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Optimal Synthesis of Multipass Heat Exchanger without Resorting to Correction Factor

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***Abstract*—**Customarily, the LMTD correction factor, F_T, is used to screen alternative designs for a heat exchanger. Designs with unacceptably low F_T values are discarded. In this paper, authors have proposed a more fundamental criterion, based on feasibility of a multipass exchanger as the only criteria, followed by economic optimization. This criterion, coupled with asymptotic energy targets, provide the complete optimization space in a heat exchanger network (HEN), where cost-optimization of HEN can be performed with only Heat Recovery Approach temperature (HRAT) and number-of-shells as variables.

***Keywords*—**heat exchanger, heat exchanger networks, LMTD correction factor, shell targeting.

I. Introduction

THE shell and tube heat exchangers are one of the most widely used equipment in the process industry. In order to achieve better heat transfer efficiency these heat exchangers are often made as multipass. Presently, the correction factor, F_T, is used to screen alternative designs for the exchangers before resorting to detailed design calculations. The value of F_T adopted for the design is selected using ad hoc criteria, $F_T > 0.8$.

It has been more than seven decades since Bowman et al [1] proposed the use of LMTD correction factor in the design of multipass shell-and-tube heat exchangers. All the other criteria proposed later [2], [3], [4], [5], [6], [7] are modifications of F_T criteria to make it computationally efficient. In all criteria proposed for calculating the number of shells in a multipass exchanger, the implicit constraint is that F_T should not fall below a certain value (0.75 or 0.8).

II. The F_T Correction Factors

In case of the simplest shell and tube heat exchanger __ the 1-2 type, the liquid in one tube pass flows in counter flow while in the other pass flows in parallel relative to shell fluid. The method of calculation of log mean temperature difference, LMTD, for counter flow as well as parallel flow is well established [8]. For the design of multipass exchangers where both types of flow coexist, an analytical expression for estimating actual mean temperature difference was developed by [9] and later modified by [1]. In this design practice, a

correction factor F_T is introduced into the basic heat exchanger design equation, equation (1), to take into account the above phenomena,

$$Q = UA\,(LMTD)\,F_T\text{ , where } 0 < F_T < 1 \tag{1}$$

The F_T factor can be represented as the ratio of actual mean temperature difference in a 1-2 exchanger to counter flow LMTD for the same terminal temperatures. The physical significance of F_T is given by many authors [10], [11], [12]. F_T is usually expressed as a function of two dimensionless parameters R and S defined below:

$$\text{Heat Capacity ratio, } R = \frac{T_1 - T_2}{t_2 - t_1} \tag{2}$$

$$\text{Thermal Effectiveness, } S = \frac{t_2 - t_1}{T_1 - t_1} \tag{3}$$

The analytical equations for estimating F_T as a function of R and S for 1-2 and 2-4 exchangers are given by [8]. Design charts based on this method are available and are compiled by TEMA [13].

F_T is used to screen alternative designs before resorting to detailed design calculations. Designs with unacceptably low F_T values are discarded. A commonly used rule of thumb requires $F_T \geq 0.8$ for the design to be considered practical. However, the use of this ad-hoc criterion for 1-2 exchanger is arbitrary (and restrictive), and can lead to poor designs if not used with caution [2]. Frank [14] recommended that the 1-2 exchangers should not be designed where F_T factors approach a vertical slope, as a small departure from the design point can result in precipitous decline of F_T. Thus, the advice to the designer to refrain from designing with $F_T \leq 0.8$ comes mainly because of steep slopes of the F_T curves in that region, which prohibits the designer to estimate F_T correctly.

III. Design for Multipass Exchangers

All the approaches till date to design multipass exchangers have been F_T-centric. Designers often encounter situations where either the F_T is too low or the slope of F_T versus S curve is too large. If this happens, the designer is *advised* to consider multipass exchangers. A brief summary of these approaches is given below.

A. The Traditional Approach (explicit F_T approach)

Traditionally, the designer would approach a problem requiring multiple shells by trial and error. By assuming a

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number of shells, usually one in the first instance, the F_T is evaluated. If the F_T is not acceptable then the number of shells in series is progressively increased until a satisfactory value of F_T is obtained for each shell.

B. Method of Ahmad et al.

Ahmad et al. [2] have given an analytical expression for calculating number of shells directly,

$$N = \frac{\ln \frac{(1-RS)}{(1-S)}}{\ln W} \tag{4}$$

where, N is real (non-integer) number of shells, and

$$W = \frac{R+1+\sqrt{R^2+1}-2RX_P}{R+1+\sqrt{R^2+1}-2X_P} \tag{5}$$

Equation (4) gives a value of N that satisfies the chosen value of X_P. The problem now is - what should be the design value of X_P? And how it will affect temperature cross and consequently, F_T. Though [2] emphasized the importance of temperature cross in exchanger design, they didn't explain how X_P accounts for temperature cross. Their choice of value of $X_P = 0.9$ is based on $F_T = 0.75$ at $R = 1$, which is again arbitrary. What if a designer wants to use a lower value of X_P?

C. Method based on not allowing Temperature Cross

This method is based on a dimensionless parameter G which explicitly accounts for temperature cross in the exchanger [15], [3]. It is defined as,

$$G = \frac{T_2 - t_2}{T_1 - t_1} \tag{6}$$

F_T decreases moderately with decreasing positive G values, but falls sharply both where the temperature meet (G = 0) and where the G values are negative (temperature cross).

The parameter G is related to parameter R and S, by the equation,

$$G = 1 - S(1+R) \tag{7}$$

For any value of R there exists a minimum asymptotic value of G (corresponding to FT = -∞), say G_{min} , which represents the maximum temperature cross theoretically feasible in 1–2 exchanger.

The expression for G_{min} is,

$$G_{MIN} = \frac{\sqrt{R^2+1}-(R+1)}{\sqrt{R^2+1}+(R+1)} \tag{8}$$

It is shown by [4] that for G = 0, F_T is always above 0.8 ($0.8 < F_T < 0.83$), an acceptable value. Thus, following the criteria that temperature cross is not allowed in each shell ensures that $F_T > 0.8$. Using this fact, a simple equation is derived below to calculate the number of shells.

$$\mathrm{N} = \frac{\ln\left(\frac{\mathrm{R+G}}{\mathrm{1+RG}}\right)}{\ln(\mathrm{R})} \tag{9}$$

Equation (9) can be used to estimate the number of shells for given R and G (calculated from the terminal temperatures).

D. Method based on allowing Temperature Cross

Some authors recommend that in order to get the minimum number of shells it is necessary to allow some temperature cross [16]. For such cases a comprehensive criteria has been developed by [4]. A 1–2 exchanger designed for $G < G_{min}$ will not be feasible. Any increment in G from G_{min} will make the exchanger feasible, and improve exchanger effectiveness and F_T. Let the desired increment be Y. Then

$$G = G_{\min} + Y \tag{10}$$

where Y is a constant set by the designer. Now, the expression for estimating the number of shells can be written as

$$N = \frac{\ln \frac{(1-RG_N)}{(R+G_N)}}{\ln W} \tag{11}$$

Where G_N is G for multipass exchanger, and

$$W = \frac{\sqrt{R^2+1}\left(R+1-RY\right)-(R+1)(R-1-RY)}{\sqrt{R^2+1}\left(R+1-Y\right)-(R+1)(R-1-Y)} \tag{12}$$

Y can be correlated with X_P as,

$$Y = \frac{2(R+1)(1-X_P)}{\sqrt{R^2+1}+(R+1)} \tag{13}$$

Alternatively,

$$X_P = \frac{(R+1)(2-Y)\sqrt{R^2+1}}{2(R+1)} \tag{14}$$

Y is chosen by the designer's decision on how much temperature cross he is going to allow in the design. Author also recommends that to be compatible with the existing design practices ($F_T > .0.75$; or $X_P = 0.9$), a value of Y in the range 0.1 to 0.15 may be selected.

E. Methods based on F_T slopes

An additional method of avoiding areas of steep slopes in the F_T chart is to consider a constant F_T slope. Ahmad et al. [2] have presented a constant slope criterion in a graphical form. However, their criterion, which is good to guarantee to stay away from those regions, is very complex to use and evaluate, as the authors recognized in their paper.

IV. FALLACY OF F_T CRITERIA

Despite all the arguments put forth in favor of this criterion (F_T should be higher than a recommended minimum value), we show here that this cardinal rule of multipass exchanger design is fallacious, unnecessarily restrictive, and misleading. It is also shown by the authors that such restriction does not lead to economically optimum HEN. It is proposed that to obtain cost-optimal HEN consisting of multipass units, only the feasibility of a multipass exchanger should be a constraint.

In advancing the arguments in favor of a minimum F_T value (in each shell) for shell and tube exchanger, it is implicitly assumed that the change in S (and/ or R) affects only F_T independent of everything else. This is an incorrect notion. This fact is illustrated in the following paragraphs.

The Eqn. for F_T for a 1-2 exchanger in terms of R and S is given as,

$$F_T = \frac{\sqrt{R^2+1}}{R-1}\,\frac{\ln\dfrac{(1-S)}{(1-RS)}}{\ln\dfrac{(1-S)+(1-RS)+S\sqrt{R^2+1}}{(1-S)+(1-RS)-S\sqrt{R^2+1}}} \quad (15)$$

The design equation for the exchanger can be written as,

$$Q = UA(LMTD)F_T \quad (16)$$

The counter flow LMTD (used in above equation) can be written as,

$$LMTD = \left(\frac{(T_2-t_2)-(T_1-t_1)}{\ln\left(\dfrac{T_2-t_2}{T_1-t_1}\right)}\right) = \left(\frac{gS((R-1)}{\ln\left(\dfrac{1-S}{1-RS}\right)}\right) \quad (17)$$

Where g is the greatest temperature difference in the exchanger,

$$g = T_1 - t_1 \quad (18)$$

The effective temperature difference in a 1-2 exchanger is thus,

$$\Delta T_{eff} = (LMTD)F_T = \left(\frac{gS((R-1)}{\ln\left(\dfrac{1-S}{1-RS}\right)}\right)\times$$

$$\frac{\sqrt{R^2+1}}{R-1}\,\frac{\ln\dfrac{(1-S)}{(1-RS)}}{\ln\dfrac{(1-S)+(1-RS)+S\sqrt{R^2+1}}{(1-S)+(1-RS)-S\sqrt{R^2+1}}}$$

Or $$\Delta T_{eff} = \frac{gS\sqrt{R^2+1}}{\ln\dfrac{(1-S)+(1-RS)+S\sqrt{R^2+1}}{(1-S)+(1-RS)-S\sqrt{R^2+1}}} \quad (19)$$

It is ΔT_{eff}, not F_T alone, which affects the area of the exchanger, and consequently, the cost.

To expose the fallacy of steep fall in driving force for $F_T < 0.8$, let us look at the behavior of F_T, LMTD, and ΔT_{eff} with S (for given R). It is known that for a given value of R, there exists a S_{max} beyond which the 1-2 exchanger becomes thermodynamically infeasible, and going for higher number of shells is the only option.

Following figures show the variation of LMTD, F_T, and ΔT_{eff} with S for different R values (Figure 1 for R=1, figure 2 for R=2, figure 3 for R=3, and figure 4 for R=4).

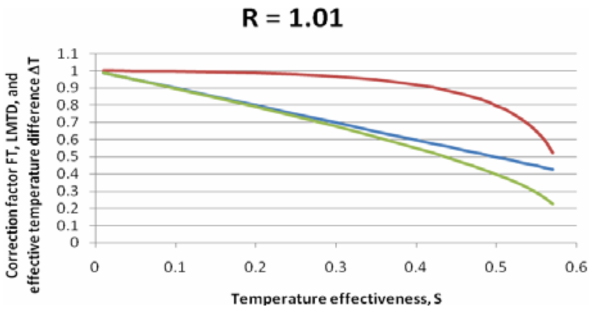

Fig. 1 Variation of correction factor FT, LMTD, and effective temperature difference with S for R = 1.01

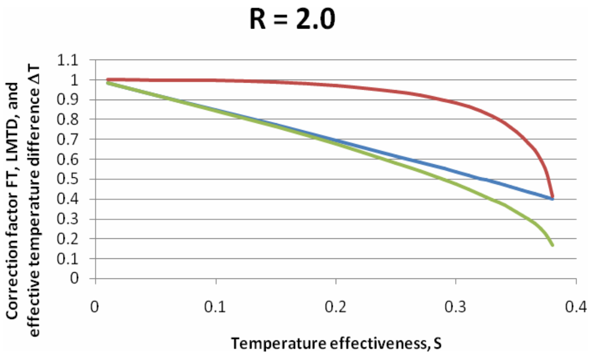

Fig. 2 Variation of correction factor FT, LMTD, and effective temperature difference with S for R = 2.0

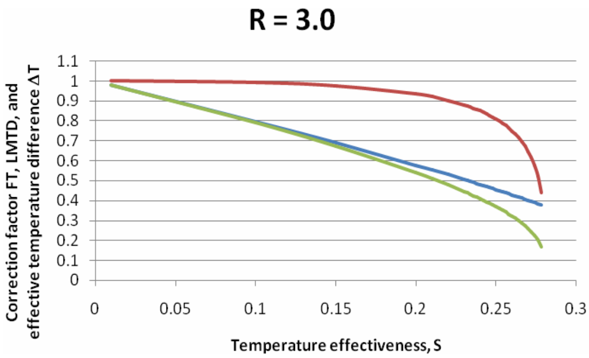

Fig. 3 Variation of correction factor FT, LMTD, and effective temperature difference with S for R = 3.0

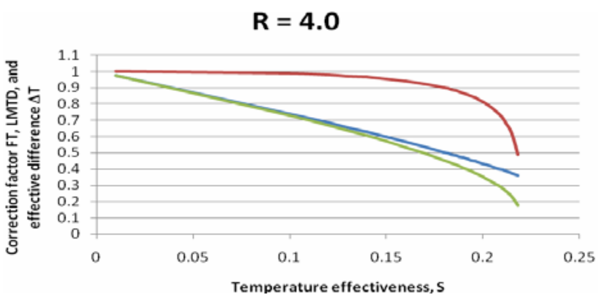

Fig. 4 Variation of correction factor FT, LMTD, and effective temperature difference with S for R = 4.0

It can be seen from these figures that for all R values, with increasing S; F_T, LMTD and ΔT_{eff} all decrease. It is also to be noted that the fall in value of LMTD and ΔT_{eff} is gradual and not steep. The fall in the value of LMTD with S is almost linear. The fall in the value of ΔT_{eff} with S is steep only in the region very near to infeasibility ($S \cong S_{\max}$), where the F_T values are far below the recommended value.

V. Number of Shells Calculation Based on Feasibility Criterion

Therefore, the value of F_T need not be a limiting criterion in estimating number of shells. In fact, we need not calculate F_T at all, when determining total number of shells in HEN. The feasibility of a multipass exchanger should be the only criteria, with overall cost as the final arbiter. The procedure is outlined below.

The equation for estimating number of shells is given as,

$$N = \frac{\ln\left(\frac{1-RS}{1-S}\right)}{\ln\left(\frac{1-RS_1}{1-S_1}\right)} \tag{20}$$

Where S_1 is the temperature effectiveness in each shell of multipass exchanger having overall effectiveness S.

The maximum value of effectiveness for given R is given as,

$$S_{MAX} = \frac{2}{\sqrt{R^2+1}+(R+1)} \tag{21}$$

Substituting S_{MAX} for S_1 in Eqn (20) we get,

$$N = \frac{\ln\left(\frac{1-RS}{1-S}\right)}{\ln\left[\frac{\sqrt{R^2+1}-(R-1)}{\sqrt{R^2+1}+(R-1)}\right]} \tag{22}$$

The above equation gives the absolute minimum number of shells needed in an exchanger. The above equation gives "real" number of shells, which has to be rounded-up, resulting in improved effectiveness.

When real number of shells N is rounded up to integer number of shells, M, an improvement in S and consequently F_T happens. This improvement is calculated from the equation,

$$S_{improved} = \frac{1-\left(\frac{1-RS}{1-S}\right)^{1/M}}{R-\left(\frac{1-RS}{1-S}\right)^{1/M}} \tag{23}$$

To demonstrate the validity of above proposal, following case studies are taken up from [6] and [7].

Moita et al. [6] applied various approaches to shells estimation to a set of seven exchangers (E1 to E7), reproduced in table 1 below. Six case studies are taken up from [7], also reproduced in Table 1.

For multipass exchangers, the capital cost equation is given as,

$$C = a + bN\left(\frac{A}{N}\right)^c = a + bN^{1-c}A^c \tag{24}$$

TABLE I
DATA FOR CASE STUDY EXCHANGERS

Exchanger	T_1	T_2	t_1	t_2	Q (kW)	U ($kW/m^2/K$)	Cost law coefficients a	b	c
Moita et al. (2004)									
E1	562	92	26	120	2000	0.1	0	7000	0.65
E2	381.2	314	0	336	2000	0.1	0	7000	0.65
E3	410	110	0	360	2000	0.1	0	7000	0.65
E4	560	125	1	88	2000	0.1	0	7000	0.65
E5	540	162	10	174	2000	0.1	0	7000	0.65
E6	388	322	0	330	2000	0.1	0	7000	0.65
E7	394	329	0	325	2000	0.1	0	7000	0.65
Ponce-Ortega et al. (2008)									
E8	410	110	0	360	2000	0.1	8600	670	0.83
E9	500	270	40	195	2000	0.1	0	7000	0.65
E10	500	130	40	180	2000	0.1	0	7000	0.65
E11	570	150	50	150	2000	0.1	0	7000	0.65
E12	570	150	0	200	2000	0.1	0	7000	0.65
E13	400	320	120	330	2000	0.1	0	7000	0.65

The calculations are summarized in following tables.

TABLE II
CALCULATION RESULTS FOR CASE STUDY EXCHANGERS

Ex	R	S	LMTD	F_T	S_{max}	G_{min}
E1	5.000	0.1754	197.72	0.6851	0.1802	-0.0812
E2	0.200	0.8814	138.68	0.6593	0.9010	-0.0812
E3	0.833	0.8780	76.10	Infeasible	0.6380	-0.1696
E4	5.000	0.1556	260.34	0.8874	0.1802	-0.0812
E5	2.305	0.3094	243.53	0.7789	0.3438	-0.1362
E6	0.200	0.8505	154.02	0.7797	0.9010	-0.0812
E7	0.200	0.8249	166.46	0.8317	0.9010	-0.0812
E8	0.833	0.8780	76.10	Infeasible	0.6380	-0.1696
E9	1.484	0.3370	265.74	0.9089	0.4680	-0.1625
E10	2.643	0.3043	181.31	0.5422	0.3092	-0.1263
E11	4.200	0.1923	222.98	0.8142	0.2101	-0.0927
E12	2.100	0.3509	243.67	0.6608	0.3686	-0.1427
E13	0.381	0.7500	123.83	0.7589	0.8160	-0.1268

TABLE III
SHELLS AND COST CALCULATIONS FOR CASE STUDY EXCHANGERS

Hx	Ft	N_{shells} by Eqn. (22)	Integer shells	S per shell	N_{shells} for G = 0	F_T per shell	A_{cc}	A_{12}	$Cost_{12}$ (in '000)
E1	0.6851	0.90	1	0.1754	1.18	0.6851	101.15	147.64	**179.924**
	0.6851	0.90	2	0.1330	1.18	0.9485	101.15	106.64	185.612
E2	0.6593	0.92	1	0.8814	1.20	0.6593	144.22	218.74	**232.300**
	0.6593	0.92	2	0.6716	1.20	0.9463	144.22	152.40	234.095
E3		3.06	4	0.5666	4.32	0.7594	262.82	346.10	508.508
		3.06	5	0.5061	4.32	0.8599	262.82	305.65	**507.151**
		3.06	6	0.4573	4.32	0.9066	262.82	289.89	522.277
E4	0.8874	0.63	1	0.1556	0.83	0.8874	76.82	86.57	**127.171**
	0.8874	0.63	2	0.1086	0.83	0.9757	76.82	78.73	152.391
E5	0.7789	0.76	1	0.3094	1.05	0.7789	82.13	105.44	**144.557**
	0.7789	0.76	2	0.2141	1.05	0.9543	82.13	86.06	161.460
E6	0.7797	0.81	1	0.8505	1.07	0.7797	129.86	166.55	**194.581**
	0.7797	0.81	2	0.6290	1.07	0.9589	129.86	135.42	216.796
E7	0.8317	0.74	1	0.8249	0.97	0.8317	120.15	144.47	177.399
E8		3.06	4	0.5666	4.32	0.7594	262.82	346.10	117.232
		3.06	5	0.5061	4.32	0.8599	262.82	305.65	110.375
		3.06	6	0.4573	4.32	0.9066	262.82	289.89	**109.064**
E9	0.9089	0.51	1	0.3370	0.72	0.9089	75.26	82.81	123.550
E10	0.5422	0.95	1	0.3043	1.31	0.5422	110.31	203.46	221.619
	0.5422	0.95	2	0.2223	1.31	0.9289	110.31	118.75	**199.050**
E11	0.8142	0.75	1	0.1923	1.00	0.8142	89.69	110.16	148.735
E12	0.6608	0.88	1	0.3509	1.22	0.6608	82.08	124.20	**160.801**
	0.6608	0.88	2	0.2483	1.22	0.9373	82.08	87.57	163.303
E13	0.7589	0.80	1	0.7500	1.09	0.7589	161.51	212.81	**228.189**
	0.7589	0.80	2	0.5272	1.09	0.9518	161.51	169.68	251.028

Following observations can be made from above results:

1. Obeying the restriction on minimum F_T value may result in expensive exchangers. In E1, E2, and E12 minimum cost exchangers have $F_T < 0.75$, while in E5, E6, and E13 the minimum cost exchangers have $F_T < 0.8$.
2. Note that E3 and E8 are same except cost law coefficients. Ponce-Ortega et al. [7] report that the minimum cost exchanger will always have $F_T > 0.8$ which is an incorrect conclusion. To illustrate this point, following table lists four exchangers, all with same terminal temperatures but different cost laws:

TABLE IV
DATA FOR ILLUSTRATING EFFECT OF COST LAW COEFFICIENTS

Exchanger	T_1	T_2	t_1	t_2	Q (kW)	U (kW/m^2/K)	Cost law coefficients		
							a	b	c
E3	410	110	0	360	2000	0.1	0	7000	0.65
E8	410	110	0	360	2000	0.1	8600	670	0.83
E14	410	110	0	360	2000	0.1	8600	670	0.70
E15	410	110	0	360	2000	0.1	8600	670	0.60

TABLE V
RESULTS OF EXCHANGERS OF TABLE 4.

Hx	N_{shells} by Eqn. (22)	Integer shells	S per shell	N_{shells} for G = 0	F_T per shell	Acc	A_{12}	$Cost_{12}$
E3	3.06	4	0.5666	4.32	0.7594	262.82	346.10	508.508
	3.06	5	0.5061	4.32	0.8599	262.82	305.65	507.151
	3.06	6	0.4573	4.32	0.9066	262.82	289.89	522.277
E8	3.06	4	0.5666	4.32	0.7594	262.82	346.10	117.232
	3.06	5	0.5061	4.32	0.8599	262.82	305.65	110.375
	3.06	6	0.4573	4.32	0.9066	262.82	289.89	109.064
E14	3.06	4	0.5666	4.32	0.7594	262.82	346.10	69.432
	3.06	5	0.5061	4.32	0.8599	262.82	305.65	68.225
	3.06	6	0.4573	4.32	0.9066	262.82	289.89	69.285
E15	3.06	4	0.5666	4.32	0.7594	262.82	346.10	47.542
	3.06	5	0.5061	4.32	0.8599	262.82	305.65	48.119
	3.06	6	0.4573	4.32	0.9066	262.82	289.89	49.779

VI. APPLICATIONS TO HEN DESIGN

In HEN design practice, various targets are set prior to synthesis of HEN. These targets are:

1. Minimum energy (utility) targets
2. Minimum network area target
3. Minimum units target
4. Minimum shells target

The shells target and units target are not mutually exclusive, and in using exchanger capital cost equation for multipass exchangers (Eqn. 24) shells target replaces units target.

In the cost equation, both exchanger area and number-of-shells appear. It has been argued previously [17] that "total minimum network area" as an independent target is not advisable. It is also shown in the above work that one can replace area by number of shells in assessing practically feasible heat recovery.

The minimum energy targets are HRAT-dependent. The absolute limit on energy recovery is placed by asymptotic energy targets which correspond to HRAT = 0.

Hence, based on above discussion, the problem of design optimization of HEN (consisting of multipass exchangers) can be put in most simplified manner possible. It requires only two bounds on optimization space – asymptotic energy targets, and shells target based on equation (22). It must be emphasized here that both the targets can only be approached, but never achieved. Thus, they provide the completely defined, widest thermodynamically feasible optimization space with just two variables – HRAT and number-of-shells.

VII. CONCLUSIONS

The following points can be made concerning the criteria and the approach advocated in this paper:

1. The correction factor F_T is a misleading parameter when used to restrict design options available for optimization.
2. A new criterion for 1-2 exchanger feasibility has been proposed that does not relate to F_T. Instead, it is based on the premise that all feasible multipass exchangers must be considered for cost-based optimization.
3. The approach and the equations introduced in the paper are useful in simplifying the task of synthesis and optimization of heat exchanger networks consisting of multipass exchangers.

NOTATION

A heat exchanger area, m^2
F LMTD correction factor, dimensionless
G Dimensionless temperature approach, $\frac{(T_2 - t_2)}{(T_1 - t_1)}$
G_1 G for one shell
LMTD log mean temperature difference, K
M integer number of shells
N real (non-integer) number of shells

R heat capacity ratio, $\frac{(T_1 - T_2)}{(t_2 - t_1)}$ dimensionless

S temperature effectiveness, $\frac{(t_2 - t_1)}{(T_1 - t_1)}$ dimensionless

S_1 S for one shell
T_1 hot fluid inlet temperature, K
T_2 hot fluid outlet temperature, K
t_1 cold fluid inlet temperature, K
t_2 cold fluid outlet temperature
ΔT_{eff} actual mean temperature difference, K
X_P Ahmad et al.'s parameter, dimensionless
U overall heat transfer coefficient

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