HUNGARIAN JOURNAL
OF INDUSTRIAL CHEMISTRY
VESZPRÉM
Vol. 30. pp. 1 - 5 (2002)

WATER TEMPERATURE DISTRIBUTION IN A VERTICAL CROSS-SECTION OF A WET COUNTERFLOW COOLING TOWER

D. ŠKOBALJ, Z. ZAVARGÓ[1] and L. JUHÁSZ[1]

(" Vujić-Valjevo", Alekse Dundića 61/1, 14000 Valjevo, YU
[1]Faculty of Technology, University of Novi Sad, Bul. Cara Lazara 1, 21000 Novi Sad, YU)

Received: November 29, 2000

The conventional method of cooling tower calculation does not take into account heat exchange under the fill. The basic reasons for this are: substantially less amount of heat is exchanged under the fill than in the fill and the definition of physical model of heat transfer is rather complicated. Nevertheless, in the case of cooling tower of greater dimension, this method of calculation may give uncorrect results. There are very few authors who treat this problem by experiments. The results obtained in this work show that the heat exchange under the fill is significiant.

Keywords: cooling tower, heat exchange, temperature distribution, counterflow

Introduction

In industrial and energetic plants, water is commonly used as cooling medium. Due to lack of industrial water, in most countries, there are in use only recirculated cooling systems. The main part of these systems are cooling towers in which water is cooled by atmospheric air. In the commonly used wet cooling tower the water and the air are in direct contact. There are several types of cooling towers depending on the air and water stream direction. One of the types is the counterflow cooling tower (*Fig.1*). The first theorethical formulation of water cooling in the counter cooling towers was given by Walker et al. [1]. According to this theory there are two independent coefficients: heat and mass transfer coefficients. Merkel [2] was the first who realized the conection between these two phenomena. The amount of heat transferred from water to air, according to Merkel, is proportional to the difference in the enthalpy of the saturated air and the enthalpy of the humid air. Merkel [2] was the first who recognised the relation between these two processes. He gave the first appliciable formulation of differential equation of water cooling proces. According to this formulation, the amount of heat transfer is proportional to the difference in enthalpy of the saturated air and the humid air in the main stream. In determining the value of heat transfer it is sufficiant to use only one empirical coefficient, which includes both heat and mass transfer processes. The results of experimental investigation gave a certain deviation from the Merkel theory. According to some references this deviation is due to approximation in the Merkel equation [3] while in some others the Merkel theory is fully rejected [4]. There are also a great deal of engineering calculation procedures which are differing in a level of approximation of the theory. The main reason for such great number of procedures lies in the fact that simultaneous momentum, heat and mass transfer in the cooling towers is one of the most complicated processes in the enginerring practice. Most of these procedures are based on the Merkel theory. Because of its simplicity and relatively satisfactory results, the Merkel theory is widely used and accepted in most well known international standards as a procedure for cooling tower performance calculation [5,6]. However, heat and mass transfer, according to this procedure, are taken into account only in the fill, while the space above and under the fill are neglected. The relatively high price of the cooling tower fill demand the need to include the effect of water cooling in the zone under the fill. The experimental investigation shows that effect of cooling in the zone under the fill cannot be neglected. It enables to use less fill, keeping the same cooling intensity.

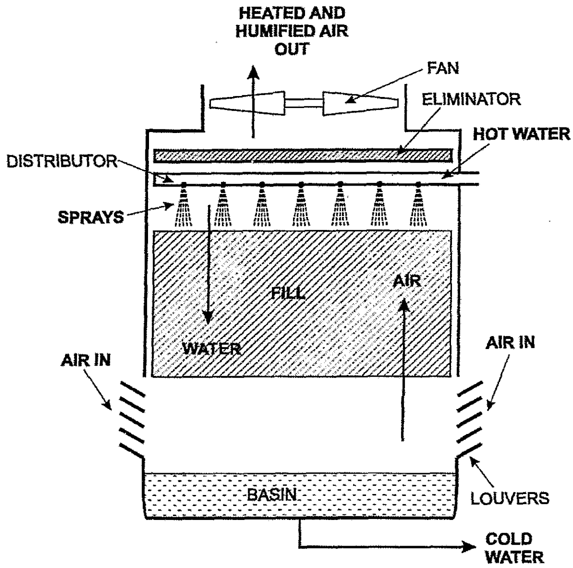

Fig.1 Wet counterflow cooling tower

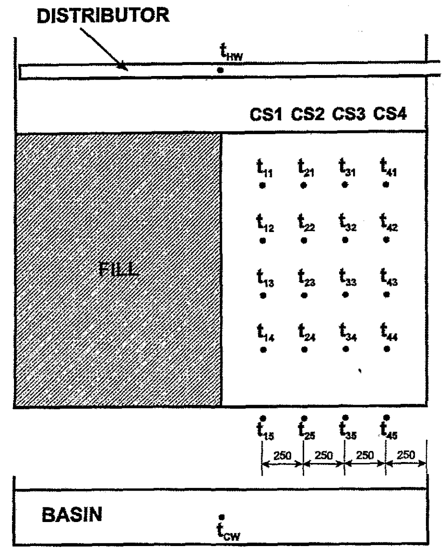

Fig.2 Thermoelements arrangement in the investigated cooling tower

Merkel theory

The wellknown international standards (DIN, CTI) used in the Merkel formulation for counterflow cooling tower performance calculations, often called as standard procedure [5,7]. The equation which describes heat and mass transfer according to Merkel is:

$$\dot{m}_a dh_a = \beta(h_{as} - h_a)\cdot dV \qquad (1)$$

Setting air heat gain equal to water heat loss

$$\dot{m}_a \cdot dh_a = \dot{m}_W \cdot dh_W = \dot{m}_W \cdot c_{p_W} \cdot dt \qquad (2)$$

Combining with *Eq.(1)* we have

$$\frac{\beta \cdot V}{\dot{m}_W} = \int_{t_{w2}}^{t_{w1}} \frac{c_{pw} dt_w}{h_{as} - h_a} \qquad (3)$$

The integral term in the above equation is known as Merkel number

$$Me = \int_{t_{w2}}^{t_{w1}} \frac{c_{pw} dt_w}{h_{as} - h_a} \qquad (4)$$

The analytic solution of the integral (4) is not known. One way to solve it is to have an approximate analytic function between h_{as} and t_w (linear or parabolic for example). Another way is to solve the integral (4) numerically. The left side of *Eq.(3)* can be written in the following form, connecting it with the fill characteristics:

$$\frac{\beta \cdot V}{\dot{m}_W} = A \cdot \lambda^n \cdot L \qquad (5)$$

Experimental

Water temperature measurement

The schematic arrangement of Ni-CrNi thermoelements is shown on *Fig.2*. The following temperatures were measured: the inlet hot water temperature t_{HW}, the outlet cold water temperature t_{CW}, 16 temperatures in the fill (four in each vertical cross-section) and four temperatures under the fill. The thermoelements are mounted in a way to ensure the water film temperature measurement and not the two-phase or fill temperature. The used arrangement of thermoelements enables us to have a temperature field in the whole cooling tower and not only in the inlet and outlet of the system.

The measurement results are given in *Tables 1-4*. The vertical water temperature distribution in each vertical cross-section are shown on *Figs.4-5*.

The fill

To increase contact surfaces, as well as time exposure, a fill is installed below the water distribution system, in the path of the air. The two types of fill in use are splash-type and film type. In the splash-type fill the water is cascaded through successive elevations of splash bars arranged in staggered rows. Film-type fill maximises contact area and time by causing the water to flow in a thin layer over closely spaced sheets, principally polyvinil chloride (PVC), that are arranged vertically. The aim is to have a fill of minimum size and maximum contact surface.

In this work PVC film-type was used. The *Me* number vs. λ is given on *Fig.3* [8].

Table 1 Water temperature distribution in the investigated wet counterflow cooling tower

$\dot{m}_w = 13.27\ kg/s\,;\ \dot{m}_a = 19.30\ kg/s\,;\ n = 975\,rpm\,;\ t_{wb} = 9.0^0C$

t in the distributor	t_{HW} = 23.25°C			
	Vertical cross-sections			
	CS1	CS2	CS3	CS4
t in the fill	t_{11} = 22.50°C	t_{21} = 23.00°C	t_{31} = 18.25°C	t_{41} = 22.25°C
	t_{12} = disconnected	t_{22} = 19.00°C	t_{32} = 17.50°C	t_{42} = 20.00°C
	t_{13} = 16.00°C	t_{23} = 18.50°C	t_{33} = 17.25°C	t_{43} = 16.00°C
	t_{14} = 15.00°C	t_{24} = 16.00°C	t_{34} = 16.00°C	t_{44} = 14.50°C
t under the fill	t_{15} = 11.00°C	t_{25} = 11.50°C	t_{35} = 11.00°C	t_{45} = 11.25°C
t in the basin	t_{CW} = 11.50°C			

Table 2 Water temperature distribution in the investigated wet counterflow cooling tower

$\dot{m}_w = 13.27\ kg/s\,;\ \dot{m}_a = 13.27\ kg/s\,;\ n = 750\,rpm\,;\ t_{wb} = 9.5^0C$

t in the distributor	t_{HW} = 28.25°C			
	Vertical cross-sections			
	CS1	CS2	CS3	CS4
t in the fill	t_{11} = 27.50°C	t_{21} = 27.75°C	t_{31} = 21.25°C	t_{41} = 27.50°C
	t_{12} = disconnected	t_{22} = 23.50°C	t_{32} = 19.75°C	t_{42} = 26.00°C
	t_{13} = 19.00°C	t_{23} = 22.25°C	t_{33} = 19.00°C	t_{43} = 19.25°C
	t_{14} = 17.50°C	t_{24} = 19.00°C	t_{34} = 17.50°C	t_{44} = 17.75°C
t under the fill	t_{15} = 14.25°C	t_{25} = 16.00°C	t_{35} = 13.50°C	t_{45} = 15.00°C
t in the basin	t_{CW} = 15.30°C			

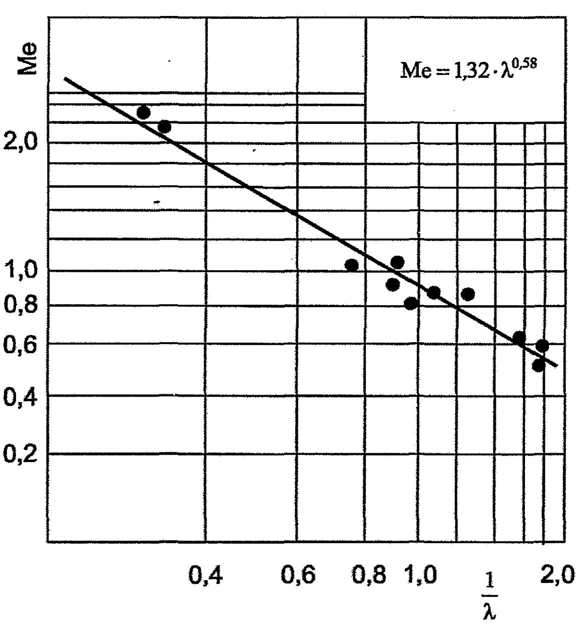

Fig.3 The investigated PVC fill *Me* number

Results and Discussion

The measured temperature values are given in *Tables 1* and 2. The water vertical temperature distributions are presented on *Figs.4* and *5*. From these figures the temperature drops above the fill, in the fill and under the fill are determined. The obtained temperature drops are presented in *Tables 3* and *4*.

In the vertical cross-section 3(CS3) there is a great heat transfer in the zone between the distributor and the fill. The great temperature drop in this zone is due to disproportional water distribution in the distributor and disproportional fill packing. The effect of this is that less amount of water is in contact with greater amount of air, this is that consequence we have a more intensive cooling in the zone between the distributor and the fill. The analysis of other vertical cross-sections shows that the water distribution is similar, and the temperaturedrops in the cooling tower zones are logical. From *Table 3* (CS1) it is evident that the temperature drop above the fill is close to 4% and under the fill 26% of the whole temperature drop in the cooling tower In the other experiment, *Table 4*, these temperature drops are about 3% and 20%.

Conclusion

The conventional method of cooling tower calculation does not take into account heat exchange under the fill. The heat transfer under the fill can be neglected in the case of cooling towers of smaller dimension. In the case of cooling towers of greater dimension the zone under the fill can be significiant and the temperature drop in this zone cannot be neglected. The results of this experiment lead to this conclusion.

Table 3 Water temperature drops in the investigated wet counterflow cooling tower

$\dot{m}_w = 13.27\ kg/s\ ;\ \dot{m}_a = 19.30\ kg/s\ ;\ n = 975\,rpm\ ;$

$t_{wb} = 9.0^0C$

	CS1	CS2	CS3	CS4
	Absolute *t* drop [°C]			
Δt_{DF}	0.45	0.1	3.45	0.85
Δt_F	8.60	8.15	4.80	8.60
Δt_{FB}	3.20	3.50	4.00	2.55
Δt_{TOT}	12.25	11.75	12.25	12.00
	Relative *t* drop [°C]			
$\Delta t_{DF}/\Delta t_{TOT}$	0.0367	0.0085	0.282	0.072
$\Delta t_F/\Delta t_{TOT}$	0.700	0.723	0.392	0.72
$\Delta t_{FB}/\Delta t_{TOT}$	0.260	0.298	0.326	0.21

Table 4 Water temperature drops in the investigated wet counterflow cooling tower

$\dot{m}_w = 13.27\ kg/s\ ;\ \dot{m}_a = 13.27\ kg/s\ ;\ n = 750\,rpm\ ;$

$t_{wb} = 9.5^0C$

	CS1	CS2	CS3	CS4
	Absolute *t* drop [°C]			
Δt_{DF}	0.45	0.45	5.05	0.65
Δt_F	10.80	9.40	6.60	10.20
Δt_{FB}	2.75	2.40	3.10	2.40
Δt_{TOT}	14.00	12.25	14.75	13.25
	Relative *t* drop [°C]			
$\Delta t_{DF}/\Delta t_{TOT}$	0.0322	0.0368	0.3423	0.0491
$\Delta t_F/\Delta t_{TOT}$	0.7714	0.7673	0.4474	0.7698
$\Delta t_{FB}/\Delta t_{TOT}$	0.1964	0.1959	0.2103	0.1811

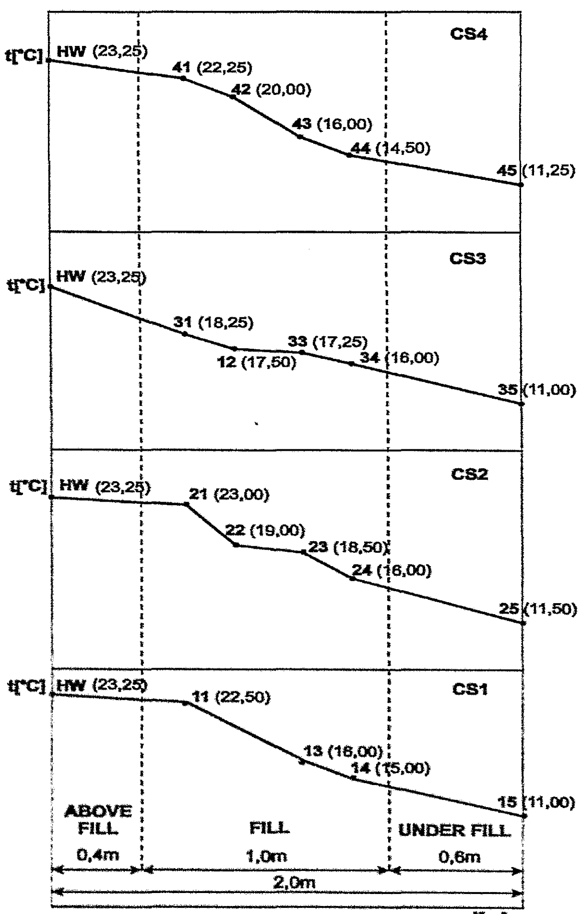

Fig.4 Vertical water temperature distribution according to *Table 1*

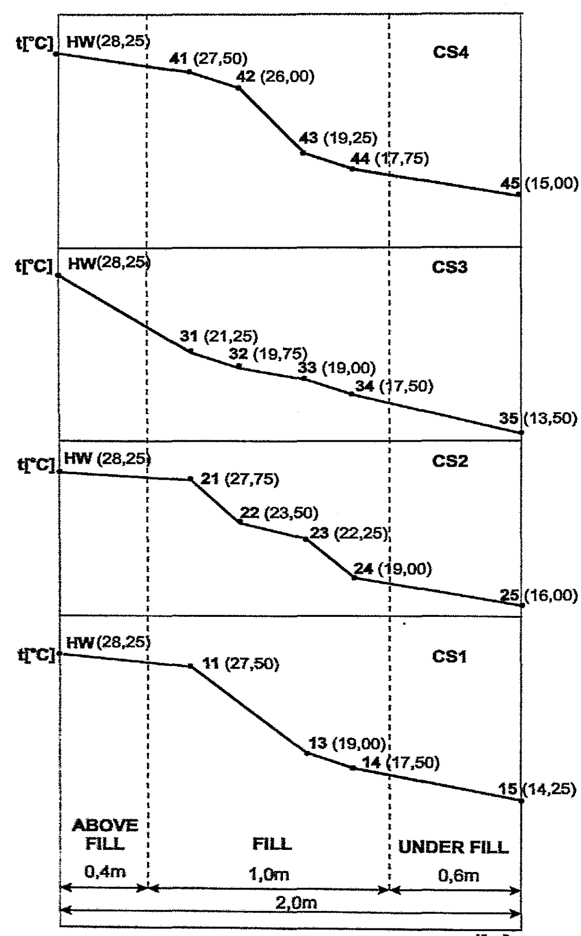

Fig.5 Vertical water temperature distribution according to *Table 2*

SYMBOLS

A	fill coefficient, m^{-1}
C_{p_w}	water heat capacity, $Jmol^{-1} K^{-1}$
h_a	enthalpy of air, $Jmol^{-1}$
h_{as}	enthalpy of saturated air, $Jmol^{-1}$
h_w	enthalpy of water, $Jmol^{-1}$
L	fill height, m
l	height, m
$\dot{m}_a$	air mass flow rate, kgs^{-1}
$\dot{m}_w$	water mass flow rate, kgs^{-1}
Me	Merkel dimensionless number
n	revolution per minute, rpm
n	dimensionless fill coefficient in *Eq.(5)*
t	temperature, ^0C
t_w	water temperature, ^0C
t_{w_1}	inlet water temperature, ^0C
t_{w_2}	outlet water temperature, ^0C
t_{HW}	hot (inlet) water temperature, ^0C
t_{cw}	cold water temperature (in the basin), ^0C
t_{wb}	wet-bulb temperature, ^0C
t_{ij}	temperature in the *i-th* vertical cross-section and *j-th* horizontal cross-section, ^0C
V	fill volume, m^3

Greek symbols

β	volumetric heat and mass transfer coefficient, $kg\ m^{-3}s$
λ	air number
Δt_{DF}	temperature drop distributor-fill, ^0C
Δt_F	temperature drop in the fill, ^0C
Δt_{FB}	temperature drop fill-basin, ^0C
Δt_{TOT}	temperature drop distributor-basin, ^0C

Abbreviations

CS1, CS2,…	vertical cross section 1, 2,…
CW	cold water
HW	hot water
ij	i-th column, j-th row

REFERENCES

1. WALKER W. H., LEWIS W. K. and Mc Adams W. H.: Principles of Chemical Engineering, McGraw-Hill, New York 1923
2. MERKEL F.: Verdunstungskühlung, VDI Forschunsarbeiten, 1925, No. 275
3. VADIGAROGIN G. and PASTOR E. J.: An Investigation of the Accuracy of the Merkel Equation for Evaporative Cooling Tower Calculations, ASME Paper No. 54-h7-59, Proc. of the AIAA/ASME Thermographys and Heat Transfer Conference, Boston, 1974
4. KLENKE W.: Heat and Mass Transfer at Evaporative Cooling and Testing of Cooling Towers (in German), Diss.Techn.Univ., Braunschweing, 1964
5. Cooling Tower Institute: Cooling Tower Performance Curves, Houston,1967
6. DIN 1947: Leistungs versuche an Kühltürmen (VDI-Kühltürmegelen), 1951
7. Cooling Tower Institute: Acceptance Test Code for Water Cooling Towers: ATC-105, Houston, 1982
8. NINIČ, N. and VEHAUC A.: Investigation and characterization of cooling tower plastic fills, Institution Boris Kidrič Vinča, Beograd, 1986