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Thermal Design of Recuperator of MIDREX Direct Iron Reduction Plant

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Abstract

One of the important components of the sponge iron production line in the Midrex process is the recuperator. It has the role of heat exchange between combustion products exiting from the reformer and three independent streams of combustion air, natural gas and feed gas. The current research addresses the thermal design of such recuperators with two design and off-design approaches. In this regard, the development of correlations for thermophysical properties of fluids, extraction and use of suitable thermal and hydraulic relations and developing a solution algorithm considering interactions of tube-bundles were implementd. Also, the thermal calculation process was validated using the available data and the difference in heat transfer surface area was observed to be less than 8%. Also, the maximum difference in tube side and shell side temperatures between the calculation results and validation data was 4% and 7%, respectively, which indicates high accuracy of the calculations. Finally, as case studies, two different designs were presented for a specific set of process conditions and the corresponding results were compared. Based on the comparison, the maximum tube side temperature difference was 4% and for shell side was 1%, which means that the performance of these two designs is relatively similar.

Keywords: Recuperator; Heat Recovery; Thermal-Hydraulic Design; Heat Exchanger; Tube-Bundle; Sponge Iron; MIDREX.

1. Introduction

MIDREX process recuperator is one of the most important components of the sponge iron production plants, and so the knowledge of its design is very important in iron and steel industries. The aim of the current research is to achieve the technical knowledge of thermal-hydraulic design of MIDREX process recuperator including fresh air, feed gas and natural gas tube-bundles based on both Design and Off-Design approaches. Presenting the correlations of the thermophysical properties of the flows as polynomials of the temperature parameter is another innovation of the current research with the aim of increasing the accuracy of thermal-hydraulic calculations.

2. Modeling

Figure 1 shows the schematic of recuperator tube-bundles including hot air, hot feed gas, cold feed gas, and natural gas and cold air.

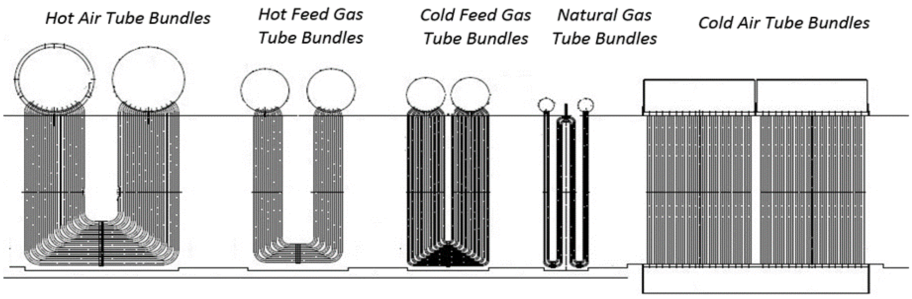

Figure 1. Schematic of MIDREX tube-bundles in the recuperator

The heat transfer relations for both sides of the shell and the recuperator tube bundle were extracted according to the geometry and arrangement of the recuperator tube bundles. It should be noted that the Nusselt number is used as a heat transfer criterion for heat transfer calculations in the design of heat exchangers. Equations (1) and (2) correspond to Nusselt numbers of flow over tubes (i.e. shell side) in vertical and bend configurations, respectively [1,2]. Also, for the tube side, various correlations from different references [3-7] were evaluated and finally equation (3) was selected.

$$Nu_{VS} = C_1\, Re^{\frac{1}{2}}\, Pr^{\frac{1}{3}} \qquad 1.05 \le X_L \le 3,\; 1.05 \le X_T \le 3 \tag{1}$$

$$Nu_{BS} = \varepsilon_{\varphi}\, Nu_{VS} \tag{2}$$

$$Nu_{VHT} = \frac{\frac{f}{8} Re\, Pr}{1.07 + 12.7\sqrt{\frac{f}{8}}\left(Pr^{\frac{2}{3}} - 1\right)} \tag{3}$$

$$f = (1.82\, Ln(Re) - 1.64)^{-2}$$

Due to the high temperature in the recuperator (up to 1125°C), the effect of radiation on heat transfer cannot be neglected. In the hot air tube bundle, radiation contributes maximally to heat transfer. The set of radiative heat transfer coefficient relations is from (4) to (7). The parameter L is the characteristic length related to geometric features. P_c and P_w are the partial pressures of carbon dioxide and water vapor in the flow under consideration. T_g and T_o are the gas temperatures passing over the tube bundle and the tube surface temperatures, respectively [8-10].

$$L = \frac{1.08(S_T S_L - 0.785 D^2)}{D} \tag{4}$$

$$K = \frac{(0.8 + 1.6\, P_w)\left(1 - 0.00038\, T_g\right)(P_c + P_w)}{[(P_c + P_w)\, L]^{0.5}} \tag{5}$$

$$\epsilon_g = 0.9\,(1 - e^{-KL}) \tag{6}$$

$$h_r = \frac{\sigma\, \epsilon_g\, [T_g^4 - T_o^4]}{(T_g - T_o)} \tag{7}$$

3. Validation

With the aim of checking the accuracy of design relationships and algorithms used in Design and Off-Design approaches, as well as verifying the results of design calculations, a sample design data-sheet provided by a designer company of MIDREX recuperator has been taken into consideration. The relevant process data is according to Table 1.

Table 2 shows the comparison between results obtained from the Design calculation of this work and the datasheet provided by the designer company. The relatively small deviations between the design results and the datasheet indicate a geed agreement and so the calculation process seems to be valid.

4. Results of Design Calculations

In this section results for a sample recuperator design are presented. The process input data for the design and temperature calculations are shown in Table 3. Also, the supplementary thermal and hydraulic design results are presented in Table 4.

5. Conclusions

The heat recovery system (recuperator) is considered as an important part of the direct reduction of iron process based on MIDREX technology. The thermal design of this type of recuperator is much more complicated than conventional recuperators because it consists of several sequential tube-bundles, in which the performance of each bundle affects the performance of the next ones. In this work, developing correlations of thermophysical properties in the form of polynomial functions of temperature for the flows forming the recuperator, developing an algorithm and applying the Design approach and the Off-Design approach, and extracting and using the appropriate thermal and hydraulic transfer relations and analyzing the sensitivity of their accuracy for the design process and recuperator simulation were performed.

Table 1. Process datasheet provided by designer company

	Standard Flow (m^3/hr)		Temperature (C) Shell Side		Temperature (C) Tube Side	
Stream	Shell Side	Tube Side	Inlet	Outlet	Inlet	Outlet
Hot Air	153544	130288.5	1125	848	231	648
Hot Feed Gas	153544	122029.5	848	741	422	553
Cold Feed Gas	153544	122029.5	741	517	138	422
Natural Gas	153544	10153	517	494	25	303
Cold Air	153544	130288.5	494	363	50	231

The calculation process of thermal-hydraulic design presented in this article was validated comparing with the datasheet of a foreign company expert in designing the MIDREX recuperator. Also, using the extracted calculation process, one example of design calculations was presented for a set of design input data. In general, it can be claimed that during the current research, the acquisition of technical knowledge of the thermal-hydraulic design of the MIDREX recuperator was successfully achieved.

Table 2. Comparison of design mode results with the designer datasheet

	Heat transfer area of the tube bundles $A_T(m^2)$		
Recuperator Part	Datasheet	Design Calculations	Percentage Difference (%)
Hot Air	483.13	467.41	6.68
Hot Feed Gas	212.01	225.53	6.38
Cold Feed Gas	480.29	517.25	7.70
Natural Gas	49.23	53.07	7.80
Cold Air	531.87	560.58	5.40

Table 3. Process inputs and temperature outputs for the sample design

Recuperator Part	Tube Side Mass Flow (kg/sec)	Shell Side Mass Flow (kg/sec)	Inlet Temp. Tube Side (C)	Outlet Temp. Tube Side (C)	Inlet Temp. Shell Side (C)	Outlet Temp. Shell Side (C)	Press. Drop Tube Side (Pa)	Press. Drop Total Shell (Pa)
Hot Air	32.8738	40.1818	225	675	1125	813.82	4000	1000
Hot Feed Gas	19.5744	40.1818	340	560	813.82	626.44	8000	
Cold Feed Gas	19.5744	40.1818	142	340	626.44	466.30	2000	
Natural Gas	3.6808	40.1818	25	370	466.30	393.96	9000	

Recuperator Part	Tube Side Mass Flow (kg/sec)	Shell Side Mass Flow (kg/sec)	Inlet Temp. Tube Side (C)	Outlet Temp. Tube Side (C)	Inlet Temp. Shell Side (C)	Outlet Temp. Shell Side (C)	Press. Drop Tube Side (Pa)	Press. Drop Total Shell (Pa)
Cold Air	32.8738	40.1818	63	225	393.96	271.90	1000	

Table 4. Supplementary results for the sample design

Recuperator Part	Tubes No. Transverse $N_T (\#)$	Tubes No. Longitudinal $N_L\ (\#)$	Tube Pressure Drop Range (Pa)	Shell Pressure Drop (Pa)	Heat Transfer (MW)	Radiation Contribution (%)	Transverse Tube Spacing $S_T\ (mm)$	Longitudinal Tube Spacing $S_L\ (mm)$
Hot Air	34	9 + 9	526 - 966	95	8.2265	71.24	117.7	130.2
Hot Feed Gas	28	6 + 6	750 - 1386	6	4.7215	38.58	143.9	127
Cold Feed Gas	28	8 + 8	2350 - 3865	1	3.8756	23.27	143.9	92.1
Natural Gas	36	2 + 2 + 2 + 2	2016 - 2674	0.4	1.6982	18.00	111	75
Cold Air	24	15 + 15	181 - 363	13	2.6124	18.44	168.9	140

6. References

[1] Khan WA (2004) *Modeling of Fluid Flow and Heat Transfer for Optimization of Pin-Fin Heat Sinks*. Ph.D. Thesis, University of Waterloo, Canada

[2] Žukauskas A (1972) *Heat transfer from tubes in crossflow*. *Advances in heat transfer*, vol. 8, pp. 93-160.

[3] Petukhov BS, Popov VN (1963) Theoretical calculation of heat exchange an fictional resistance in turbulent flow in tubes of an incompressible fluid with variable physical properties, *High Temp*. (USSR) 1, 69–83.

[4] Dittus FW, Boelter LMK (1930) Heat transfer in automobile radiators of the tubular type, Univ. *California Publ*. Eng. 2: 443–461.

[5] Sieder EN, Tate GE (1936) Heat transfer and pressure drop of liquids in tubes, *Ind. Eng. Chem* 28: 1429.

[6] Gnielinski V (1976) New equations for heat and mass transfer in turbulent pipe and channel flow, Int. *Chem. Eng*. 16: 359–368.

[7] Filonenko GK (1954) Hydraulic resistance in pipes, *Teploenergetika* 1: 40–44.

[8] Ganapathy V (2014) Steam generators and waste heat boilers: for process and plant engineers. *CRC Press*.

[9] Ganapathy V (2003) Industrial Boilers and Heat Recovery Steam Generators. *CRC Press*.

[10] VDI heat atlas (2010) *Springer*, Berlin Heidelberg. https://doi. org/10 1007: 978-3.