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Design and Development of the simulation tool for thermal sizing of Evaporative Condenser

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Abstract
In this paper heat and mass transfer of Evaporative Condenser is designed in MatLAb. Paper presents the analysis of evaporative condenser for various thermal load. This analysis includes the mass flow rate of refrigerant, heat transfer coefficient and the no of tubes required for the removal of the heat load. The mathematical code of thermal sizing of evaporative condenser is with experimental analysis. This code will help the engineers to design the evaporative condenser as this code works with MatLab which is famous engineering tool and easily available.

Keywords: Evaporative condenser, Refrigerant inside the tube banks, condensation inside the tubes.

1. Introduction

Evaporative Condensers are widely used in industry because of the cost efficiency, lower water consumption compared to water cooled condenser and are easier to design and maintain. For removal same amount of heat load evaporative condenser occupy less volume than the Air Cooled Condenser.
This paper includes application of various mathematical modeling to form the code to design evaporative condensers of various capacities. The condensation inside the tube is based on Mathematical Modeling of The Thome-El Hajal-Cavallini [1] flow model which calculate the heat transfer coefficient for the local parameters. For theprediction of heat transfer between the refrigerant and water, relation is given by Tovaras. For the heat transfer coefficient between a water film and air is based on Grimison equation.Lewis equation is used to determine mass transfer coefficient of water.
The model of Parker and Treybal[2] is the first to gavecomplete mathematical model for evaporative condenser which considered the changes in water temperature sprayed over the tube surface.
Using an appropriate mathematical model has to offer huge advantages being used for operation and performance analysis of evaporative condenser. This paper presents the application of those mathematical models and equation to form the code which will simulate the performance of the Evaporative Condenser.
Model of evaporative condenser can be seen in fig. 1.Primary component of an evaporative condenser is tube banks which are arranged in serpentine manner in which refrigerant flows in downward direction, outer surface of the tube bank is sprayed with the water which flows from top to bottom and air which flows from bottom to top. The heat transfer takes place in two steps,first is heat transfer between the refrigerant inside the tube and water, second step is heat transfer between water and air.The heat transfer process which takes place in evaporative condenser is intricate.

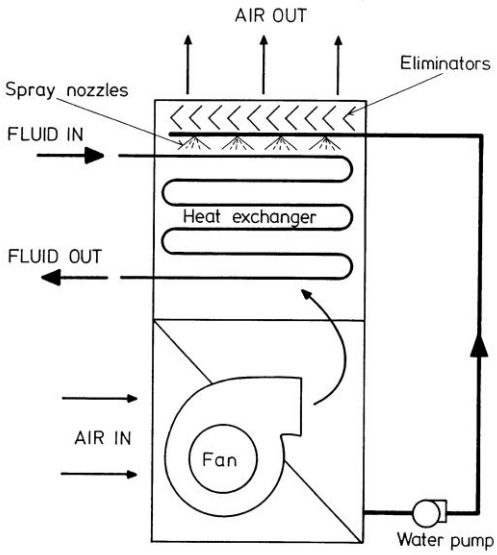

Fig.1. Model of evaporative condenser.[3]

Latent heat of water vapor is carried away along with some amount of moisture which humidifies the air on loosing latent heat some part of water vapor condenses back on the surface of condenser and is reuse in next cycle. Temperature of air has no specific role it can be higher, lower or even equal to the temperature of water, depending upon the ambient conditions. (Refer the points 1, W and 1', W' in fig. 2).

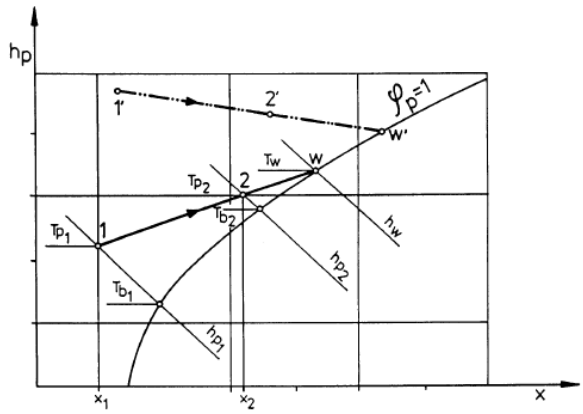

Fig. 2. Change in air properties from initial to final stage; 1, 1'-intial state of air, 2, 2'-final state of air [4].

Significant factor which controls the heat exchange between water and air is the air enthalpy it must be lower than the corresponding state of saturation at water temperature (points W and W'). The $(h_p - x)$ diagram (Fig. 2) shows the changes of air parameters in the heat exchanger.

This paper presents how the processes are connected and how they can help users to analyze the evaporative condenser. There is no commercial software available for the design of evaporative condenser. "MATLAB" is the mathematical tool which is gaining popularity in recent times. It is showing more effective reduction in the design and development time and increased efficiency in design process. "REFPROP" is another tool which consists of fluid properties data base. All the thermal properties are taken from this tool in design.In this paper simulation tool is created by using "MATLAB" & for property data "REFPROP" has used.

2. Simulation Algorithm

Evaporative Condenser is consists of tube banks in which hot refrigerant is flowing. Phase change occurs while refrigerant condenses inside the tubes resulting in higher heat transfer coefficient. Refrigerant condenses into liquid form at the end of tube.

At start the inputs for the simulation are Refrigerant which will flow through the evaporative condenser, temperature, pressure, Length of the complete tube, no. of passes and heat capacity.

For the simulation element by element approach is used. Tube length that is given by the user is divided into small element of 1 mm size, for that one element heat balance equation will give the heat lost by refrigerant which will be integrated over whole tube

$$A_L = \frac{(2\pi - \theta)}{8}[d_{int}^2 - (d_{int}^2 - 2\delta)^2] \quad (9)$$

$$\alpha(x) = \frac{\alpha_f \theta + (2\pi - \theta)\alpha_c}{2\pi} \quad (8)$$

and total heat transfer will be known.

For the sake of simplicity of the calculation assume following:

- Steady state heat transfer and time independent equations.

$$f_i = 1 + \left(\frac{u_g}{u_L}\right)^{1/2}\left(\frac{(\rho_L - \rho_G)g\delta^2}{\sigma}\right)^{1/4} \quad (10)$$

- Heat loss to environment is neglected.

$$Q_p = \alpha_p(T_w - T_p)A_o \quad (1)$$

- Conduction along axis of the tube is neglected.
- Variation in KE and PE is neglected.

$$W = \beta_x(x''(T_w) - x)A_m \quad (2)$$

$$Q_o = U(T_f - T_w)A_i \quad (3)$$

2.1 Mathematical Equations

$$U = \frac{1}{\frac{d_{ext}}{d_{int}}\left(\frac{1}{\alpha_{int}}\right) + \frac{d_{ext}}{d_{in}}\left(\frac{L}{k_r}\right) + \frac{1}{\alpha_{ext}}} \quad (4)$$

- The heat transfer between the air and water surface:
- The mass of water evaporated into air due to evaporation:
- The heat transferred from refrigerant to water

The overall heat transfer coefficient U is calculated from below equation.

2.2 Refrigerant side heat transfer coefficient

The heat transfer coefficient for superheated, subcool

$$Nu = \frac{\alpha_{int} d_{int}}{k} = 0.023 Re^{4/5} Pr^n \quad (5)$$

and for condensation is different. For each type of process computer program will choose the relation according to condition.

2.2.1 Subcooling and superheating heat transfer coefficient

For subcool and superheat process following relation will be choose by the program. This relation is known as Dittus-Boelter equation,

Where n is 0.3 for dessuperheating and subcooling

Heat transfer coefficient can be calculated using eq. (5)

$$\varepsilon = \frac{\varepsilon_H - \varepsilon_r}{\ln(\varepsilon_H/\varepsilon_r)} \quad (6)$$

at the refrigerant mean temperature.

2.2.2 Heat transfer Coefficient for Condensation inside the tube.

The implementation of Thome-El Hajal-Cavallini flow pattern based on intube condensation heat transfer model is done as follows:

1. Calculate the local vapor void fraction using:

$$\alpha_c = cRe_L^n Pr_L^m \frac{k_L}{\delta} f_i \quad (7)$$

2. Find local flow pattern using the flow pattern map and necessary transition velocities at the sum of X;
3. Choose the type of flow pattern (annular, intermittent, mist, stratified-wavy or stratified);

$$Re_{air} = \frac{w_o d_z \rho_p}{\mu_p} \quad (17)$$

4. If the flow is annular or intermittent or mistThen$\theta = 0$ and α_c is determined with

$\alpha(x) = \alpha_c$in

Where δ is obtained by solving and f_i with

$$\theta_{strat} = 2\pi - 2\left\{\pi(1-\varepsilon) + \left(\frac{3\pi}{2}\right)^{1/3}\left[1 - 2(1-\varepsilon) + (1-\varepsilon)^{\frac{1}{3}} - \varepsilon^{1/3}\right] - \frac{1}{200}(1-\varepsilon)\varepsilon[1-2(1-\varepsilon)][1+4((1-\varepsilon)^2+\varepsilon^2)]\right\} \quad (11)$$

$$\theta = \theta_{strat}\left[\frac{\dot{m}_{wavy-}\dot{m}}{\dot{m}_{wavy} - \dot{m}_{strat}}\right]^{0.5} \quad (12)$$

Then α_c can be calculated using (6) and α_f Using,

$$\alpha_f = 0.728\left[\frac{\rho_L(\rho_L - \rho_g)gh_{LG}K_L^3}{\mu_L d_{int}(T_{sat} - T_w)}\right] \quad (13)$$

And finally $\alpha(x)$ is determined using (8) where δ is obtained with (9) and f_i with (10).

5. For fully stratified flow, equation (11) can be used and θ_{strat} is set equal to θ, then α_c and α_f are calculated using (7) and (13) and $\alpha(x)$ is determined using (8) where δ is obtained with (9) and f_i is determined with (10).

2.2.3 Spray water heat transfer coefficient

Heat transfer coefficient for spray water can be calculated by following correlation those are,Tovaras et.al.(1984) (Zalewski and Gryglaszwski, 1997) proposed a correlation for this heat transfer coefficient as a function of water and air Reynolds number (Re_w)and (Re_{air}) and water Prandtl number (Pr_w). This correlation for water flowing downstream across the horizontal tubes has the following form.[4]

In the range Re_{air}= 690 to 3000:

$$Nu_{ext} = 3.3 \times 10^{-3} Re_w^{0.3} Re_{air}^{0.15} Pr_w^{0.61} \quad (14)$$

For Re_{air}= 3000 to 6900:

$$Nu_{ext} = 1.1 \times 10^{-2} Re_w^{0.3} Pr_w^{0.62} \quad (15)$$

For Re_{air}> 6900:

$$Nu_{ext} = 0.24 Re_w^{0.3} Re_{air}^{-0.36} Pr_w^{0.66} \quad (16)$$

The Nusselt and Reynold number can be defined by the following relations:

$$Re_w = \frac{4G}{\mu_w} \quad (18)$$

$$Nu_{ext} = \left(\frac{\nu_w^2}{g}\right)^{1/3} \frac{\alpha_{ext}}{\lambda_w} \quad (19)$$

Relations are valid in the range: Pr_w= 4.3 to 11.3; Re_w = 160 to 1360.

The above models and relation are used to find out the heat transfer coefficient for various flow pattern and phase of refrigerant, air and water.

3. Program Algorithm

I) Input from the user- required capacity, temperature and pressure at inlet of condenser coil, water temperature, and ambient condition of air, thickness of the tube, tube layout, tube length and no. of pass.

II) Calculation of pitch, air velocity according to tube layout, determination of dryness fraction.

III) Determination of whether the flow phase is superheated, subcool or condensation.

IV) If the flow is superheated flow then call the function to calculate the heat transfer coefficient.

I) If the flow is condensate flow then call the function to decide the flow pattern and heat transfer coefficient for respective flow pattern.

II) Repeat this in for loop to get the heat transfer capacity of one tube.

III) To calculate the no of tubes required is equal to the total heat transfer and heat transfer capacity of one tube.

Algorithm for evaporative condenser is shown in Fig. 3.

The above algorithm is used in the MatLab which can determine the properties of evaporative condenser. The functions used in MatLab code can be seen in fig. 3.

Results and Conclusion

Heat transfer coefficient for condensing refrigerant (ammonia) for different water temperature can be shown in Fig. 4. This heat transfer is based on Zalweski's correlation.

Experimental data and result from the code are having error in the range of -9.1% to 6.5%. MatLab Program can be used to calculate the dimension and analyze the evaporative condenser.

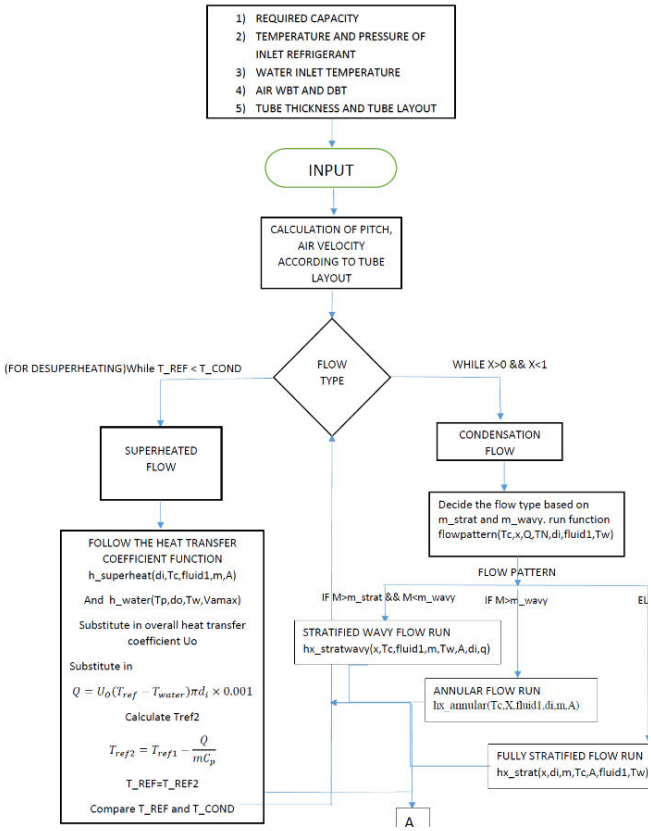

Fig 3. Program algorithm used in MatLab code.

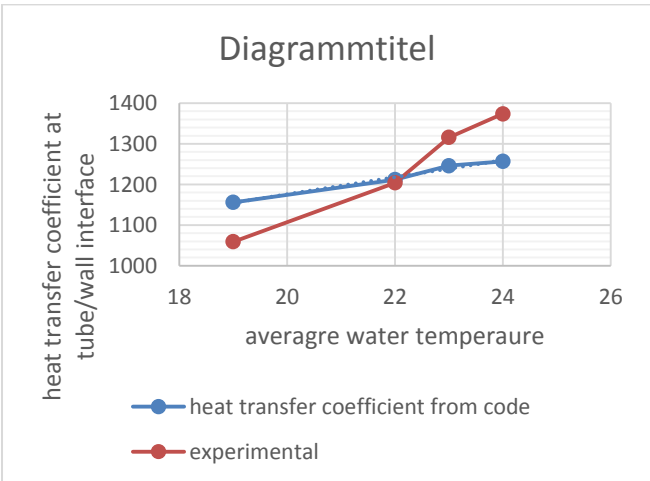

Fig 4. Experimental VS heat transfer coefficient.

Nomenclature

c	constant(0.003)
d_{ext}	Outer diameter of tube(m)
d_{int}	Inner diameter of tube(m)
f_i	Roughness correction factor
g	Acceleration due to gravity(m/s^2)
$h_{r,int}$	Refrigerant specific enthalpy at inner(kJ/kg)
$h_{r,out}$	Refrigerant specific enthalpy at outer(kJ/kg)
h_w	Sump water enthalpy(kJ/kg)
h_{LG}	Enthalpy of condensation(kJ/kg)
h_{wmu}	Specific enthalpy of make-up water(kJ/kg)
$k = k_L$	Refrigerant liquid thermal conductivity(w/mk)
k_r	Thermal conductivity for tube walls(w/m-k)
L	Length of the tubes(m)
$\dot{m}_{air}$	Mass flow rate of air(kg/s)
$\dot{m}_{mwu}$	Mass flow rate of make-up water (kg/s)
$\dot{m}_r$	Mass flow rate of refrigerant(kg/s)
$\dot{m}_{strat}$	Mass flow rate of stratified refrigerant(kg/s)
Nu_{ext}	Nusselt no at external side of tubes
Pr_L	Prandtl no of liquid refrigerant
Q_p	H.T. from water to air (kW)
$\dot{q}$	Heat rejected or ambient heat transfer rate (kW)
Re_w	Reynold no of spray water
Re_L	Reynold no of liquid refrigerant
Re_{air}	Reynold no of air
T_{sat}	Temperature of refrigerant film(k)
T_w	Temperature of tube wall(k)
U	Overall heat transfer coefficient(W/m^{2}k)
u_g	Velocity of gaseous refrigerant(m/s)
u_L	Velocity of liquid refrigerant(m/s)
W	Mass of water evaporated (kg)

Greek letters

α_c	Convective condensation heat transfer coefficient (W/m^{2}k)
α_{int}	Average heat transfer coefficient at refrigerant side(W/m^{2}k)
α_{ext}	Average heat transfer coefficient at water air side(W/m^{2}k)
α_f	Mean heat transfer coefficient of film(W/m^{2}k)
$\alpha(x)$	Local heat transfer coefficient at this vapor quality(W/m^{2}k)
δ	Liquid refrigerant film thickness(m)
ε	Logarithmic mean void fraction
ε_H	Horizontal void fraction
ε_r	Rouhani void fraction
θ	Stratified wavy angle
θ_{strat}	Stratified liquid angle
λ_w	Thermal conductivity of spraying water(w/m-k)
μ_L	Dynamic viscosity of liquid refrigerant(kg/m-s)
ρ_G	Density of gaseous refrigerant(kg/m^3)
ρ_L	Density of liquid refrigerant
σ	Viscous shear stress
υ_w	Velocity of spray water

Refernces

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