paste, α_B, is estimated in someway it is possible to determine the thickness of the deposit crust, δ, by means of the heat conductivity of the latter, $\lambda \sim 1.5$ kg. cal./m/hour/°C. Assuming that the layer is a plane surface it follows that,

$$\frac{1}{\alpha_1} = \frac{1}{\alpha_B} + \frac{\delta}{\lambda}$$

$$\delta = \lambda\left(\frac{1}{\alpha_1} - \frac{1}{\alpha_B}\right).$$

Calculations of this kind are, however, without real technical value as long as λ_B cannot be determined reliably. A certain indication of the actual magnitude of α_B is obtained by calculating α_1 values using a K-value determined experimentally on new, clean hairpin tubes and the previously calculated value for α_a; according to this estimate λ_B lies between 150 and 350 kg. cal./m²/hour/°C. depending on the temperature region and these values are in accordance with K-values for coal paste heat exchangers.

2. Increase in pressure drop.

Theoretically it should be possible to make conclusions on the average thickness of crusts from the pressure drop. The friction coefficient ζ is considered as constant. For the clean tube the subscript "0" is used

$$\Delta P_0 = \zeta \frac{L}{D_1} q_0$$

In the above equation, L signifies the linear length of a hairpin tube including the linear length of the return bends, etc.; the back-pressure $q_0 = \frac{w_0^2}{2g} \gamma_b$ in the unrestricted diameter is directly dependent on the throughput of hydrogen, paste and oil but also on pressure and temperature. Subscript "b" in this case signifies the state of the tube wall in actual operation. It is assumed that the diameter decreases from D_1 to D_b so that $D_b = D_1 - 2\delta$, where δ does not have to have the same value as in the previous discussion. The product flow rate then must increase with the ratio of the diameters and the actual pressure drop Δp_b (kg/m²) as compared to the calculated pressure drop will be in accordance with the following equation:

$$\frac{\Delta P_b}{\Delta P_0} = \left(\frac{D_1}{D_b} \right)^5$$

$$\frac{\delta}{D_1} = \frac{1}{2} \left(1 - \sqrt[5]{\frac{\Delta P_0}{\Delta P_b}} \right)$$

For thicknesses which are small in comparison to the diameter, the equation is simplified to the following form:

$$\frac{\Delta P_0}{\Delta P_b} = \left(1 - \frac{2\delta}{D_1} \right)^5 \sim 1 - 10 \frac{\delta}{D_1}$$

$$\frac{\delta}{D_1} \sim \frac{1}{10} \left(1 - \frac{\Delta P_0}{\Delta P_b} \right)$$

The values for ΔP are taken from plant data which are corrected for the pressure drop due to the pipe and check valve outside the preheater and due to the heat exchanger; the corrected values are then calculated for a single hairpin tube. Δq_0 must be calculated by using certain assumptions. Checking can be limited to the mixture section. The following calculation may serve as example.

It should be put through:

hydrogen: W standard m³/hour, $\gamma_r \sim 0.25$ kg./standard m³, paste (including pasting and flushing oil): B kg./hour, $\gamma_B \sim 900$ kg./m³.

Average values for pressure and temperature in the preheater are 700 atm. and 375°C. and the compressibility is taken as ~ 1.2. From these assumptions it follows:

$$\frac{\gamma_w}{\gamma_r} = \frac{700}{1} \times \frac{288}{273 + 375} \frac{1}{1.2} = 258$$

	Operating Volume	Weight		
Hydrogen	$\frac{W}{256}$	0.25 W	Product velocity	$W_B = \dfrac{(\frac{W}{256} + \frac{B}{900})}{3600 \frac{\pi}{4} D_1^2}$
Paste + Oil	$\frac{B}{900}$	B	Sp. gravity of mixture $\}\gamma_b$	$= \dfrac{0.25 W + B}{\frac{W}{256} + \frac{B}{900}}$

The back pressure then is:

$$\gamma_o = \frac{1}{2g} \frac{(\frac{W}{256} + \frac{B}{900})^2}{(3600 \frac{\pi}{4} D_1^2)^2} \times \frac{0.25 W + B}{\frac{W}{256} + \frac{B}{900}}$$

$$= \frac{\left(\frac{W}{256} + \frac{B}{900}\right)\left(\frac{W}{4} + B\right)}{19.62 (3600 \frac{\pi}{4} D_1^2)^2}$$

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or transformed for the paste throughput B:

$$\gamma_o = \frac{1}{19.62} \frac{B^2}{(3600 \frac{\pi}{4} D_1^2)^2} (1 + 1/4 \frac{W}{B}) (\frac{1}{256} \frac{W}{B} + \frac{1}{900})$$

$$= \frac{1}{19.62 \cdot 900 (3600 \frac{\pi}{4} D_1^2)^2} B^2 (1 + \frac{1}{4} \frac{W}{B})(1 + \frac{900}{256} \frac{W}{B})$$

In order to obtain a value close to 1 for the correction factor which is independent from $\frac{W}{B}$ a "standard mixture" is chosen containing equal parts of W and B. The equation is then transformed as follows:

$$= \frac{1}{19.62 \cdot 900 (3600 \frac{\pi}{4} D_1^2)^2} B^2 (1 + \frac{1}{4}) (1 + \frac{900}{256}) F$$

$$= \frac{5.6}{19.62 \cdot 900 (3600 \frac{\pi}{4} D_1^2)^2} B^2 F$$

The correction factor becomes then:

$$F = \frac{(1 + \frac{1}{4} \frac{W}{B}) (1 + 3.48 \frac{W}{B})}{5.6}$$

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For $D_1 = 0.09$ m = 9 cm

$$q_o = \frac{5.6}{19.62 \cdot 900 \cdot 22.9^2} \; B^2 F$$

$$= \frac{B^2 F}{1.65 \cdot 10^6}$$

Table 2 and figure 2 give F for various values of $\frac{B}{W}$.

<div align="center">Table 2</div>

$\frac{B}{W}$		0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
$\frac{1}{4}$	$\frac{W}{B}$	0.5	0.417	0.357	0.313	0.278	0.250	0.227	0.208
3.48	$\frac{W}{B}$	6.96	5.80	4.98	4.35	3.87	3.48	3.16	2.90
	F	2.13	1.72	1.45	1.26	1.11	1.0	0.91	0.84

In the region under consideration the following approximation happens to be valid:

$$F \sim \frac{W}{B} \quad \text{and also}$$

$$q_o \sim \frac{B \cdot W}{1.65 \cdot 10^6}$$

For values for $\frac{B}{W}$ smaller than those given in the above table F increases more rapidly than indicated by the approximate equation.

The pressure drop per hairpin tube with clean walls can be calculated from the following equation assuming $L \sim 30$ m and a friction coefficient $\zeta \sim \frac{1}{30} \pm 5\%$:

$$\Delta P_o = \frac{1}{30} \left| \frac{30}{0.09} \right| q_o$$

$$= 11.1\%$$

$$= \frac{6.7}{10^6} \left| B^2 F \right| \text{kg/m}^2$$

For comparison of the determined and calculated pressure drop it is better to use "atmosphere" as unit which leads to the following equation.

$$\Delta P_o = \frac{6.7}{10^{10}} \; B^2 F.$$

If B is expressed in tons/hour the equation is simplified to:

$$\Delta P_o \sim \frac{6.7}{10^4} \ B_{(tons/hour)}^2 \ F$$

$$\sim \frac{B_{(tons/hour)}^2 \ F}{1500}$$

Using an approximation the following simple expression results:

$$\Delta P_o \ (atm) \sim \frac{6.7}{10^{10}} \ B_{(kg/hour)}^2 \ \frac{W}{B}$$

$$= \frac{6.7}{10^{10}} \ B_{(kg/hour)} \ W_{(m^3/hour)}$$

$$\sim \frac{B_{(tons/hour)} \ W_{(1000 \ m^3/hour)}}{1500}$$

On the basis of this expression a diagram as in figure 3 can be drawn. A nomograph for the relation of the thickness of the crusts and the pressure drop is given in figure 4.

In order to check on the increase of the crust thickness δ with on-stream time it is best to use the actually determined pressure drop, converted to one hairpin tube, ΔP_b, from which the apparent friction coefficient ζ_b corresponding to the original internal diameter D_i can be calculated as follows:

$$\Delta P_b = \zeta_b \ \frac{L}{D_i} \ q_o$$

$$\zeta_b = \frac{D_i}{L} \ \frac{\Delta P_b}{q_o}$$

$$= \frac{0.09}{30} \ \frac{\Delta P_b \circ 10^4}{B^2 F} \ 1.65 \circ 10^6$$

$$= \frac{\Delta P_{b(atm)}}{B^2 F} \ 50 \circ 10^6$$

$$\zeta_b \sim 50 \ \frac{\Delta P_{b(atm)}}{B_{(tons/hour)}^2 \ F}$$

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