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Heat and mass transfer in shower cooling towers

Heat and mass transfer (MVK160)

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Abstract

This report focus on shower cooling towers. In the report a model for heat and mass transfer in a cooling tower is derived. Simplifications of the calculations are made and discussed. An introduction to the use and construction of cooling towers is given.

Figure 1: Natural draft wet cooling hyperboloid towers at Didcot Power Station, UK [1].

Nomenclature

A	area	[m^2]
c_p	specific heat at constant pressure	[kJ/kg K]
Δh_{ev}	latent heat of evaporation	[kJ/kg]
m	mass flow rate	[kg/s]
Q	heat flow rate	[W]
T	temperature	[K]
V	volume	[m^3]
Greeks		
α	convective heat transfer coefficient	[W/m^2 K]
ζ	humidity	[kg_w/kg_a]
Subscripts		
a	air	
c	convection	
d	droplet	
ev	evaporation	
ma	moist air	
s	saturation	
w	water	

Introduction

Cooling towers are mainly found in process industries, such as chemical industries and power plants. They are used to cool process fluids, mostly water, in places far from heat sinks as rivers or seas. They are rarely used in Swedish power generation, but are more common in other European countries. An argument to use the atmosphere as heat sink instead of rivers or seas is to avoid local thermal pollution.

There are several kinds of different designs, but basically air cools the water through evaporation and convection. Usually the air is in direct contact with the water. As the water circulated in the tower is being contaminated with salt and other impurities, the working fluid is not being used for this purpose. Instead a heat exchanger is used to transfer heat between the working fluid and the water in the cooling tower. The air is being drawn through the tower either by natural draft, as in the towers in figure 1, or forced by a fan. This design is called mechanical draft [1].

To make the interface between air and water as large as possible a packing in the tower is often used, consisting of wood or glass fibre plates. This gives raise to a big pressure drop from bottom to the top of the tower, which increases the power consumption of the fan used to force the air through the tower. To avoid this, a tower without any stacking can be used. This design is called a Shower Cooling Tower, SCT. In this case droplets are formed in the top of the tower, which then falls freely through the air to the bottom. As the air and droplets are moving in opposite directions, the system can be treated as a counter current heat exchanger. Now the heat transfer is dependent on the size and quantity of the droplets, and of course of the height of the tower [3].

Problem statement

There are several different problems related to heat and mass transfer occurring in a cooling tower. At first there is convection cooling between the water and the air. Also, when the air is heated, it can absorb more moisture, which will lead to evaporation of some of the water. The energy consumed by the evaporation process is taken from the remaining water, which cools it further. As the temperature changes along the height of the tower, heat and mass transfer coefficients are being changed continuously. To simplify the equations they are considered constant in this report. Further, losses due to windage are not being taken into account.

Literature study

Reports on heat and mass transfer in cooling towers has been published every now and then during the past years. For example X. Qi, Z. Liu and D. Li published a report in 2007 with some major simplifications made. The same year X. Qi and Z. Liu wrote another report on the same subject, this time with fewer simplifications making the result more accurate. In 2000 N. Milosavljevic and P. Heikkilä wrote “A comprehensive approach to cooling tower design”, which this report is based on.

Project description

The amount of energy removed from the water equals the amount of energy added to the air. A control volume of the tower is shown in figure 2. The energy is given off through convection and evaporation. Then the energy balance for the droplets yields

$$dQ_d = dQ_c + dQ_{ev} \quad [2] \tag{1}$$

The mass transfer due to evaporation can be written as

$$dm_w = \frac{\alpha}{c_{pma}} \cdot (\xi_s - \xi_a) dA \tag{2}$$

Energy flow due to evaporation can then be written as

$$dQ_e = \frac{\alpha}{c_{pma}} \cdot (\xi_s - \xi_a) \cdot \Delta h_{ev} dA \tag{3}$$

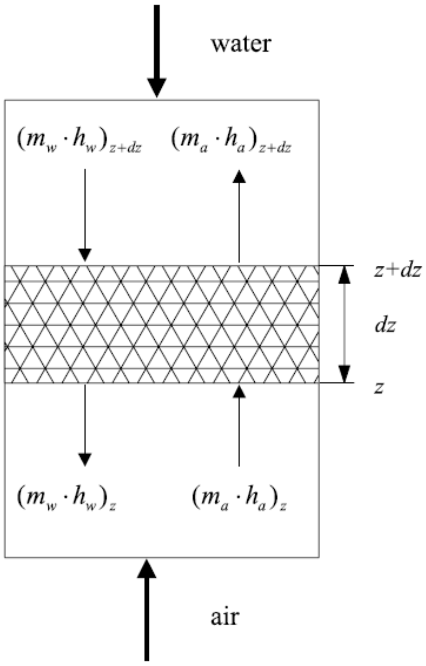

Figure 2: Control volume of the tower [4].

Energy flow due to convection can be written as

$$dQ_c = \alpha \cdot (T_w - T_a) dA \tag{4}$$

Combining equations (1), (3) and (4) yields the overall balance for heat transfer between droplets and air as

$$dQ_d = \left[\alpha \cdot (T_w - T_a) + \frac{\alpha}{c_{pma}} \cdot (\xi_s - \xi_a) \cdot \Delta h_{ev} \right] dA \text{ [4]} \tag{5}$$

Knowing the amount of energy needed to be rejected, it is possible to calculate the area needed. This area is directly connected to the quantity and size of the droplets and the height of the tower.

To use this model, two more simplifications have to be made. First, the temperature difference between air and water has to be constant. Secondly, the difference between the actual air humidity and the highest possible air humidity has to be the same through the tower.

Conclusion

It can be seen that heat and mass transfer in cooling towers is a complex process, involving not only thermodynamically problems, but also problems related to for example aerodynamics. To derive the equation for the heat transfer a lot of simplifications are made. For a more correct formulation attention has to be paid to varying values of the heat and mass transfer coefficients. Temperature and humidity differences will change along the tower, and losses due to windage will occur. When modelling the droplet, the shape of the droplet should be considered. Though, in most advanced calculations it is taken to be spherical. Even Lewis factor, which describes the relation between heat and mass transfer, is often considered unity. Mostly the droplets and the air are assumed to move vertically, which is not always the case in reality.

References

[1] http://en.wikipedia.org/wiki/Cooling_towers, 29 April 2008

[2] Qi, X., Liu Z. and Li, D., Prediction of the performance of a shower cooling tower based on projection pursuit regression, 3 July 2007

[3] Qi, X. and Liu Z., Further investigation on the performance of a shower cooling tower, 11 September 2007

[4] Milosavljevic, N. and Heikkilä, P., A comprehensive approach to cooling tower design, 20 June 2000