Heat Transfer Analysis of

Compact Heat Exchangers Using Standard Curves

In previous issues of Qpedia Thermal eMagazine [1,2], we covered some fundamental and practical aspects of heat exchangers. In this issue, we will concentrate on compact heat exchangers and how to use standard curves for heat transfer analysis. Compact heat exchangers are a class of heat exchangers which features at least one of the fluids, on one side, as a gas. They generally have a very large heat transfer area per unit volume (>700 m^2/m^3) [3]. Most of the applications of compact heat exchangers are in the area of electronics cooling, because space for a cooling device is typically at a premium. Generally, the heat exchangers used in electronics cooling are of the air-to-liquid type. The heat transfer coefficient on the air side is significantly smaller than the liquid side, hence increasing the surface area on the air side can compensate for the low value of the heat transfer coefficient. Compact heat exchangers can come in different shapes and forms [3]. They can be made as

- Flat tubes (liquid) – continuous plate (air)
- Round tube (liquid) – continuous flat plate (air)
- Round tube (liquid) – round disks (air)
- Flat plate (liquid) – folded fin (air) single pass or multi-pass

Flow passages are generally very small (hydraulic diameter D_h < 5 mm) and the flow is considered laminar. Kays and London [4] have compiled a large volume of data for different heat exchanger configurations. The data plotted is in the form of the Colburn factor (J_H) and friction factor as a function of Reynolds number (Re), as shown in figure 1. The Colburn J_H factor is defined as:

$$J_H = StPr^{2/3}$$

Where,

The Stanton number is defined as:

$$St = \frac{Nu}{RePr}$$

Nu, Re and Pr are Nusselt, Reynolds and Prandtl numbers, respectively.

After considering all of the constraints and identifying the heat exchanger type, the engineer must look at the graphs and match the heat exchanger configuration to the available data, if it is available, and extract the information from there.

The following example shows how to use curves to solve a heat exchanger problem:

Consider a circular tube-circular fin compact heat exchanger as shown in figure 1.

The liquid water transfers the heat from hot components through the aluminum tube. Ambient air is blown through the fins attached to the tubes to remove the heat from hot fluid. Calculating the overall heat transfer coefficient on the air side:

The geometrical dimensions of this heat exchanger and other information are as follows:

Tube outside diameter = 9.65 mm

Fin pitch = 343 per m

Flow passage hydraulic diameter = 3.929×10^{-3} m

Fin thickness = 0.46×10^{-3} m

Free flow are/frontal area = $\frac{A_{ff}}{A_{fr}} = \sigma = 0.524$

Heat transfer area/total volume = $\alpha = 0.524$

Fin area/total area = $\frac{A_f}{A}$ = 0.91

Inside tube diameter = 6 mm

$\dot{m}_c$ = air mass flow rate (cold side) = 0.45 Kg/s

$\dot{m}_h$ = water mass flow rate (cold side) = 0.1 Kg/s

T_{air} = air flow temperature = 20 °C

A_{fr} = frontal area = 0.0225 m^2

The properties of air at 20 °C are as follows:

C_p = 1007 J/Kg.K

$\mu = 180\times10^{-7}\ N.s/m^2$

Pr = 0.709

The overall heat transfer coefficient for a heat exchanger is written as:

$$\frac{1}{UA} = \frac{1}{(\eta_0 hA)c} + R_w + \frac{1}{(\eta_0 hA)h} + R''_f \qquad (1)$$

The fin effectiveness η_0 can be written as:

$$\eta_0 = 1 - \frac{A_f}{A}(1-\eta_f) \qquad (2)$$

Where,

A_f = fin area
A = total heat transfer area
η_f = fin efficiency
h = heat transfer coefficient
R_w = conduction resistance due to tube walls
R''_f = fouling resistance
Subscripts c and h stand for cold and hot side, respectively.
Neglecting the fouling resistance
$R''_f = 0$
Since there are no fins inside the tubes $\eta_{0,h}=1$, the subscript h means water is the hot fluid. The overall heat transfer coefficient, for the air which is directed to the cold side, can then be written as:

$$\frac{1}{U_c} = \frac{1}{\eta_{0,c}h_c} + R_w A_c + \frac{1}{h_h(A_h/A_c)} \qquad (3)$$

$$A_h/A_c \approx D_i/D_o(1-A_f/A)$$

D_i = inner diameter of the tube
D_0 = outer diameter of the tube

The conduction resistance is calculated as:

$$R_w A_c = \frac{Ln(\frac{D_o}{D_i})}{2\pi Lk/A_c} = \frac{D_i Ln(D_o/D_i)}{2KA_h/A_c} = \frac{6\times10^{-3}Ln(9.65/6)}{2(200)(0.0559)} = 0.127\text{x}10^{-3}\ m^2.K/W \qquad (4)$$

The heat transfer coefficient of the water flow inside the tube is calculated as:

$$U_{water} = \dot{m}/\rho A = \frac{0.1}{1000\times\pi/4\times(6\times10^{-3})^2} = 3.5\,m/s$$

$$Re = \frac{\rho U_{water} D_h}{\mu} = 3.5(6\times10^{-3})/352\times10^{-6} = 59$$

This shows the flow is laminar. Assuming it is also fully developed:

Nu = Nusselt number = 4.26

h_{water} = kNu/D = 0.67(4.26)/6X10^{-3} = 486 W/m^2.K

Now calculate the air side heat transfer coefficient:

$$Re_{air} = \frac{\rho U_{air} D_h}{\mu}$$

U_{air} is the air flow velocity in the free flow area

$$\rho U_{air} = \frac{\dot{m}_{air}}{A_{ff}} = \frac{\dot{m}_{air}}{\sigma A_{fr}} = \frac{0.45}{0.524(0.0225)} = 38.16 \text{ Kg/m}^2\text{.S}$$

$$Re_{air} = \frac{38.16(3.929\times10^{-3})}{180\times10^{-7}} = 8329$$

From figure 1 [4], the Colburn factor J_H is found as:

$$J_H = 0.006$$

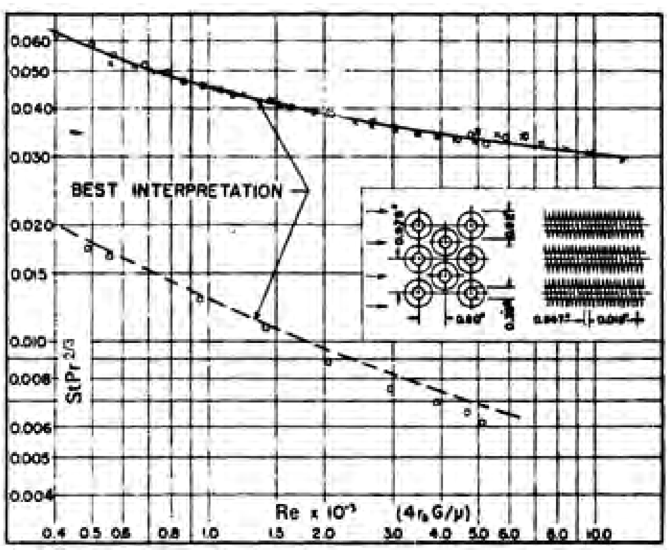

Figure 1. Colburn J_H Factor as a Function of Reynolds Number for Circular Tubes, Surface CF-8.72 [4].

The air side (cold side) heat transfer coefficient is then calculated as:

$$h_c \approx 0.006\frac{GC_p}{Pr^{2/3}} = 0.006\frac{38.16\times1007}{0.709^{2/3}} = 289 \text{ W/m}^2\text{.K}$$

Where,

G = Volumetric flow rate

C_p = Heat capacity

Calculate the fin effectiveness from Equation 2. First we need the fin efficiency. Referring to figure 2:

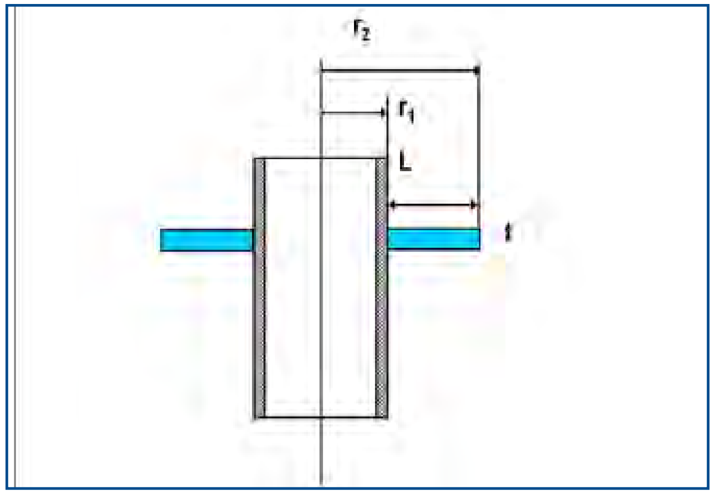

Figure 2. Schematic of Annular Fins of Rectangular Profile.

From figure (3.19) in reference [3], we can find the fin efficiency as a function of $LC^{3/2}(h/KA_p)^{1/2}$ for different values of r_{2c}/r_1. The variables are defined as:

$r_{2c} = r_2 + t/2 = 11.914$ mm
$L_c = L + t/2 = 7.089$ mm
$A_p = L_c t = 1.63 \times 10^{-6}$
$L_c^{3/2}(h/KA_p)^{1/2} = 0.561$ and $r_{2c}/r_1 = 2.46$
$\eta_{0,c} = 1 - A_f / A(1 - \eta_f) = 0.772$

Finally the overall heat transfer coefficient is calculated as:

$$\frac{1}{U_c} = \frac{1}{486 \times 0.0559} + 0.127 \times 10^{-3} + \frac{1}{0.772 \times 289}$$

Overall heat transfer coefficient on the air side (cold side):

$$U_c = 23.5\ W/m^2.K$$

In future articles we will show analytical techniques for heat exchangers, with geometries that are not referenced in any available literature, especially compact heat exchangers with very dense fins on the air side. Also, the above procedure simplified the analysis by ignoring the fouling factor. Fouling is the process of accumulation of particles on the fins or inside the liquid tubes. It depends on the fluid velocity, length of service and the type of fluid. In future articles, we will devote the topic to Fouling.

References

1. Advanced Thermal Solutions, Inc., Qpedia Thermal eMagazine, May 2007, “Heat exchangers: theory and selection”
2. Advanced Thermal Solutions, Inc., Qpedia Thermal eMagazine, Jan 2008, “Compact heat exchangers for electronics cooling”
3. Incropera, F.P, Dewitt, D.P, “Introduction to heat transfer” 1985
4. Kays, M. and London, “Compact Heat Exchangers”, Third Edition, McGraw-Hill, 1984.