Spreadsheet Add-in for Heat Exchanger Logarithmic Mean Temperature Difference Correction Factors

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ABSTRACT

This paper presents an MS Excel spreadsheet add-in for heat exchanger logarithmic mean temperature difference (LMTD) correction factors for ten heat exchanger configurations. It is a computer tool for determining the LMTD correction factors for complex heat exchanger flow arrangements. The charted correction factors for various flow arrangements were curve-fitted using the MS Excel Solver tool. Lagrange interpolation scheme was used to formulate the relevant interpolation formulas for the various flow arrangements considered. The interpolation scheme was programmed in MS Excel Visual Basic for Application as an add-in. Results obtained agree with the values from the correction-factor charts presented in the literature. The add-in is a veritable tool for spreadsheet heat exchanger design and performance analysis for design engineers as well as for educational purposes.

General Terms

Spreadsheet add-in

Keywords

heat exchangers, LMTD correction factors, curve fitting, spreadsheet add-in

1. INTRODUCTION

The process of heat exchange between two fluids that are at different temperatures and separated by a solid wall occurs in many engineering applications. The device used to implement this exchange is called a recuperative heat exchanger. Specific applications may be found in space heating, cooling and air-conditioning, power generation, waste heat recovery, separation processes and other chemical processes. The optimal design or selection of heat exchangers is an essential task of the heat exchanger engineer, especially with increasing demand for effective and efficient heat exchangers deployed in engineering systems. This task becomes more involved when complex heat exchangers are to be used. Two of the crucial steps in the thermal design of heat exchangers are the determination of the logarithmic mean temperature difference (LMTD) and the overall heat transfer coefficient (the U-value), which are required to compute the required heat transfer surface area [1, 2].

The traditional procedure for determining the corrected LMTD is as follows: obtain the inlet and exit temperatures of the hot and cold fluid streams; compute the dimensionless temperature (P) and the ratio of water equivalents of the two streams (R); determine the correction factor (Ψ) from the heat exchanger correction factor charts, which correlates P , R and Ψ as illustrated in Figure 1; compute the counter-flow LMTD; and compute the product of Ψ and LMTD to obtain the

corrected LMTD (CLMTD) for the given complex heat exchanger flow arrangement [1].

If algebraic expressions that correlate P , R and Ψ are found, the use of computers in the design and performance analysis of heat exchangers with complex flow arrangements could be facilitated, and the error associated with reading data from the P - R - Ψ chart would be eliminated. In this case, the spreadsheet design and performance analysis of heat exchangers becomes relatively simple and straightforward, especially when the relevant algebraic expressions are appended to the spreadsheet as add-ins. The MS Excel environment allows the appendage of computer programmes written in Visual Basic for Applications (VBA), called MS Excel add-in tools [3].

Therefore, this paper presents polynomial expressions and a computer tool (MS Excel add-in) for obtaining the heat exchanger LMTD correction factor for ten selected heat exchanger configurations and flow arrangements. The approach facilitates computer-aided design analysis of engineering problems and would be useful to the design engineer, and also assist in the training of the student engineers [4, 5, 6]. The charted correction factors are interpolated using the Lagrange interpolation scheme to obtain polynomial expressions for the various heat exchangers considered. This is then coded in the MS Excel environment as an add-in.

2. PROBLEM FORMULATION AND SOLUTION

The problem is to devise an automatic scheme for determining the LMTD correction factors for the popular complex heat exchangers; thus, eliminating the use of the correction factor chart, which is illustrated in Figure 1.

Using the Lagrange polynomial interpolation scheme [7, 8], one obtains the following numerical schemes for the correction factor, ψ , as a function of the dimensionless temperature, P , and the ratio of water equivalents, R :

$$\Psi_k(P, R) = \sum_{i=0}^n \Psi_{k,i} \left[\prod_{\substack{j=0 \\ j \neq i}}^n \frac{R - R_{k,j}}{R_{k,i} - R_{k,j}} \right] \quad (1)$$

Figure 1 P-R-Ψ chart for the determination of the LMTD correction factor (Ψ)

$$P = \frac{T_{11} - T_{12}}{T_{11} - T_{21}} \quad (2)$$

and

$$R = \frac{\dot{C}_1}{\dot{C}_2} = \frac{T_{22} - T_{21}}{T_{11} - T_{12}} \quad (3)$$

where k is an integer value corresponding to the heat exchanger configuration type; and n is the number of data points minus one; the first index (i) in the double indexing scheme (ij) stands for the hot ($i=1$) or cold ($i=2$) stream, while the second index (j) stands for the heat exchanger inlet ($j=1$) or exit ($j=2$) temperature; that is: T_{11} is the hot stream inlet temperature; T_{12} is the hot stream exit temperature; T_{21} is the cold stream inlet temperature; and T_{22} is the cold stream exit temperature; and the water equivalent of the hot ($i=1$) or cold ($i=2$) stream, $\dot{C}_i$ is defined as

$$\dot{C}_i = \dot{m}_i c_{pi} \quad [kW / K], i = 1, 2 \quad (4)$$

$\dot{m}_i$ [kg/s] and c_{pi} [kJ/kgK] are the mass flow rate and isobaric specific heat capacity, respectively, for the hot ($i=1$) or cold ($i=2$) stream [1].

In determining the corrected logarithmic mean temperature difference (CLMTD), the counter-flow LMTD, ΔT_{LMC} , is first obtained, which is given as (Oko, 2005)

$$\Delta T_{LMC} = \frac{1}{A} \int_0^A \Delta T(A) dA = \frac{\Delta T_b - \Delta T_s}{\ln \frac{\Delta T_b}{\Delta T_s}} \quad (5)$$

For the counter current flow, the temperature differences are given as follows:

$$(a) \dot{C}_1 > \dot{C}_2 : \Delta T_b = T_{12} - T_{21} \text{ and } \Delta T_s = T_{11} - T_{22} \quad (6)$$

$$(b) \dot{C}_1 < \dot{C}_2 : \Delta T_b = T_{11} - T_{22} \text{ and } \Delta T_s = T_{12} - T_{21} \quad (7)$$

where ΔT_b and ΔT_s are the big (b) and small (s) temperature differences, respectively, at the ends of the heat exchanger.

Therefore, the CLMTD becomes

$$\Delta T_{CLM} = \Psi \Delta T_{LMC} \quad (8)$$

The heat transfer surface area (A) is then determined from the fundamental equation of heat transfer as

$$A = \frac{\dot{Q}}{U \Delta T_{CLM}} \quad (9)$$

where $\dot{Q}$ [kW] is the heat transfer and U [kW/m²K] is the overall heat transfer coefficient or the U -value.

The heat exchanger correction factor and CLMTD are determined using the following computational algorithm:

```

start
  input inlet/exit temperatures;
  if exit temperatures are not given
    then
      use the number of transfer units-effectiveness
        method to obtain the exit temperatures;
      output result into preselected cells;
    end_then
  compute the dimensionless parameters,  $P$  and  $R$ ;
  select  $k$  **heat exchanger flow arrangement**
   $i := 0$ ;  $\psi_i := 0$ ;
  repeat
     $\psi := \psi_i$ ;
     $j := 0$ ;
    repeat
      if  $i \neq j$ 
        then
           $\psi := \psi * (R - R_{k,i}) / (R_{k,i} - R_{k,j})$ ;
        end_then
       $j := j + 1$ ;
    until  $j = n$ 
     $i := i + 1$ ;
  until  $i = n$ 
  output  $\psi$ ;
  compute the counter-flow LMTD and corrected
    LMTD;
  carry out thermal design for the heat exchanger
    surface area, if desired;
  carry out performance analysis of the heat exchanger,
    if desired;
  output final results into the specified cells;
stop

```

The computational algorithm was transformed into the Visual Basic for Application program in MS Excel as an add-in tool.

3. RESULTS AND DISCUSSION

The MS Excel Solver is a popular computer tool for curve fitting data points when there is no direct tool of curve fitting [3, 9]. The MS Excel Solver was used to curve fit the charted correction factors. The correlations for the correction factor, Ψ , as a function of the dimensionless temperature, P , at a specified ratio of the water equivalents of the two streams, R , in the interval $R \in [0.2, 0.4]$ are presented in Table 1, where k is an integer value corresponding to the heat exchanger configuration type (1 shell pass, 2 or even number of tube passes (1-2n), 2 shell passes, 4 or multiple of 4 tube passes (2-4n), 3 shell passes 6 or multiple of 6 tube passes (3-6n), 4 shell passes 8 or multiple of 8 tube passes (4-8n), 5 shell passes 10 or multiple of 10 tube passes (5-10n), 6 shell passes 12 or multiple of 12 tube passes (6-12n), Split flow shell 2 tube passes, 1 Divided flow shell pass even number of tube passes, Single pass cross flow both fluid unmixed, Single pass cross flow with one fluid mixed and the other unmixed), see the Appendix for schematic diagram of the configurations, and i is the data point corresponding to the correction factor, ψ .

Table 1 Correction Factor as a Function of Dimensionless Pressure and Heat Capacity Ratio

k	i	Correction factor, Ψ_i [-]	at R_i [-]
0	0	$-4.873P^3 + 5.150P^2 - 1.174P + 1.001$	0.200
	1	$-4.792P^3 + 4.186P^2 - 0.847P + 1.001$	0.400
	2	$-5.579P^3 + 4.044P^2 - 0.685P + 1.001$	0.600
	3	$-7.579P^3 + 4.854P^2 - 0.739P + 1.002$	0.800
	4	$-9.750P^3 + 5.637P^2 - 0.794P + 1.002$	1.000
	5	$-12.248P^3 - 6.151P^2 + 0.748P + 1.002$	1.200
	6	$-19.986P^3 - 9.962P^2 + 1.178P + 1.002$	1.400
	7	$-24.413P^3 - 11.157P^2 - 1.232P + 1.001$	1.600
	8	$-33.365P^3 + 14.353P^2 - 1.455P + 1.002$	1.800
	9	$-35.759P^3 + 13.747P^2 - 1.240P + 1.002$	2.000
	10	$-54.737P^3 + 18.049P^2 - 1.429P + 1.002$	2.500
	11	$-113.609P^3 + 35.269P^2 - 2.526P + 1.002$	3.000
	12	$-252.162P^3 + 65.926P^2 - 4.068P + 1.001$	4.000
1	0	$-14.071P^3 + 20.697P^2 - 7.117P + 1.000$	0.200
	1	$-6.293P^3 + 7.941P^2 - 2.339P + 1.000$	0.400
	2	$-5.722P^3 + 6.392P^2 - 1.687P + 1.000$	0.600
	3	$-6.771P^3 + 6.752P^2 - 1.606P + 1.001$	0.800
	4	$-8.231P^3 + 7.247P^2 - 1.505P + 1.001$	1.000
	5	$-11.979P^3 + 9.759P^2 - 1.909P + 1.001$	1.200
	6	$-15.127P^3 + 11.010P^2 - 1.882P + 1.001$	1.400
	7	$-22.008P^3 + 14.704P^2 - 2.285P + 1.001$	1.600
	8	$-35.076P^3 + 22.312P^2 - 3.327P + 1.000$	1.800
	9	$-34.844P^3 + 19.400P^2 - 2.426P + 1.001$	2.000
	10	$-68.328P^3 + 32.857P^2 - 3.595P + 1.001$	2.500
	11	$-145.351P^3 + 58.871P^2 - 5.109P + 1.000$	3.000
	12	$-403.127P^3 + 131.391P^2 - 9.363P + 1.000$	4.000
2	0	$-43.441P^3 + 70.811P^2 - 27.789P + 1.001$	0.200
	1	$-14.738P^3 + 22.121P^2 - 7.935P + 1.000$	0.400
	2	$-8.770P^3 + 11.459P^2 - 3.468P + 1.000$	0.600
	3	$-7.657P^3 + 9.153P^2 - 2.614P + 1.000$	0.800
	4	$-9.036P^3 + 9.599P^2 - 2.431P + 1.000$	1.000
	5	$-12.156P^3 + 11.775P^2 - 2.743P + 1.000$	1.200
	6	$-19.838P^3 + 17.933P^2 - 3.931P + 1.000$	1.400
	7	$-27.599P^3 + 22.345P^2 - 4.326P + 1.000$	1.600
	8	$-47.145P^3 + 35.919P^2 - 6.578P + 1.000$	1.800
	9	$-67.481P^3 + 46.527P^2 - 7.601P + 1.000$	2.000
	10	$-143.027P^3 + 83.130P^2 - 11.490P + 1.000$	2.500
	11	$-552.940P^3 + 270.110P^2 - 30.175P + 0.999$	3.000
	12	$-869.914P^3 + 316.038P^2 - 26.012P + 1.000$	4.000
3	0	$-71.544P^3 + 124.149P^2 - 53.014P + 1.050$	0.200
	1	$-32.605P^3 + 52.519P^2 - 20.426P + 0.997$	0.400
	2	$-14.241P^3 + 21.245P^2 - 7.642P + 1.000$	0.600
	3	$-9.717P^3 + 12.998P^2 - 4.200P + 1.000$	0.800
	4	$-11.390P^3 + 13.552P^2 - 3.854P + 1.000$	1.000
	5	$-22.886P^3 + 25.458P^2 - 6.756P + 1.000$	1.200
	6	$-25.985P^3 + 25.754P^2 - 6.151P + 1.000$	1.400
	7	$-46.027P^3 + 42.168P^2 - 9.382P + 1.000$	1.600
	8	$-78.195P^3 + 66.440P^2 - 13.768P + 1.000$	1.800
	9	$-163.035P^3 + 128.648P^2 - 24.656P + 1.000$	2.000
	10	$-315.336P^3 + 194.804P^2 - 28.505P + 1.002$	2.500
	11	$-1737.783P^3 + 941.669P^2 - 122.693P + 1.0$	3.000
	12	$-1819.250P^3 + 755.072P^2 - 76.400P + 1.0$	4.000
4	0	$-654.453P^3 + 1188.742P^2 - 534.943P + 1.0$	0.200
	1	$-53.370P^3 + 92.083P^2 - 39.081P + 0.980$	0.400
	2	$-25.602P^3 + 41.358P^2 - 16.335P + 1.000$	0.600
	3	$-14.871P^3 + 21.933P^2 - 7.918P + 1.000$	0.800
	4	$-16.143P^3 + 21.395P^2 - 6.916P + 1.000$	1.000
	5	$-23.106P^3 + 27.637P^2 - 8.087P + 0.999$	1.200
	6	$-37.198P^3 + 39.555P^2 - 10.191P + 0.999$	1.400
	7	$-83.785P^3 + 81.898P^2 - 19.395P + 0.999$	1.600
	8	$-131.687P^3 + 116.690P^2 - 25.046P + 1.000$	1.800
	9	$-167.264P^3 + 134.884P^2 - 26.314P + 0.998$	2.000
	10	$-534.182P^3 + 357.030P^2 - 58.185P + 0.996$	2.500
	11	$-2254.758P^3 + 1270.159P^2 - 175.063P +$	3.000

k	i	Correction factor, Ψ_i [-]	at R_i [-]
5	1.035		
	12	$-2393.321P^3 + 937.029P^2 - 91.010P + 0.999$	4.000
	0	$-837.062P^3 + 1522.927P^2 - 686.254P + 1.0$	0.200
	1	$-870.687P^3 + 1518.984P^2 - 649.177P + 1.030$	0.400
	2	$-21.880P^3 + 34.798P^2 - 13.364P + 1.002$	0.600
	3	$-13.806P^3 + 20.116P^2 - 7.024P + 1.000$	0.800
	4	$-16.852P^3 + 22.788P^2 - 7.438P + 1.000$	1.000
	5	$-22.930P^3 + 28.363P^2 - 8.556P + 1.000$	1.200
	6	$-55.218P^3 + 62.759P^2 - 17.476P + 0.998$	1.400
	7	$-87.778P^3 + 86.820P^2 - 20.812P + 1.001$	1.600
	8	$-196.828P^3 + 179.023P^2 - 39.479P + 0.999$	1.800
	9	$-207.755P^3 + 167.185P^2 - 32.382P + 1.000$	2.000
	10	$-1353.721P^3 + 921.755P^2 - 153.134P + 1.0$	2.500
	11	$-143.501P^3 + 71.178P^2 - 8.847P + 1.000$	3.000
6	12	$-7933.555P^3 + 3147.121P^2 - 307.820P + 1.018$	4.000
	0	$-15.989P^3 + 23.415P^2 - 7.886P + 1.000$	0.200
	1	$-4.929P^3 + 6.262P^2 - 1.845P + 1.000$	0.400
	2	$-5.127P^3 + 5.711P^2 - 1.452P + 1.000$	0.600
	3	$-5.534P^3 + 5.331P^2 - 1.187P + 1.001$	0.800
	4	$-7.221P^3 + 6.161P^2 - 1.239P + 1.001$	1.000
	5	$-12.580P^3 + 10.178P^2 - 1.924P + 1.001$	1.200
	6	$-16.235P^3 + 11.849P^2 - 2.051P + 1.001$	1.400
	7	$-25.656P^3 + 17.450P^2 - 2.759P + 1.000$	1.600
	8	$-35.166P^3 + 21.721P^2 - 3.085P + 1.000$	1.800
	9	$-45.298P^3 + 25.728P^2 - 3.337P + 1.000$	2.000
	10	$-82.821P^3 + 39.542P^2 - 4.289P + 1.000$	2.500
	11	$-153.910P^3 + 63.335P^2 - 5.831P + 1.000$	3.000
	12	$-373.251P^3 + 119.218P^2 - 8.194P + 1.000$	4.000
7	0	$-3.291P^3 + 3.276P^2 - 0.704P + 1.000$	0.200
	1	$-3.313P^3 + 2.644P^2 - 0.507P + 1.000$	0.400
	2	$-4.030P^3 + 2.643P^2 - 0.422P + 1.000$	0.600
	3	$-5.049P^3 + 2.795P^2 - 0.390P + 1.000$	0.800
	4	$-6.567P^3 + 3.213P^2 - 0.399P + 1.000$	1.000
	5	$-9.019P^3 + 4.130P^2 - 0.477P + 1.000$	1.200
	6	$-14.599P^3 + 6.666P^2 - 0.752P + 1.000$	1.400
	7	$-18.155P^3 + 7.501P^2 - 0.760P + 1.000$	1.600
	8	$-25.262P^3 + 10.220P^2 - 1.003P + 1.000$	1.800
	9	$-26.688P^3 + 9.146P^2 - 0.734P + 1.000$	2.000
	10	$-46.146P^3 + 13.684P^2 - 0.857P + 1.001$	2.500
	11	$-68.293P^3 + 16.852P^2 - 0.791P + 1.001$	3.000
	12	$-180.183P^3 + 38.179P^2 - 1.398P + 1.001$	4.000
8	0	$-4.070P^3 + 4.645P^2 - 1.025P + 1.001$	0.200
	1	$-2.003P^3 + 1.897P^2 - 0.407P + 1.002$	0.400
	2	$-1.660P^3 + 1.277P^2 - 0.261P + 1.002$	0.600
	3	$-1.283P^3 + 0.583P^2 - 0.080P + 1.001$	0.800
	4	$-1.611P^3 + 0.590P^2 - 0.061P + 1.000$	1.000
	5	$-13.493P^3 + 5.763P^2 - 0.616P + 1.004$	2.000
	6	$-47.436P^3 + 15.322P^2 - 1.253P + 1.006$	3.000
	7	$-182.697P^3 + 47.418P^2 - 2.278P + 1.002$	4.000
	0	$-7.799P^3 + 9.502P^2 - 2.761P + 1.000$	0.200
	1	$-5.543P^3 + 5.247P^2 - 1.165P + 1.001$	0.400
	2	$-5.550P^3 + 4.129P^2 - 0.678P + 1.001$	0.600
	3	$-6.026P^3 + 3.759P^2 - 0.508P + 1.002$	0.800
	4	$-6.512P^3 + 3.464P^2 - 0.437P + 1.004$	1.000
9	5	$-22.710P^3 + 8.592P^2 - 0.678P + 1.004$	2.000
	6	$-54.417P^3 + 15.318P^2 - 0.932P + 1.005$	3.000
	7	$-259.538P^3 + 60.180P^2 - 1.633P + 1.003$	4.000

To obtain the correction factor (Ψ) one substitutes P into the correlations in Tables 1 that correspond to the heat exchanger flow arrangement under consideration and interpolates for Ψ with R serving as the interpolation point.

3.1 Examples

As illustrations of the use of the developed spreadsheet add-in to determine the correction factors and other thermal design parameters for heat exchangers, the following three examples are provided:

3.1.1 Example 1: Determination of the Correction Factors

Use the data tabulated in Table 2 to determine the correction factors for the various shell-tube heat exchanger configurations [10].

Table 1 Input Data for Example 2

S/No	Quantity	Symbol	Units	Value
1	tube side inlet temperature of the hot stream	t_{11}	°C	80.00
2	tube side exit temperature of the hot stream	t_{12}	°C	40.00
3	shell side inlet temperature of the cold stream	t_{21}	°C	20.00
4	shell side exit temperature of the cold stream	t_{22}	°C	50.00

Solution

Key in the developed MS Excel formula, =HCF(k , A, B, C, D), in any desired MS Excel cell; where k , A, B, C and D are cell references holding numerical values of the integer (k) that corresponds to the heat exchanger flow arrangement, tube side inlet temperature (A), tube side exit temperature (B), shell side inlet temperature (C) and shell side outlet temperature (D), respectively; holding down ctrl+shift keys, highlighting the four adjacent cells and pressing the enter key output the results shown in Table 3, which tabulates, among others, the dimensionless parameters P and R , the correction factor (ψ) and the corrected LMTD ($CLMTD$).

Table 3 MS Excel Add-in Output Data for Example 1

Heat Exchanger Class	P	R	ψ	LMTD [°C]	CLMTD [°C]
1 shell pass, 2 or even number of tube passes	0.67	0.75	0.540	24.66	13.31
2 shell passes, 4 or multiple of 4 tube passes	0.67	0.75	0.911	24.66	22.48
3 shell passes, 6 or multiple of 6 tube passes	0.67	0.75	0.962	24.66	23.73
4 shell passes, 8 or multiple of 8 tube passes	0.67	0.75	0.979	24.66	24.15
5 shell passes, 10 or multiple of 10 tube passes	0.67	0.75	0.987	24.66	24.34
6 shell passes, 12 or multiple of 12 tube passes	0.67	0.75	0.991	24.66	24.44
Split flow shell, 2 tube passes	0.67	0.75	0.951	24.66	23.45
1 Divided flow shell pass, even number of tube passes	0.67	0.75	0.573	24.66	14.13
Single pass cross flow both fluid unmixed	0.67	0.75	0.629	24.66	15.51
Single pass cross flow with one fluid mixed and the other unmixed	0.67	0.75	0.700	24.66	17.27

The counter-flow $LMTD$ for the problem is constant, $LMTD_c = 24.66$ [°C], which is higher than any of the $CLMTD$ of the heat exchanger configurations considered. With the use of the $LMTD_c$ value, one would have under-designed the heat

exchangers because less surface area would be provided, which would not be able to match the intended heat transfer load. The results show that for the six types of shell and tube heat exchangers considered, the $CLMTD$ value increases progressively with the number of shell passes, which means that given the same heat transfer surface area U -value, the effectiveness of the shell and tube heat exchangers increases with increasing numbers of shell passes. Cengel [10] reported 0.92 correction factor read from chart for 2 shell passes, 4 or multiple of 4 tube passes with the same input data, which is about 1.0 % deviation from that obtained with the spreadsheet add-in. Although this deviation is acceptable for most engineering applications, it cannot be directly traced to the approach adopted in this study, since reading data from charts as Cengel [10] is always prone to errors.

3.1.2 Example 2: Determination of the Heat Exchanger Surface Area

45.4 kg/h of water is to be heated from 10 to 77 °C with flue gases having an initial temperature of 166 °C. The mass flow rate of the gases is 182 kg/h and their specific heat is 1.05 kJ/kgK. The overall heat transfer coefficient may be taken as 114 W/m²K. Calculate the size of the heating surface for a 1 - 2 shell-tube heat exchanger [1].

Solution

Input data:

$$\dot{m}_w = 0.0126 \text{ kg/s}; t_{21} = 10 \text{ °C}; t_{22} = 77 \text{ °C}; t_{11} = 166 \text{ °C}; \dot{m}_g = 0.0506 \text{ kg/s}; c_{pg} = 1.05 \text{ kJ/kgK}; U = 0.114 \text{ kW/m}^2\text{K}; c_{pw} = 4.18 \text{ kJ/kgK}; 1\text{-}2 \text{ shell-tube heat exchanger};$$

The results obtained with the spreadsheet add-in are shown in Table 4. The results indicate that with the use of only the counter-flow LMTD for the design would lead to under-designing the heat exchanger surface area by 10.21%.

Table 4 MS Excel Add-in Output Data for Example 2

S/N	Quantity	Symbol	Units	Formula	Value
1	heat capacity ratio	ω	-	$\omega = \dot{m}_w * c_{pw} / (\dot{m}_g * c_{pg})$	0.995
2	flue gases exit temperature	t_{12}	°C	$t_{12} = t_{11} - \omega * (t_{22} - t_{21})$	99.31
3	counter flow big temperature difference	Δt_b	°C	$\Delta t_b = t_{11} - t_{22}$	89.00
4	counter flow small temperature difference	Δt_s	°C	$\Delta t_s = t_{12} - t_{21}$	89.31
5	counter flow LMTD, $LMTD_c$	Δt_{LMC}	°C	=HCF(0, t_{11} , t_{12} , t_{21} , t_{22})	89.15
6	heat exchanger correction factor	ψ	-	=HCF(0, t_{11} , t_{12} , t_{21} , t_{22})	0.898
7	corrected LMTD, $CLMTD$	Δt_{CLM}	°C	=HCF(0, t_{11} , t_{12} , t_{21} , t_{22})	80.06
8	Heat transfer rate	$\dot{Q}$	kW	$\dot{Q} = \dot{m}_w * c_{pw} * (t_{22} - t_{21})$	3.540
9	Heat transfer surface area without correction factor	A_{cf}	m ²	$A_{cf} = \dot{Q} / (U * \Delta t_{LMC})$	0.3483
10	Heat transfer surface area with correction factor	A	m ²	$A = \dot{Q} / (U * \Delta t_{CLM})$	0.3879
11	Percentage change in heat transfer surface area	ϵ	%	$\epsilon = ((A - A_{cf}) / A) * 100$	10.21

3.1.3 Example 3: Determination of Exit Temperatures, Correction Factors and Heat Transfer Rates

Use the flow and fluid properties of the six heat exchangers, HX1- HX5 [11] and HX6 [10], shown in Table 5 to carry out thermal analysis of the given six heat exchangers.

Table 5 Input Data for the Six Heat Exchangers, Example 3

Flow and Fluid Properties	Heat Exchanger					
	HX1		HX2		HX3	
	Tube	Shell	Tube	Shell	Tube	Shell
heat capacity, c_p , kJ/kgK.	2.05	2.47	2.47	2.05	2.05	2.28
mass flow rate, $\dot{m}$, kg/s.	116.1	32.3	125.5	232.3	116.1	10.9
inlet temperature, t_{11}, t_{21} , °C.	441	365	457	370.1	581	382
number of passes.	2	1	2	1	2	1
heat transfer surface area, A , m^2 .	418		379		327	
heat transfer coefficient, U , kW/ m^2 K.	0.3033		0.3916		0.1737	

Table 5 Continues

Flow and Fluid Properties	Heat Exchanger					
	HX4		HX5		HX6	
	Tube	Shell	Tube	Shell	Tube	Shell
heat capacity, c_p , kJ/kgK.	2.05	2.28	2.05	2.47	4.18	2.13
mass flow rate, $\dot{m}$, kg/s.	116.1	56.0	232.3	32.2	0.2	0.3
inlet temperature, t_{11}, t_{21} , °C.	365	480	506	431	20	150
number of passes.	2	1	2	1	8	1
heat transfer surface area, A , m^2 .	418		418		1.76	
heat transfer coefficient, U , kW/ m^2 K.	0.3341		0.2928		0.310	

Solution

Figure 2 shows the sketch of temperature distribution along any of the heat exchangers.

Figure 2 Sketch/Diagram of any of the Heat Exchangers

The heat exchanger performance analysis is carried out as follows:

- obtain the exit temperatures, T_{12} and T_{22} by keying in the MS Excel user defined function (add-in), =EFFNTU2(A, B, C, D, E, F, G) in any desired cell, where A, B, C, D, E, F and G stand for error bound, heat transfer coefficient, inlet temperature of the hot stream; inlet temperature of the cold stream, water equivalent of the hot stream, water equivalent of the cold stream and the flow configuration, respectively;
- use the function HCF(k, H, I, J, K) to obtain the counter-flow LMTD, correction factor and corrected LMTD; and
- with the corrected LMTD obtained, compute the heat transfer rate.

The results of the thermal analysis are shown in Table 6. Cengel [10] provided results for heat exchanger HX6, which are in agreement with results for HX6 as shown in Table 6. HX4 bears the largest thermal load, and the lowest thermal load is borne by HX6. The reason is attributed to the largest and lowest values of the product of overall heat transfer coefficient and heat transfer surface area for heat exchanger HX4 and HX6, respectively. The exit temperatures for both streams are highest in HX3, which is attributed to the mass flow rates, heat capacities and inlet temperatures of the fluid streams.

Table 6 MS Excel Add-in Output data for Example 3

Quantity	Heat Exchanger					
	HX1		HX2		HX3	
	Tube	Shell	Tube	Shell	Tube	Shell
water equivalent, $\dot{C}$, kW/K	238.0	79.8	310.0	476.2	238.0	24.9
exit temperatures, T_{12}, T_{22} , K	423.3	417.7	429.9	387.7	563.8	547.2
correction factor	0.85		0.92		0.99	
counter-flow LMTD	38.20		64.40		87.98	
corrected LMTD	32.47		59.25		87.1	
heat transfer rate, Q , kW	4116.64		8793.84		4947.36	

Table 6 Continues

Quantity	Heat Exchanger					
	HX4		HX5		HX6	
	Tube	Shell	Tube	Shell	Tube	Shell
water equivalent, $\dot{C}$, kW/K	238.0	127.7	476.2	79.54	0.84	0.64
exit temperatures, T_{12}, T_{22} , K	398.9	416.8	496.9	485.8	66.2	89.6
correction factor counter-flow	0.98		0.78		0.98	
LMTD					76.45	
corrected LMTD	64.01		30.16		74.92	
heat transfer rate, Q , kW	8939.25		3691.76		40.88	

4. CONCLUSION

An MS Excel add-in for heat exchanger LMTD correction factor has been developed for ten popular heat exchanger configurations, $k = 0, 1, \dots, 9$. It is a tool for direct computation of the *LMTD* correction factors, which eliminates the existing cumbersome graphical and iterative methods [12]. Results obtained are accurate enough for engineering applications. Several examples have been used to demonstrate the utility of the add-in tool, which is user friendly (interactive), robust and flexible. Apart from the stand-alone application of this spreadsheet add-in tool, it can also be integrated into a larger plant design software for improved productivity. Of course, the add-in is also a veritable tool for the effective teaching of the thermal design of heat exchangers in higher institutions of learning [6, 13]. The spreadsheet add-in if integrated into a larger plant can also be used by practicing engineers for heat exchanger design, simulation and selection.

5. REFERENCES

- [1] Oko, C.O.C. 2005. Introductory Heat Transfer: An algorithmic approach, 2nd Edition, Pam Unique publishing company limited, Port Harcourt.
- [2] Bell, J.K. and Mueller, C.A. 2001. Wolverine engineering data Book II, Wolverine tube Inc., www.wlv.com/products/databook/ch2_2.pdf, Retrieved: 28/03/10.
- [3] Liengme, B.V. (2000) A Guide to Microsoft Excel for scientist and engineers, Butterworth-Heinemann, London.
- [4] Oko, C.O.C., Diemuodeke, E.O. and Akinlade, I.S. 2010. Design of hoppers using spreadsheet, Journal of Research in Agricultural Engineering, Vol. 56(2), pp. 53-58.
- [5] Lona, L.M.F., Fernandes, F.A.N., Roque, M.C. and Rodrigues, L. 2000. Developing an educational software for heat exchangers and heat exchanger networks projects, Journal of Computer and Chemical Engineering, Vol. 24(2-7), 1247-1251.
- [6] Tan, F.L. and Fok, S.C. 2006. An educational computer-aided tool for heat exchanger design, Journal of Computer Application in Engineering education, Vol. 14(2), 77-89.
- [7] Chapra S.C., Canale R.P. (2002) Numerical methods for engineers, 4th Ed., Tata McGraw-Hill, New Delhi,

- [8] Oko, C.O.C. (2008) Engineering computational method: An algorithmic approach, 1st Edition, University of Port Harcourt Press, Port Harcourt.
- [9] Mustafa, G. 2000. Correlations for some Thermophysical Properties of Air, International Drying Symposium, NL, Wageningen.
- [10] Cengel, Y.A. (2007), Heat and mass transfer, 3rd Ed., Tata McGraw-Hill, New Delhi.
- [11] Ebieto, C.E (2010) Finite element analysis of shell and tube heat exchangers, M.Eng Thesis, Department of Mechanical Engineering, University of Port Harcourt, Port Harcourt.
- [12] Fakheri, A. (2003) Alternative approach for determining log mean temperature difference correction factor and number of shells of shell and tube heat exchangers, Journal of Enhanced Heat Transfer, Vol.10(4), pp. 407-420.
- [13] Leong, K.C., Toh, K.C. and Leong, Y.C. 1998. Shell and tube heat exchanger design software for education application, Int. Journal of Engineering Education, Vol. 4(3), 217-224.

APPENDIX

Heat Exchanger Configurations

<i>k</i>	Heat Exchanger Configuration
3	<p>4 shell passes 8 or multiple of 8 tube passes (4-8n)</p>
4	<p>5 shell passes 10 or multiple of 10 tube passes (5-10n)</p>
5	<p>6 shell passes 12 or multiple of 12 tube passes (6-12n)</p>
6	<p>Split flow shell 2 tube passes</p>

<i>k</i>	Heat Exchanger Configuration
7	<p>1 Divided flow shell pass even number of tube passes</p>
8	<p>Single pass cross flow both fluid unmixed</p>
9	<p>Single pass cross flow with one fluid mixed and the other unmixed</p>