Design of Cross Flow Heat Exchanger Using Performance Charts

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***Abstract*— The manuscript reviews the various steps involved in the design of a cross flow heat exchanger. Performance charts describing the thermal performance of the heat exchanger in terms of dimensionless parameters are used to develop the preliminary design of the heat exchanger. The preliminary design involves choosing the required number of heat exchanger passes, the required number of transfer units (NTU) and the capacity rate ratio for a given heat transfer application. These dimensionless parameters account for material, flow and thermal characteristics of the heat exchanger. In addition, NTU accounts for heat exchanger size, flow configuration and the type of heat exchanger. Since the preliminary design accounts for all the major characteristics of the heat exchanger, this approach is beneficial in optimizing the heat exchanger during the design phase. Performance charts indicate that indefinitely increasing the surface area (or NTU) does not increase the rate of heat transfer. There exists a threshold limit beyond which increasing the surface area adds no benefit to the heat exchanger. Instead, it just adds weight, material and cost of the heat exchanger. It must be noted that an undersized heat exchanger for a given application may not deliver the required heat transfer and while an oversized heat exchanger will increase the capital cost. Hence, it is very important to choose the right parameters during design of a heat exchanger. From the preliminary design, the detailed design for the heat exchanger can be readily extrapolated. The benefits of using performance charts in the design of a cross flow heat exchanger are described in the manuscript.**

***Index Terms*—crossflow heat exchanger, performance charts, heat exchanger optimization, heat exchanger design, heat exchanger steady state analysis.**

I. Introduction

Crossflow heat exchangers are very popular and commonly employed in process and manufacturing industries, residential applications, car radiators, etc. Typically, most cross flow heat exchangers are gas to liquid heat exchangers wherein the gas is the external fluid and liquid is the tube side fluid. Both fluids do not come in contact and they exchange heat through the tube wall. Like other heat exchangers, cross flow heat exchangers also come in different flow configurations such as parallel flow, counter flow and pure cross flow. Every flow configuration has its merits and demerits and the choice of flow configuration is mainly based on the existing piping arrangement and the requirements in the industry.

This paper describes the steps required in the design of a cross flow heat exchanger using performance charts. Performance charts describe the performance of a cross flow heat exchanger in terms of essential dimensionless parameters. These parameters are number of transfer units (NTU), capacity rate ratio, and heat exchanger effectiveness. All variables required in the design of the cross flow heat exchanger are cumulatively accounted by these three dimensionless parameters. From the available inputs and the requirements, the required heat exchanger effectiveness can be readily computed. From the required effectiveness, using performance charts, it is fairly straight forward to determine the required number of passes, capacity rate ratio and the NTU. The detailed design of the heat exchanger can then be extrapolated from these parameters.

It must be recognized that the heat exchanger NTU accounts for size, surface area available for heat transfer, materials of construction, flow properties, thermal properties etc. The performance charts clearly describe the variation of heat exchanger's performance with respect to NTU and capacity ratio. Therefore, determining the right NTU and capacity rate ratio helps in designing the right heat exchanger for the given application.

There are many references in the literature pertaining to the design of the cross flow heat exchanger and only a few pertinent references are discussed herein. Silaipillayarputhur and Idem [1] presented the matrix approach in the design of the crossflow heat exchanger. Therein, the performance of the crossflow heat exchanger was evaluated at every pass of the heat exchanger. This approach helped the design engineers in optimizing the heat exchanger based on its performance. As an extension of [1], Silaipillayarputhur and Idem [2] considered validation of matrix approach. Therein, they considered a heat exchanger operating at a chemical facility in Chattanooga, TN. They applied matrix techniques to estimate the performance of the heat exchanger and compared with the actual performance data. Silaipillayarputhur et al. [3] considered the development of performance tables for multi pass parallel cross flow heat exchangers. Therein, the performance at each pass of the heat exchanger were expressed through meaningful tables. Dimensionless parameters such as effectiveness, capacity rate ratio, and number of transfer units that govern the steady state performance of the heat exchanger were used to describe the performance of the heat exchanger at every pass. Silaipillayarputhur et al. [4] considered the performance of cross flow heat exchanger subjected to various flow configurations. Parallel cross flow, counter crossflow and pure

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crossflow were considered for the analysis. Kays and London [5] provided detailed information on the design of compact heat exchangers. Silaipillayarputhur and Al Mughanam prescribed performance charts for cross flow heat exchangers. Therein the performance of the cross flow heat exchanger was prescribed in terms of meaningful dimensionless parameters.

II. NOMENCLATURE

A	net positive suction head available (psig)
A'	inlet pressure to the pump (psig)
C	vapor pressure of the fluid being pumped (psig)
c	tank A pressure (mm of Hg; gage)
D_H	available head in the tank A (ft)
d	diameter of the pipe after the pump (m)
f	Reynolds number (dimensionless)
A	Heat transfer surface area
A'	Heat transfer surface area per unit length
C	Heat capacity rate of a fluid
c	Specific heat at constant pressure
D_H	Hydraulic diameter of the heat exchanger
d	Diameter of the tube
f	Fouling factor
G	Maximum mass flux
h	Heat transfer coefficient
j	Colburn j-factor
k	Thermal conductivity
L	Equivalent flow length of the heat exchanger
l_{tube}	Length of tube
m	Fin effectiveness parameter
$\dot{m}$	Mass flow rate
npass	Number of passes
n_{tube}	Number of tubes
NTU	Overall number of transfer units
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
rt	Resistance
S_T	Centerline distance between adjacent tubes in transverse direction
S_L	Centerline distance between adjacent tubes in lateral direction
S_F	Fin density
U_o	Overall heat transfer coefficient
V	Velocity

Greek Letters

ε	surface roughness for steel pipe (mm)
υ	kinematic viscosity (m^2/s)
$\bar{\delta}$	Fin thickness
ε	Effectiveness, matrix approach
η	Efficiency
ϕ	Fin effectiveness parameter
γ	Ratio of finned area to outside area
μ	Dynamic viscosity
ρ	Density
φ	Dimensionless fin effectiveness parameter
σ	Ratio of minimum flow area to frontal area of a heat exchanger
θ	Angle of inclination of the corrugations of the plate fin

Subscripts

A	External fluid (hot fluid)
f	Fin
fr	Frontal
I	Inside
min	Minimum
max	Maximum
o	Outside
o	Overall
sum	Sum
w	Tube side fluid (cold fluid)

III. PRELIMINARY DESIGN OF THE CROSS FLOW HEAT EXCHANGER

The cross flow heat exchanger considered in the analysis is a gas to liquid heat exchanger. Consider Figure 1 describing a cross flow heat exchanger in parallel flow configuration. Almost all cross flow heat exchangers are finned cross flow heat exchangers as fins enhance the surface area and thus the heat transfer.

The preliminary design of the crossflow heat exchanger considers the selection of the number of heat exchanger passes, an appropriate NTU and capacity rate ratio for the heat exchanger. In this analysis, the heat exchanger is assumed to operate under steady state conditions and it is assumed that the equipment is perfectly insulated. The fluids are assumed to be unmixed and the external fluid (gas) is treated as the minimum capacity rate fluid. For brevity, the development of performance charts [6] are not described herein. Figures 2 through 4 describe the performance charts for parallel and counter cross flow heat exchanger. For brevity, only performance and single pass and four-pass heat exchanger are described herein. The performance charts describe the performance of the heat exchanger with respect to heat exchanger passes, heat exchanger effectiveness, NTU and capacity ratio. A pass in a cross flow heat exchanger refers to the tube passes and it can be seen as the number of times a fluid particle would travel through the entire length of the heat exchanger.

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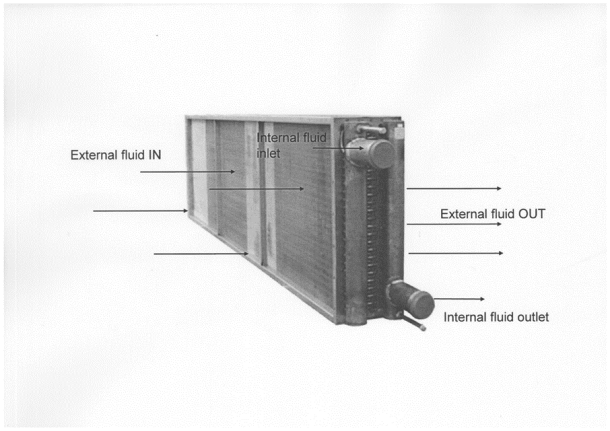


Fig. 1. Finned cross flow heat exchanger (parallel flow configuration)

IV. Detailed Design of the Cross Flow Heat Exchanger

Conventionally, the detailed design of the cross flow heat exchanger aims at determining the NTU of the heat exchanger. However, this parameter has been readily determined by using the performance charts. NTU of the heat exchanger can be given as follows [5]

$$NTU = \frac{U_o \cdot A_o}{C_{min}} \quad (1)$$

Or

$$NTU = \frac{U_o \cdot A_o}{(\dot{m} \cdot c)_A} \quad (2)$$

The other parameters such as the required overall heat transfer coefficient Uo and the required surface area Ao for heat transfer must be determined such that they account for the selected NTU. The required surface area for the heat exchanger may be given as [2]

$$A_o = A'_o l_{tube} n_{tube} n_{pass} \quad (3)$$

Where the heat transfer surface area per unit length is given as [2]

$$A'_o = \left\{ \frac{2S_L S_T S_F}{\cos\theta} + \pi d_o \left(1 - \bar{\delta} S_F\right) \right\} \quad (4)$$

The required overall heat transfer coefficient may be expressed as [2]

$$U_o = \frac{1}{A'_o l_{tube} rt_{sum}} \quad (5)$$

The overall resistance to heat transfer rtsum may be given as [2]

$$rt_{sum} = rt_{h_i} + rt_{f_i} + rt_w + rt_{f_o} + rt_{h_o} \quad (6)$$

Where rthi is the internal convection resistance given as [2]

$$rt_{h_i} = \frac{1}{h_i \pi d_i l_{tube}} \quad (7)$$

and the external convection resistance is given as [2]

$$rt_{h_o} = \frac{1}{h_o \eta_o A'_o l_{tube}} \quad (8)$$

The internal heat transfer coefficient inside the tube may be given as [2]

$$h_i = \frac{k_i Nu_i}{d_i} \quad (9)$$

Where the Nusselt number Nui based on fully developed turbulent flow in a tube can be given as [2]

$$Nu_i = 0.023 Re_i^{0.8} Pr_i^{0.4} \quad (10)$$

Assuming steady incompressible flow inside the tubes the Reynolds number per tube may be given as [5]

$$Re_i = \frac{4\dot{m}_w}{n_{tube} \pi d_i \mu_i} \quad (11)$$

The external convection heat transfer coefficient may be given as [2]

$$h_o = j c_A G Pr^{-2/3} \quad (12)$$

Where the Colburn j-factor is expressed as [2]

$$j = 0.116 Re_o^{-0.372} \quad (13)$$

The Reynolds number of external fluid may be expressed as [2]

$$Re_o = \frac{G D_H}{\mu_o} \quad (14)$$

The maximum mass flux G may be defined as [2]

$$G = \rho_A V_{max} \quad (15)$$

The hydraulic diameter of the external (finned) side of the heat exchanger may be given as [2]

$$D_H = \frac{4 A_{min} L}{A_o} \quad (16)$$

The equivalent flow length may be given as [2]

$$L = n_{pass} S_L \quad (17)$$

The minimum flow area can be expressed as [2]

$$A_{min} = \sigma A_{fr} \quad (18)$$

The frontal area of the heat exchanger is given as [2]

$$A_{fr} = n_{tube} S_T l_{tube} \quad (19)$$

The ratio of minimum flow area to frontal area of a heat exchanger may be given as [2]

$$\sigma = \left\{ \frac{(S_T - d_o)(1 - \bar{\delta} S_F)}{S_T} \right\} \quad (20)$$

The maximum air velocity is given as [2]

$$V_{max} = \frac{V_{min}}{\sigma} \quad (21)$$

Where the minimum air velocity is expressed as [2]

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$$V_{min} = \frac{\dot{m}_A}{\rho_A A_{fr}} \quad (22)$$

The overall surface efficiency is given by [2]

$$\eta_o = 1 - \frac{A_f}{A_o}\{1 - \eta_f\} \quad (23)$$

Where the fin efficiency is given by [2]

$$\eta_f = \frac{\tanh\{0.5 d_o m\phi\}}{0.5 d_o m\phi} \quad (24)$$

Where

$$\phi = (\varphi - 1)\cdot(1 + 0.35\ln\varphi) \quad (25)$$

The dimensionless ratio φ is defined as [2]

$$\varphi = \frac{S_T - 0.5 d_o}{0.5 d_o} \quad (26)$$

And parameter m is given as [2]

$$m = \sqrt{\frac{2h_o}{k_f \bar{\delta}}} \quad (27)$$

The total finned area may be given as [2]

$$A_f = \gamma A_o \quad (28)$$

Where

$$\gamma = \frac{A'_f}{A'_o} \quad (29)$$

And the finned area per unit length is defined as [2]

$$A'_f = \frac{2 S_L S_T S_F}{\cos\theta} \quad (30)$$

The fouling resistances on the tube side and on the external side due to dust and scale formation may be given as [2]

$$rt_{f_i} = \frac{f_i}{A_i} \quad (31)$$

$$rt_{f_o} = \frac{f_o}{\eta_o A_o} \quad (32)$$

The wall conduction resistance can be defined as [2]

$$rt_w = \frac{\ln(d_o/d_i)}{2\pi k_w l_{tube}} \quad (33)$$

The equations described in this section helps to develop the detailed design of the heat exchanger. The design accounts for the heat exchanger size, flow rates, fin design, material characteristics and fouling. Using the described equations a model can be developed to account for the required NTU of the heat exchanger.

V. CONCLUSIONS

This paper presents the design of cross flow heat exchanger using performance charts. Performance charts help to choose the required heat exchanger passes, NTU and capacity rate ratio. NTU is a direct function of heat transfer surface area and it is a common understanding that increasing the surface area enhances heat transfer. However, from performance charts it was clearly seen that there exists a certain threshold NTU, beyond which increasing the NTU doesn't enhance the heat transfer. Choosing that optimum NTU is beneficial as it optimizes the heat exchanger equipment. Since NTU is a direct function of heat exchanger surface area, a higher NTU than the required means more material, more weight and more capital cost. Likewise, a heat exchanger having a lower NTU than the requirement may not deliver the required heat transfer. Similarly, choosing an appropriate capacity rate ratio has a direct impact on pump power and fan power. Therefore, choosing the right capacity rate ratio has a direct impact on the operational cost of the heat exchanger. Once the NTU, capacity rate ratio and the number of heat exchanger passes are fixed, it is fairly straightforward to extrapolate the detailed design of the cross flow heat exchanger.

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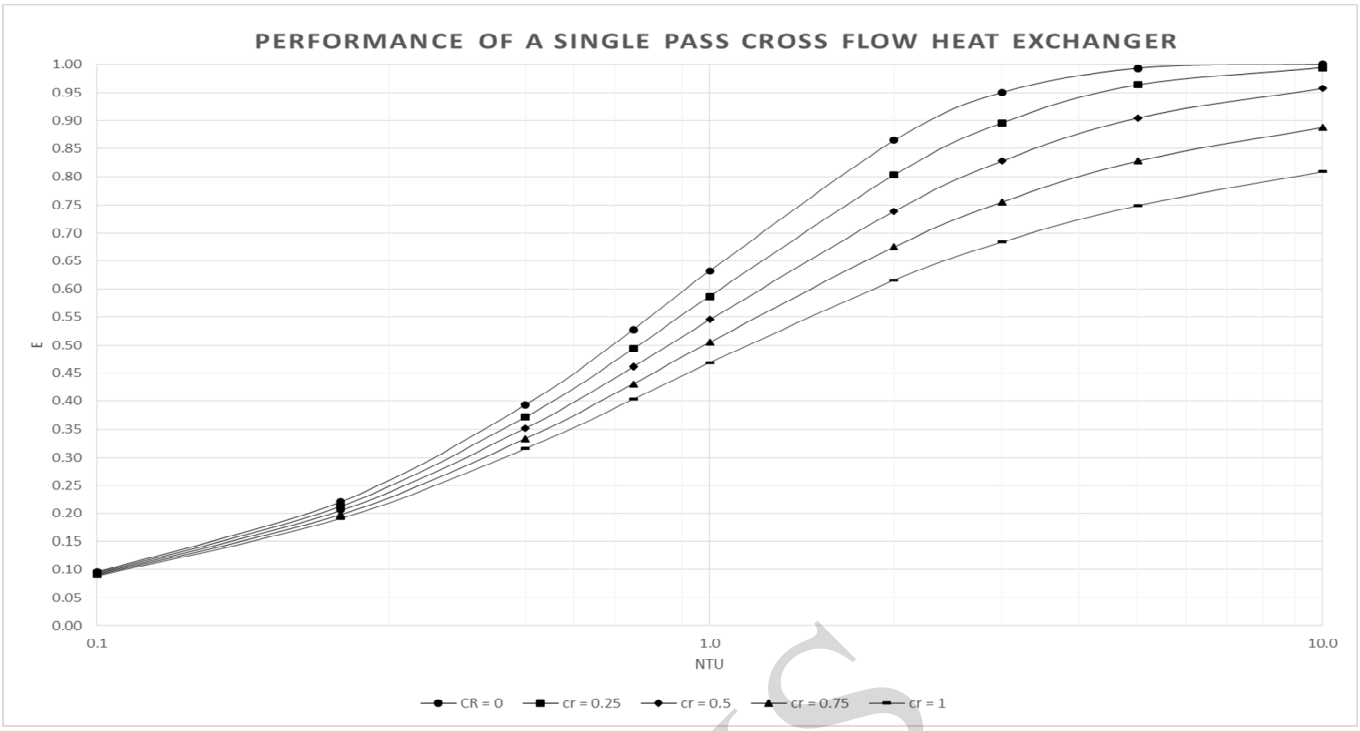


Fig. 2. Performance chart – Single pass cross flow heat exchanger

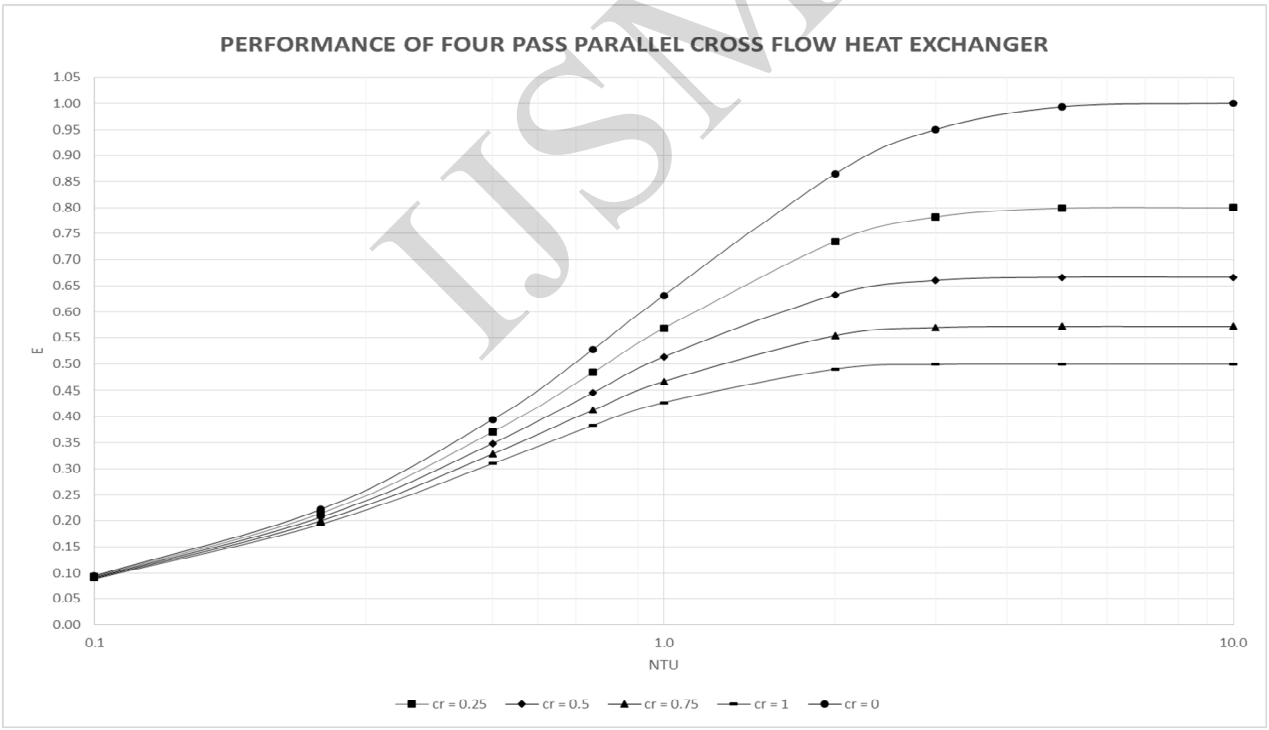


Fig. 3. Performance chart – Four pass parallel cross flow heat exchanger

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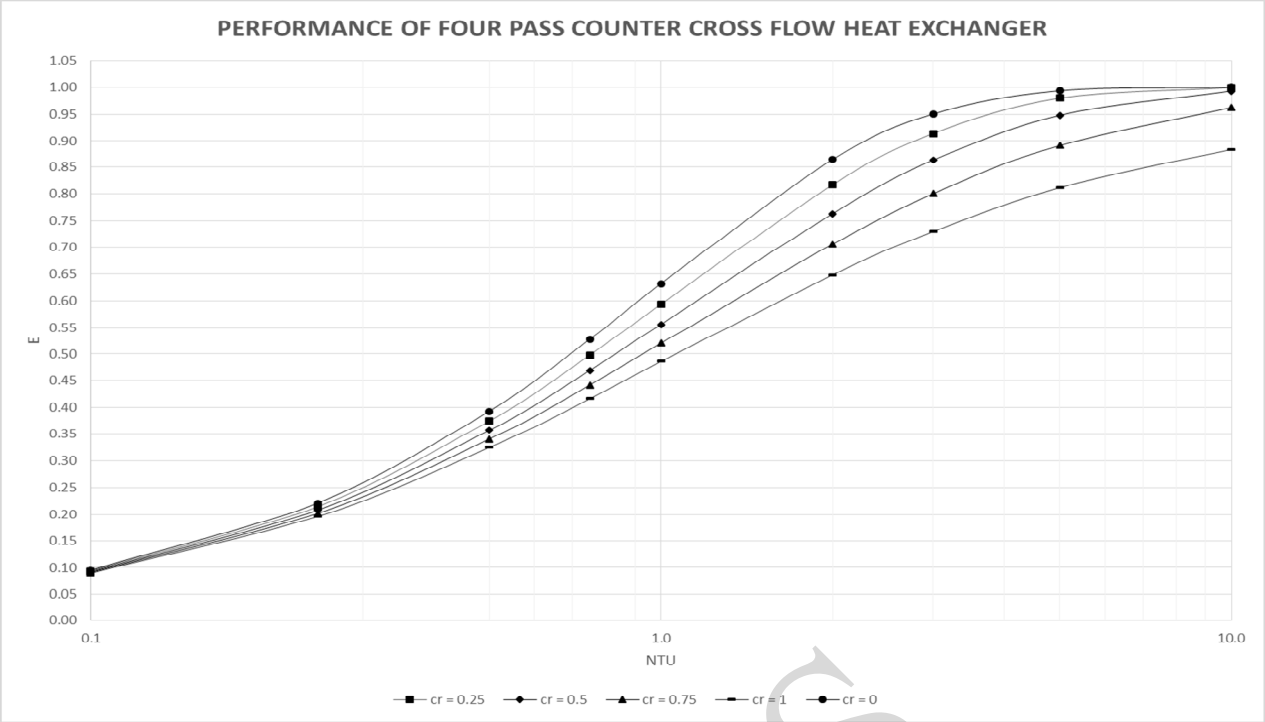


Fig. 4. Performance chart – Four pass counter cross flow heat exchanger

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