Thermal and Flow Assessment of Rotating Plate Air Preheaters - An Optimization Case Study

A. Narayana Teja[1], M. Dakshina Murty[2]
[1,2] BHEL Corporate Research and Development, Hyderabad 500093, Telangana, India
*Corresponding author Email: teja@bhel.in

Abstract
Rotating-plate regenerative Air Pre-Heaters (RAPH) play a critical role of recovering heat from the waste flue gas thereby increasing the overall efficiency of a thermal power plant. The heating plate elements in this periodic Heat exchanger are arranged in a matrix configuration in baskets that rotate at low rpm, after ensuring that the design meets pressure and temperature conditions. The effective design of these plates in the RAPH, where heat exchanges between fresh air and exhaust flue gas gains utmost importance. Most conventional programs base the sizing of RAPH plates on gas and air side temperature distributions. In certain cases, like in the current work catering to applications related to emission reduction, prediction of metal temperature distribution is essential. This is for design of new profiles of RAPH plates catering to Selective Catalytic Reduction, that require enamel coating on a section of the plates. The area that is to be enamel coated is to be optimized. An analytical program is developed to predict transient metal temperatures and coating area required for the RAPH plates. The results from it are validated with experimental flow and temperature results. The close match of experimental and analytical findings enables the usage of this program for predicting metal temperature distribution of RAPH plate elements, thereby reducing the time and cost of repetitive experimentation. The results have been applied to form the design basis of Air Preheater metal temperatures for an 800 MW Supercritical plant.

Keywords: Rotary Air Preheater, Heat Transfer Optimization, Plate Element Matrix, Transient metal temperature, Selective catalytic reduction

Nomenclature

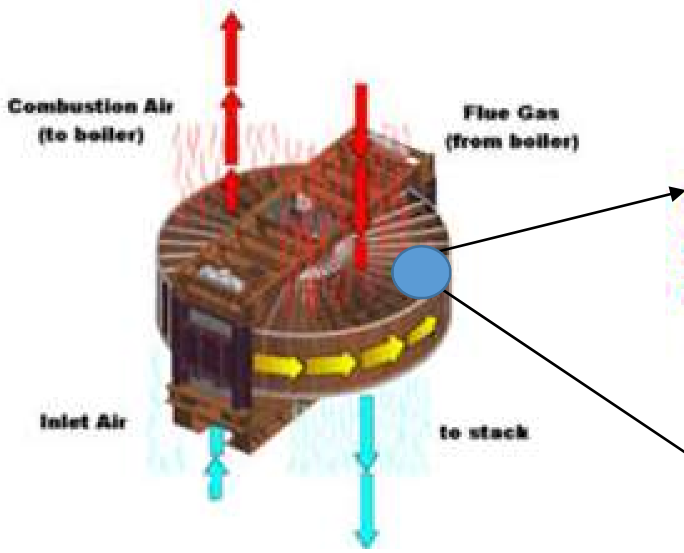
ε_v	Volumetric porosity
ρ_m	Density of metal plates
c_m	Specific heat of metal plates
ω	RPM of RAPH
r	Dimension along plate radial distance
ε_x	Surface porosity in x direction
K_m	Thermal conductivity of metal plates
ε_y	Surface porosity in y direction
h	Heat transfer co-efficient
A_s	Specific heat transfer area
T_f	Fluid temperature (Air, Gas)
T_m	Temperature of metal plates
ρ_f	Fluid density (Air, Gas)
$c_{p,f}$	Fluid specific heat (Air, Gas)
$v_{f,y}$	Velocity of the fluids (Air, Gas)
K_f	Thermal conductivity of the fluids (Air, Gas)
L	RAPH basket height

1. Introduction
Rotating-plate regenerative air preheaters (RAPH) improves the economy of a power plant by saving the cost in heating up of the fuel air and also recovers waste heat in the exhaust gas. It has been found that, for every 22 ^{o}C

rise in temperature pick-up in air preheater an increase of 1 % efficiency of the overall cycle of Power plant is obtained. The Ljungstrom type Rotary Air Preheater is mostly adopted by thermal power industry and is the Air preheater referred in this paper [1].
For upcoming thermal power plants, the mandated emission norms are stringent [2]. Therefore, a lot of studies are ongoing, to increase the heat transfer of the RAPH and to improve overall efficiency of Thermal power plant so as to conform to the new norms. To reduce the NOx emitted from flue gas, it is required to have Selective Catalytic Reduction (SCR) upstream of RAPH. This process requires ammonia injection in the flue gas stream and is adsorbed onto a catalyst, in the process reducing NOx to Nitrogen and moisture. The excess ammonia (called ammonia slip) forms Ammonium Bi-Sulphate (ABS) due to reaction with SOx present in the flue gas stream. This is a sticky powdery substance which forms in temperature ranges of 180-200 ° C and erodes the RAPH Plates. It deposits on the plates in this particular temperature range of flue gas. In order to prevent the Plate from erosion and for better RAPH performance, a thermally conductive enamel material is to be coated on the RAPH Plate. As it is not economical, the whole Plate would not be coated. *The optimization of plate area that is to be coated; with neither adverse impact on the catalytic process nor losing the cost economic aspect is to be achieved.* The enamel coating area is to be optimized for this temperature range. Thus a method to predict metal temperature distribution of RAPH Plates is developed as an analytical program from first principles. The temperature profiles predicted from analytical program are validated with data obtained from experimentation on plate elements in stationary disposition. Air and Gas Side Heat Transfer Co-efficient are also predicted in the program.

2. Description of Air Preheater

RAPH has corrugated plates stacked in baskets which rotate with very low speeds of 1-2 rpm, as in Fig1.



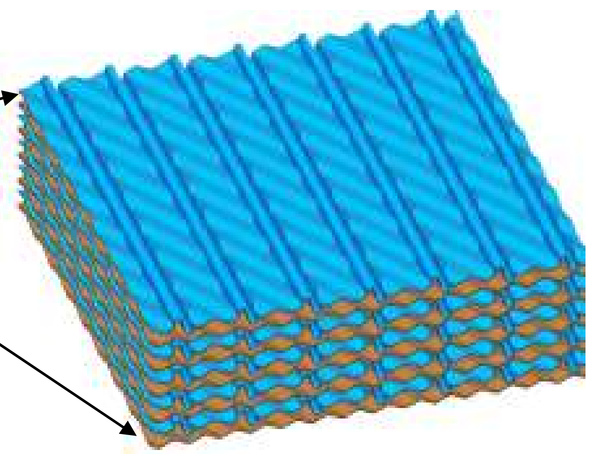


Fig 1: Typical Rotary Air Preheater

Fig 2: Typical RAPH Plate Element stack

The corrugation on Plates decides the heat transfer area available and the pressure drop that occurs in the basket [3]. However, based on the metal temperature criteria also the Plates are stacked in the RAPH. The colder side of RAPH is least corrosive because of low metal temperature. On the other side, hot zone Plates are susceptible to corrosion so better care is required for longer usage. Objective is to optimize the enamel coating area, required in the hot plate zone for temperature range of 180-200 ° C.

3. Analytical Methodology and Governing Equations:

Rotary air preheaters have a specific operating principle where heat is transferred from the hot gas to the inlet air by means of a rotating matrix [4], and heat lost or gained by the matrix yields the partial differential equations for determining the regenerator behavior. The differential equations are reduced to algebraic form for obtaining the temperature distribution. Without loss of generality, the following assumptions are made prior to solving the governing differential equations

- All plate surfaces are smooth and no deposits present (fouling absent).
- No leakage of air, gas (mass conservation) and adiabatic heat transfer (energy conservation).

- Conduction in fluid is neglected in radial and circumferential directions
- Conduction is absent in radial direction between adjacent Plates
- Thermal properties of metal matrix are treated constant.

A control volume approach is adopted and the energy equations are solved for the metal, air, gas dimensions passing through the control volume. The control volume is indicated in Fig 3

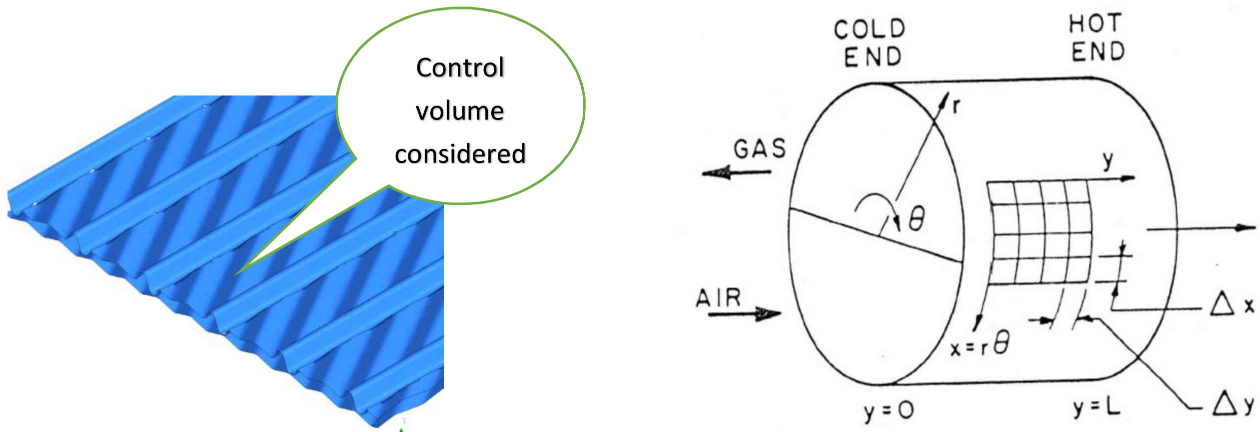


Fig 3: RAPH Plates and Control volume

The energy equations for metal and fluid sections as in (1), (2) are solved

$$\varepsilon_v \, \rho_m \, c_m \, \omega \; r \, \frac{\partial T_m}{\partial X} = \varepsilon_x \, \frac{\partial}{\partial x} \left(K_m \, \frac{\partial T_m}{\partial X} \right) + \varepsilon_y \, \frac{\partial}{\partial y} \left(K_m \, \frac{\partial T_m}{\partial Y} \right) + h \, A_s \left(T_f - T_m \right) \tag{1}$$

$$(1 - \varepsilon_v) \, \rho_f \, c_{p,f} \, v_{f,y} \, \frac{\partial T_f}{\partial y} = \left(1 - \varepsilon_y\right) \frac{\partial}{\partial y} \left(K_f \, \frac{\partial T_f}{\partial y} \right) + h \, A_s \left(T_m - T_f \right) \tag{2}$$

The Objective function as in (3) is, f (x, y) is: Minimize area of RAPH plates in the basket for temperature above 180 ºC

$$f(x, y) = Minimize \; (n * x * y), \qquad for \; T_m(x, y) > 180 \;\; and \;\; 0 \le x \le 2r \, \pi \;\; and \;\; 0 \le y \le L \tag{3}$$

In addition, the boundary conditions from (4) to (11) are imposed to satisfy the above 3 conditions.

$$T_f(x, L) = \; T_{gas,in}(x), \qquad 0 \le x < r \, \pi \tag{4}$$

$$T_f(x, 0) = T_{air,in} \; (x), \qquad r \, \pi < x \le 2r \, \pi \tag{5}$$

$$V_{f,y}(x, L) = \; V_{gas,in}(x), \qquad 0 \le x < r \, \pi \tag{6}$$

$$V_{f,y}(x, 0) = \; T_{air,in}(x), \qquad r\pi < x \le 2r\pi \tag{7}$$

$$T_m \; (0, y) = \; T_m(2r\pi, y) \qquad at \; x = 0 \tag{8}$$

$$T_m \; (2r\pi, y) = \; T_m \; (0, y) \qquad at \; x = 2r\pi \tag{9}$$

$$-K_m \partial T_m \frac{(x,0)}{\partial y} = \; h_{end} \; [T_m \; (x, 0) - \; T_f \; (x, 0)] \tag{10}$$

$$-K_m \; \partial T_m \frac{(x,L)}{\partial y} = \; h_{end} \; [T_m \; (x, L) - \; T_f \; (x, L)] \tag{11}$$

HTC and metal temperatures are solved iteratively, until convergence (metal temperature difference < 0.1 C) is achieved. Colbourn and friction factors are computed for generation of j, f characteristics for RAPH plates.

Colbourn's Factor for Thermal characterization

It is an empirical means correlating convection heat transfer transmission through fluid films. The Colbourn analogy [5] introduces the j-factor as

$$j = \frac{Nu}{Re\,Pr^{1/3}} \qquad (12)$$

Above relation is well valid for heat transfer in moderate and for flows with high Reynolds number.

Friction factor for Flow characterization

The fanning friction factor [4], f is a dimensionless number used in fluid flow calculations. It is defined as

$$f = \rho \frac{D_h}{2L} \frac{\Delta P}{G^2} \text{ ; where } G = \frac{\dot{m}}{A} \qquad (13)$$

4. Analytical Program Results

Table 1 lists the cases that are analyzed and for which experimentation is also carried out. The inputs to execute the program are not limited to those mentioned in Table 1.

Table 1: Analytical Program and Experimental Test Cases

	Program Inputs		Operational Conditions	
Case No	Air/Gas inlet temperature, C	Air Velocity m/s	Damper opening, %	Heater capacity, kW
1	25/70	25	60	105
2	35/65	32	80	105
3	30/70	35	100	105
4	34/75	15	40	105
5	28/80	8	20	62
6	35/95	8	20	105

The temperature results from the program developed are displayed in Fig 4a and 4b, corresponding to cases 1 and 6 as per Table 1. They plot the variation of air and gas side metal temperatures along the axial flow length of the Air Preheater Plate.

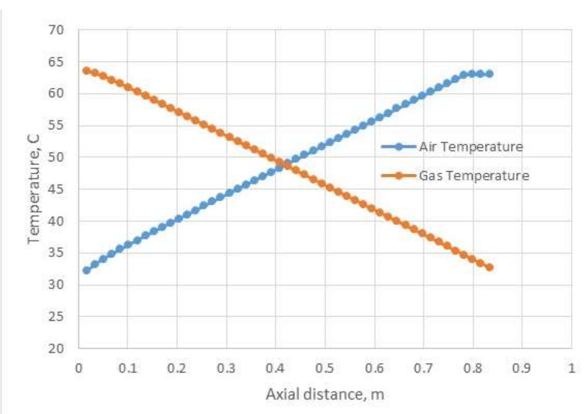


Fig 4a: Case1 Axial Air & Gas side Metal Temp

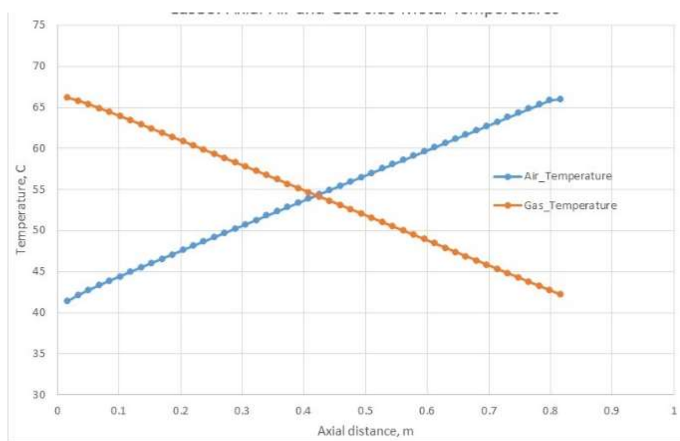


Fig 4f: Case6 Axial Air & Gas side Metal Temp

5. Experimental Set-up and Testing

The Experiments on RAPH Plate stacks have been carried out in a lab scale hot air test facility (Patented). The facility is so designed and operated so as to replicate the functioning of Rotating-plate regenerative air preheaters into a stationary stacked basket of RAPH Plates. The DU (Double Undulated) Series of hot and intermediate layer Plates has been the mainstay of the Air heater industry and is the configuration studied in the paper. The Plates are pre-heated with the help of variable-rating electric heater coils. After the air reaches the desired temperature above ambient temperature, the heaters are cut-off. Air temperature is measured at inlet and outlet of duct periodically. Temperature and flow are varied with heater controls and damper operation. The experiment is repeated for 6 cases. Lab scale set-up and testing is shown in Fig 6.

Fig 6: Experimentation in Hot Air Lab Test facility

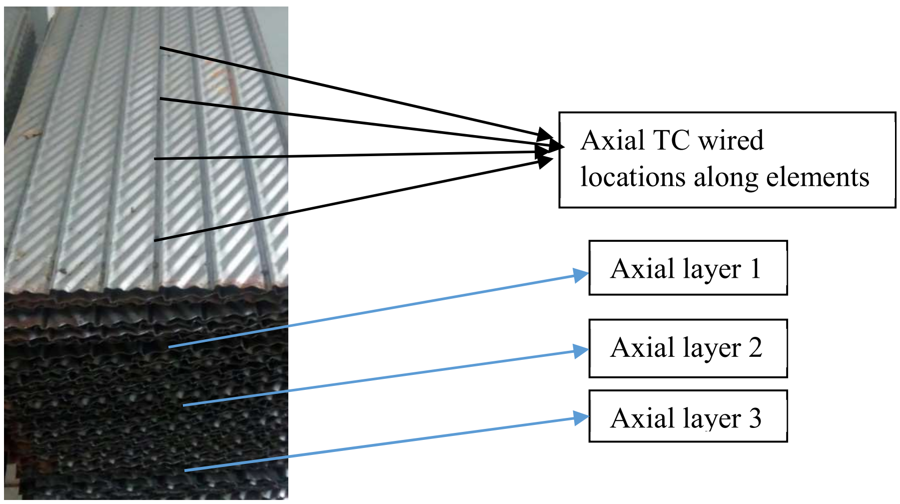


Fig 7: RAPH Plates and configuration in hot air test facility

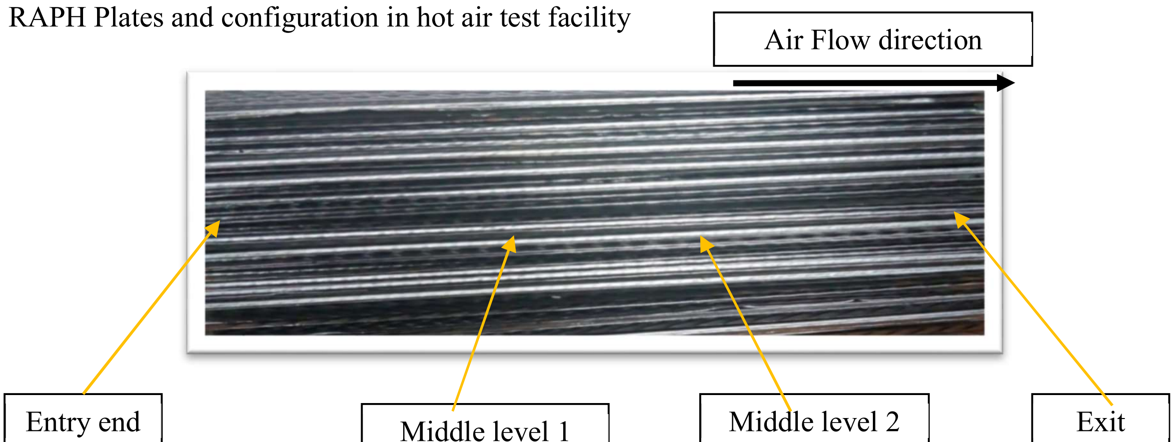
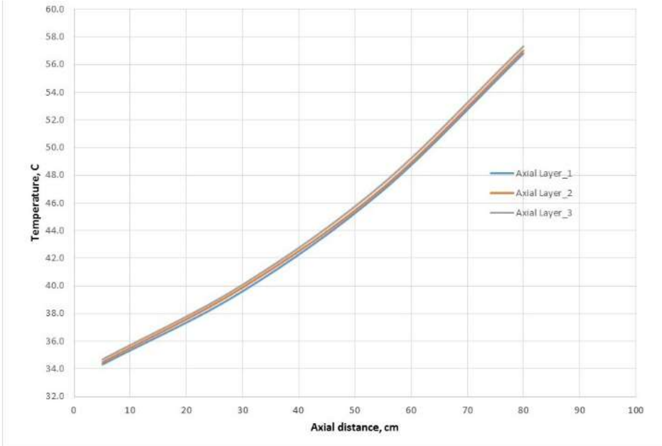


Fig 8: Thermocouple fixing locations for RAPH Plates in Hot Air Test facility

6. Experimental Results

The experimental metal temperature distribution in 3 Axial layers, along the length locations on RAPH Plates as per Fig 7 have been plotted for the 6 cases listed in Table 2. The 4 locations are at entry end of basket, middle level 1, middle level 2 and exit end of the basket, as depicted in Fig 8. The trends of the experimental metal temperature distribution are similar to that obtained from program and are plotted in Fig 9a, 9b corresponding to cases 1 and 6, as per Table 1.



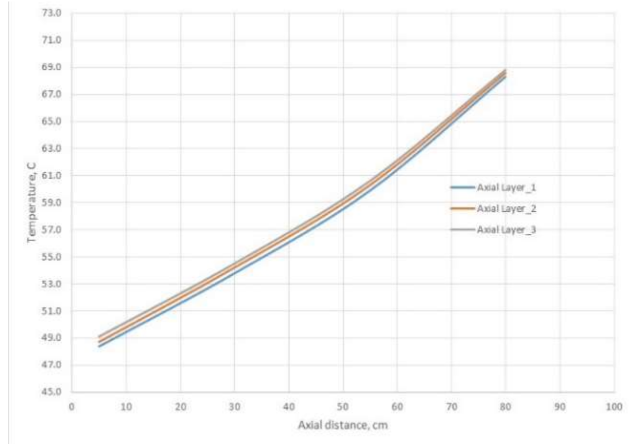
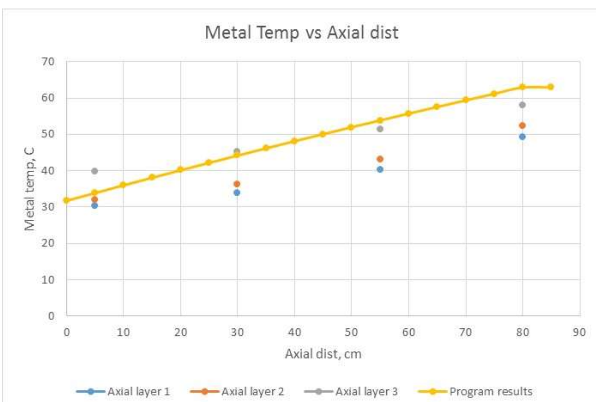


Fig 9a: Case1 Axial Metal Temperatures

Fig 9f: Case6 Axial Metal Temperatures

7. Comparison of Experimental and Analytical Results

Thermal results from analytical program and experimentation (thermocouple data points) are compared case-wise. Trend of metal temperature with axial distance can be observed all the 6 cases. Results corresponding to cases 1 and 6 as per Table 1, are presented in Fig 11a and Fig 11b.



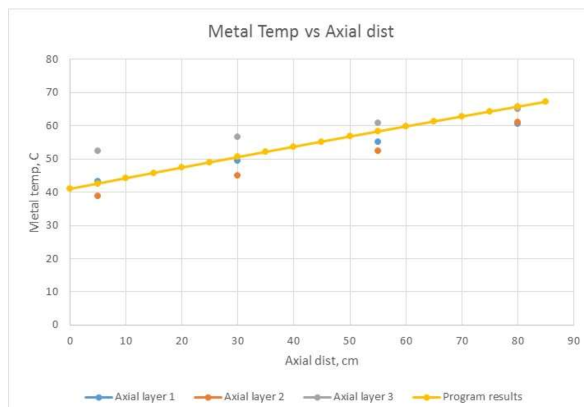


Fig 11a: Case1 Analytical & Experimental Temp

Fig 11b: Case6 Analytical & Experimental Temp

8. Results and Discussion

A non-conventional testing approach is developed for prediction of enamel coating area required for Rotating Plate Air Preheaters. An analytical program is developed to predict the complete metal temperature plot of these RAPH Plates stacked in a basket. The program is experimentally validated with plates in lab scale test facility, in static disposition. The results from both approaches are in close agreement, with an average error of 5.1%. *The area that is to be coated is obtained as 40% of the axial length of the hot side element.*

9. Conclusions

The aim of the investigation in this paper is to generate transient and steady state metal temperature distribution of Rotary Air Preheater (RAPH) Plate elements and compare the analytical program results with experimental data for benchmarking. The significant points in the optimization study undertaken can be summarized as follows:

I. Methodology is developed for prediction of metal temperatures in entire RAPH plates matrix, thus improving RAPH effectiveness.
II. Parametrized metal temperature prediction tools for any new RAPH Plate profile developed.
III. Results indicate that transient axial metal temperature profile is parabolic in nature.

IV. Program has been applied to estimate actual RAPH metal temperatures for 800 MW thermal power plant. The actual hot, intermediate, cold end metal temperatures were in close agreement (1.3%-3.4% deviation) with program prediction**.**

V. For new RAPH with SCR-DeNOx systems, enamel coating is essential to prevent ABS formation. The program accurately predicts the area and location from where coating is required, based on developed temperature profiles. This optimized (40%) plate area coating is sufficient to arrest corrosion.

VI. The program helps save on material and enamel cost, with accurate prediction of plate depths that are to be coated, rather than bulk coating on entire plate element.

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