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EXPERIMENTAL STUDY ON HEAT AND MASS TRANSFER IN COOLING TOWERS

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Abstract. *In this paper, the results of an experimental study on heat and mass transfer coefficients in packing of wet cooling towers, are presented. The investigations have been carried out at a test rig erected in the Thermal engineering laboratory of Mechanical engineering faculty, Niš. Schematic presentation of the test facility together with the distribution of measuring spots are shown.*
The packing, used during experimentation, was made of parallel plexiglass plates 5mm thick, with 40 mm distance between each other and 1200 mm in height, placed in a vertical 470×470 mm channel. During the experimentation the following quantities were varied: air flow velocity in the range 1,5-5 m/s and water flow rate in the range 2-3 m^3/h. The variation of temperature along the height of packed was measured by means of 26 appropriate placed thermocouples. The obtained results are presented by means of diagrams.

Key words: *cooling towers, experiment, numerical*

1. INTRODUCTION

In industrial and energetic installations the water plays very significant role. The main reason for it is its wide presence in the nature as well as good thermodynamic properties. There is in many countries the lack of industrial water. The quantity of available water is defining the kind of cooling system, which can be the conventional once-through condenser arrangement and the circulation one. When the condenser cooling water is available in adequate quantities then the once-through system comes into use; in contrary the designer must provide an alternate cooling system such as a circulation water cooling system with cooling tower.

The cooling towers are relatively simple in construction but with very complex heat and mass transfer processes occurring in them, from both thermal and hydrodynamic point of view, and with inlet parameters changing mainly without control either due to the

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changing of atmospheric conditions or due to feedback links with thermal power plant.

Determination of the heat and mass transfer mechanism for the counter flow of water and air in direct contact with partial evaporation of water has a theoretical and practical significance in establishing the basic equations of heat and mass transfer and in developing the methods for its solving. During the solution of this problem the experimentally obtained relations for transport coefficients and global variations of transport quantities have been used, in order to close the system of differential equations. The level of the introduced approximations is dependent on both the quality of experimental results and the accepted method of solution.

In this paper, the experimental investigations for the determination of the local heat and mass transfer coefficients in packing of wet cooling towers as the most important parameters in these processes have been described.

Experimental investigations of such a type due to its complexity are very rare. All experiments are carried out on a test rig in Thermal engineering laboratory at Mechanical engineering faculty - Niš.

2. Experimental installation

The main parts of the experimental installation have shown in Fig. 1. are numerated from 1 to 31. The basis of the installation is the cooling tower (1), 7 m in height and 470×470 mm in cross section. The tower construction structure in made of steel beams. The sides of the test section are made of metal sheet, and both the front and the rear side are transparent and are made of plexiglass plates (luplex) 3 mm thick, the front plexiglass plate is removable, so the easy access to interior of tower is able in order to replace packing or water drops separator, as well as to enable the access of various measuring probes.

Heating of water up to the defined temperature has been carried out by means of four electric boilers (5) each 30 kW of power. Adjustment of temperature is realised by thermo-regulators. The heated water is transported by pump (22) to the vessel (4) making the uniform water temperature and then by specially designed system for water distribution (17) shown in Fig.2 the water is distributed in the form of falling films over the plates of fill. The water distribution system consists 10 copper tubes Φ15×1 mm, perforated at both sides. The number of holes at one side was 45 and its diameter 1.2 mm.

By using this system the water is directly distributed over the plate sides to the left and right from the tube, and the films of falling water were uniform (without preferent flows and dry spots) across the whole surfaces of plates.

The volume flow rate is measured by standard orifice (23). In order to stabilize the flow upstream and down stream from the orifice the straight section were established.

The pressure drop at orifice meter is measured by U-tube manometer with mercury (type AH10 BOPP & REUTHER).

The water flow rate is regulated by the valves (14).

The fill (18) is made up of 11 vertical plexiglass plates 470×1200 mm and 5mm thick, with the distance of 40 mm between each other. The referent plate (25), with thermocouples for measuring air water temperature, is placed in the middle of tower.

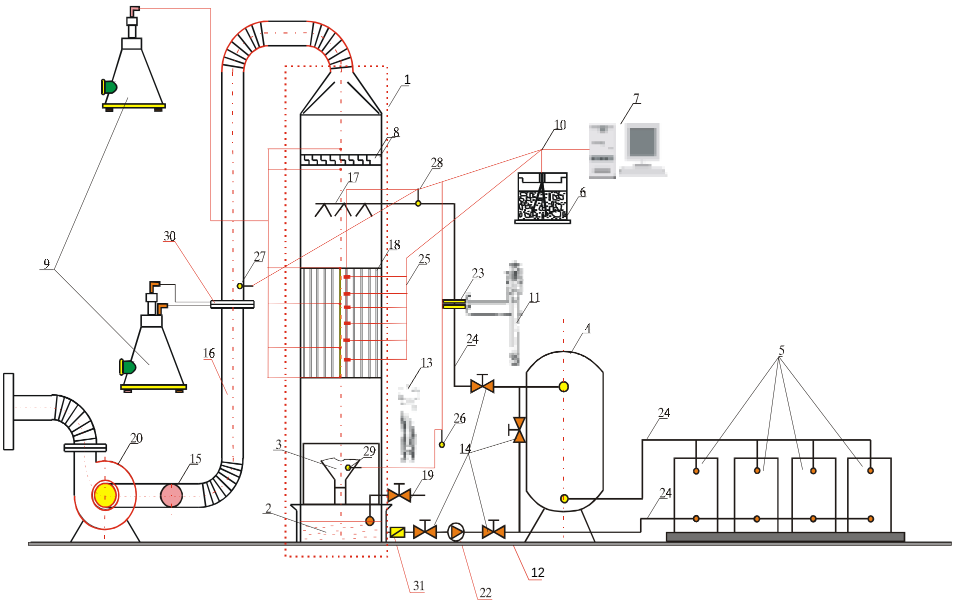

Fig. 1. Layout of experimental apparatus

Temperature is measured by the calibrated 0.2 mm chromel-alumel thermocouples with layout as in Fig. 3. Six thermocouples are measuring the air temperature and the other seven the water temperature.

Here must be emphasized that the main difficulty in measuring the local water temperature (the water temperature along the height of plate) was the achievement of fine water film, as it is mentioned earlier. These difficulties have disappeared when the fine distribution of water was achieved.

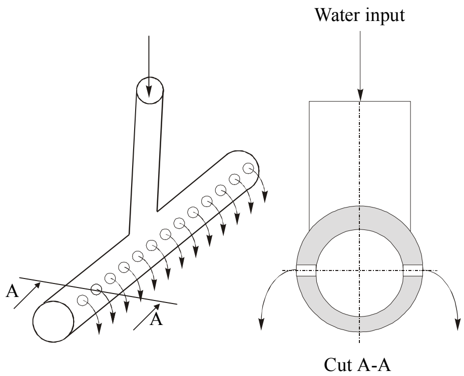

Fig. 2. Water distribution system

However, the question of accurate measurements of air temperature is remaining without appropriate answer. The thermocouples recording the air temperature in packing, due to the known effect of wet joint, have measured the temperature that corresponds neither to dry bulb nor to wet bulb temperature (this is the authors' conclusion withdrawn from the comparison between numerical and real experiment data).

With exception of the air temperatures at inlet and outlet from the apparatus, all other measured temperatures have not been taken into account due to uncertainty.

The reliable air temperature measurements in the regions of rain and packing are possible only by using the special probe able to separate droplets from air stream. The designing and construction of such a probe is left for the future work in this field.

The air temperature profile along the height of packing is determined numerically, firstly on the basis of a 1-D model and afterward on the basis of a 3-D model. The results are given in subsequent parts of the paper.

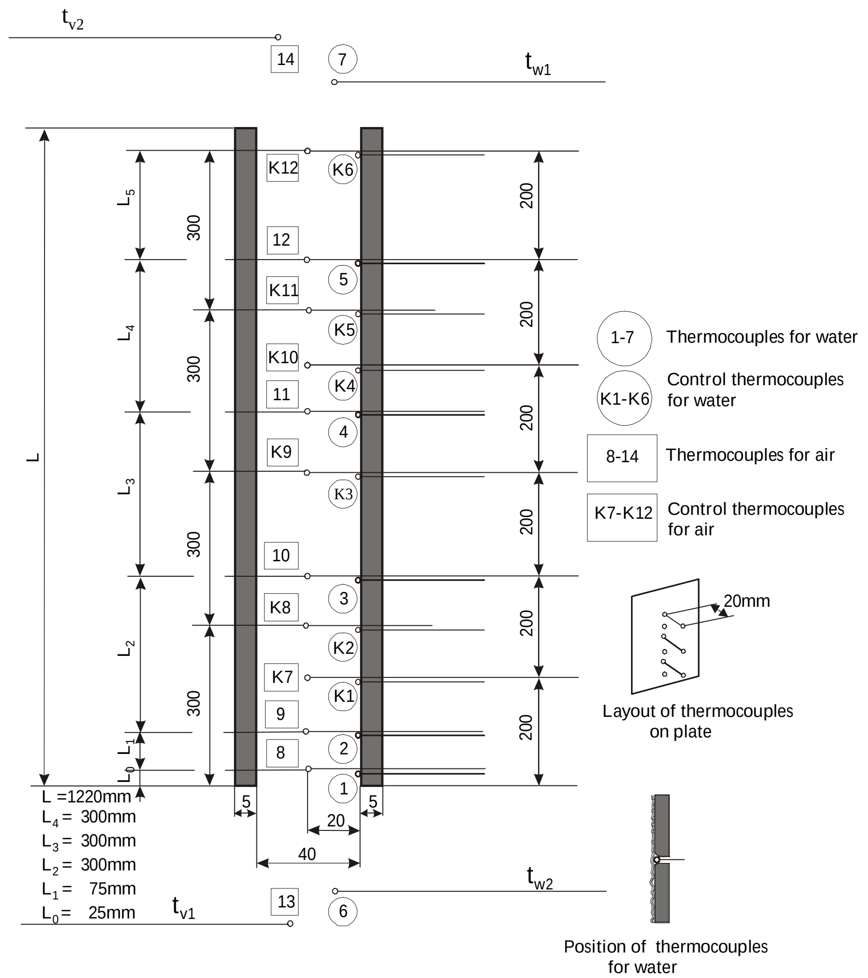

Fig. 3. Layout of thermocouples on reference plate

Thermocouples (26) and (28) are measuring the air temperature at inlet and outlet of tower while the thermocouple (30) is measuring the air temperature at orifice.

Thermocouples (28) and (29) are measuring the water temperature at inlet of water distribution system and in vessel (3) collecting the water after passing through fill and below the rain zone. For all temperature measurements the 26 thermocouples chromel-alumel 0,2 mm in diameter were used. The 13 thermocouples are connected to data acquisition system Hewlett-Packard 9133 (7) while the other 13 are used in control purposes. The cold ends of thermocouples are immersed into Dewar-vessel with mixture of ice and water (6). The cooled water is collected in pool (2) and by one -way valve (31) and a pipeline system (24) is delivered to the boilers battery (5).The compensation of evaporated water is realized by system (19).

The relative humidity of air at tower inlet is measured by Assman psychrometer measuring both the dry bulb and the wet bulb temperature. The airflow through the tower is provided by using the fan (20); the whole test section is connected on its suction side via pipeline (32) 300mm in diameter. The lengths of pipe upstream and downstream from the orifice are satisfying the conditions of flow stabilization.

Pressure drop at orifice is measured by Betz's micromanometer (9). The air enters into tower, passes the rain zone, the fill (18) and the droplet separator (8) and leaves the tower. The adjustment of airflow rate is provided by the regulation valve (15). Betz, micromanometer (9), also measures the pressure drop along the height of fill and drop separator.

3. THE ENVIRONMENT CONDITIONS FOR EXPERIMENT AND THE RANGE OF THE OPERATION PARAMETERS VARIATIONS

The experimental investigations are carried out in the period june-october 1998. The environmental parameters are permanently observed and the runs were stopped when the extreme gradients of these parameters have occurred. The experiments were carried out early in the morning or late in the evening.

The environmental parameters have been in the ranges:

- environmental air temperature:

$$t_{omin} \div t_{omax} = (15{,}6 \div 30{,}9)\ ^{o}C,$$

- relative humidity of the environmental air:

$$\varphi_{min} \div \varphi_{max} = (45 \div 85)\%,$$

- maximal measured air temperature:

$$t_{vmax} = 39\ ^{o}C.$$

Mass flow rate of air is varied within the range:

$$\dot{m}_{vmin} \div \dot{m}_{vmax} = (1777 \div 3796)\ m^3/h.$$

Mass flow rate of water is changed in the interval

$$\dot{m}_{wmin} \div \dot{m}_{wmax} = (2070 \div 2886)\ kg/h.$$

Water temperature is varied in the range:

$$t_{wmin} \div t_{wmax} = (18{,}9 \div 65{,}0)\ ^{o}C.$$

4. Experimental results

Experimentally obtained variations of water and air temperature along the height of tower as well as other characteristic quantities for experimental run (airflow rate, water flow rate and relative humidity at tower inlet) are shown in Fig. 4. The variations of air temperature along the height of tower are not shown due to difficulties in air temperature measurements in fill, and so only the outlet and inlet air temperatures in tower as well as air temperature at orifice are given. Characteristic data for experimental run 41 are given in Table 1.

Table 1.

	Exp. 41
Pressure drop at orifice for air, mmH_2O	119
Pressure drop at orifice for water, mmHg	292
Air flow rate, m^3/h	3410.2
Water flow rate, kg/h	2429.6
Relative humidity, %	79

5. Analysis of the results

On the basis of both the real experiment and the numerical experiment including 1-D and 3-D model (which structures are not given here), the authors can withdraw some interesting conclusions.

In the absence of the valid experimental results giving us the basis for valid conclusion about established pressure and velocity field, the indirect possibility for proving only remains i.e. the analysys of the agreement between experimentally obtained and predicted temperature profiles.

The more detailed results about the temperature profiles and other characteristics are given in [10]. Over 40 experimental runs were done and only a part is given here. The choice is made due to its characteristics. In Fig. 5 the comparision between real experiment and numerical 1-D experiment is shown.

In the following figures is given the comparision between real and numerical experiments (3-D numerical model).

Figures 6 and 7 show the character of variation of locall mass (heat) transfer coefficients along the height and across the horizontal cross section of cooling tower fill.

The air density variation in vertical cross section of tower is given in Fig. 8.

The air temperature variations are given for a vertical cross section in Fig. 9 and a horizontal cross section in Fig. 10.

In Figures 11 and 12 the water temperature variations are given respectively for a vertical cross section and for a horizontal cross section.

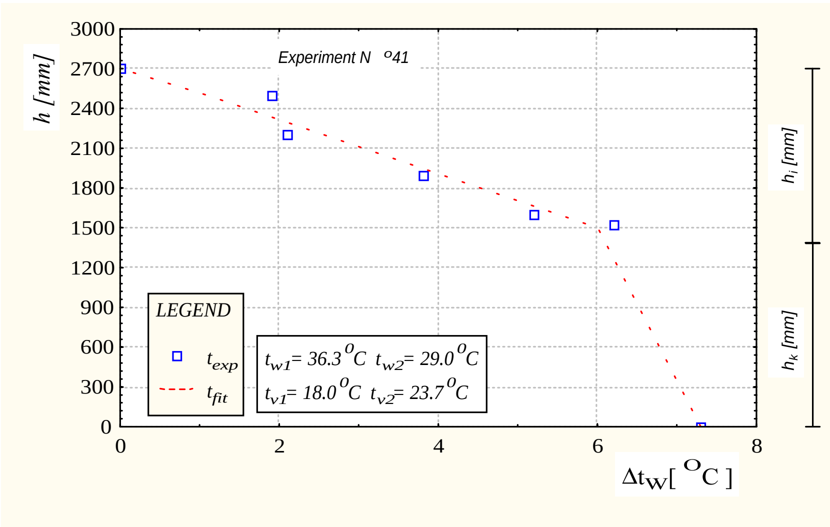

Fig. 4. Variation of water temperature along height of tower and other characteristic quantities of experimental run No. 41

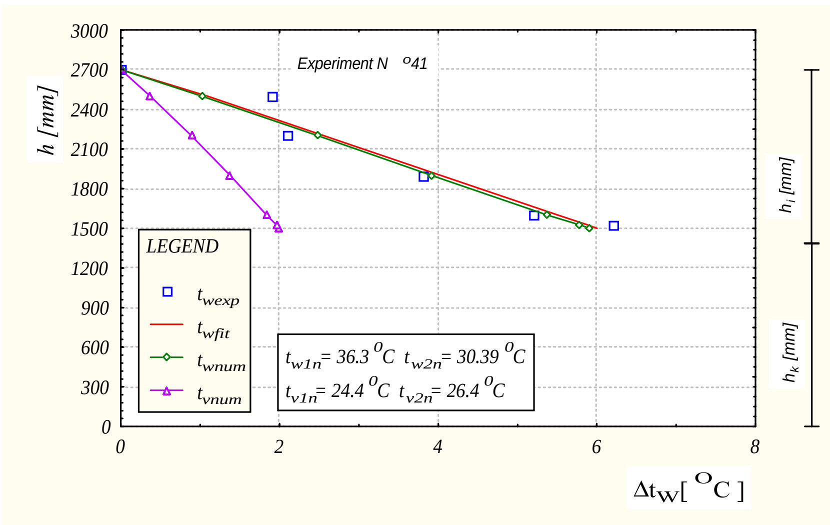

Fig. 5. Variation of water and air temperatures along height of tower and other characteristic quantities of experimental run No. 41

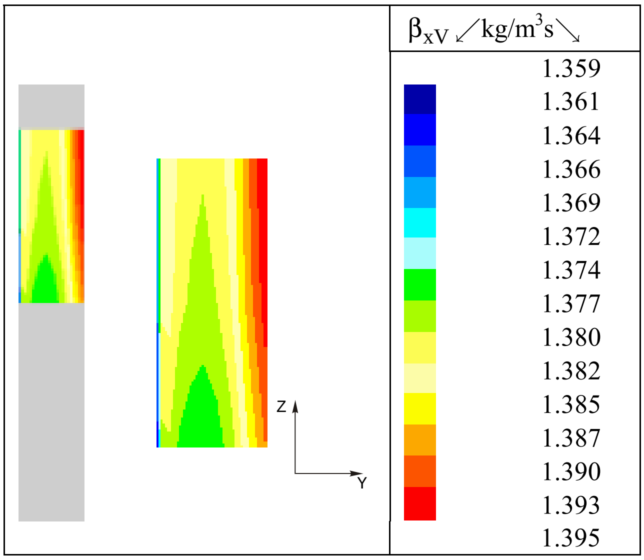

Fig. 6. Local mass transfer coefficient - vertical cross section

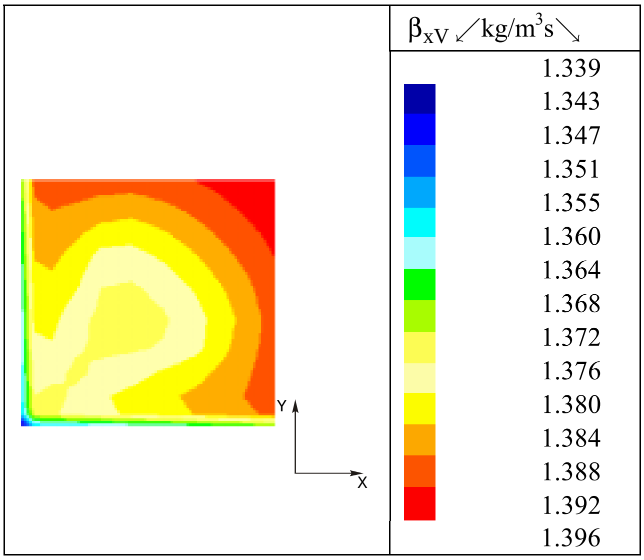

Fig. 7. Local mass transfer coefficient - horizontal cross section at packing inlet

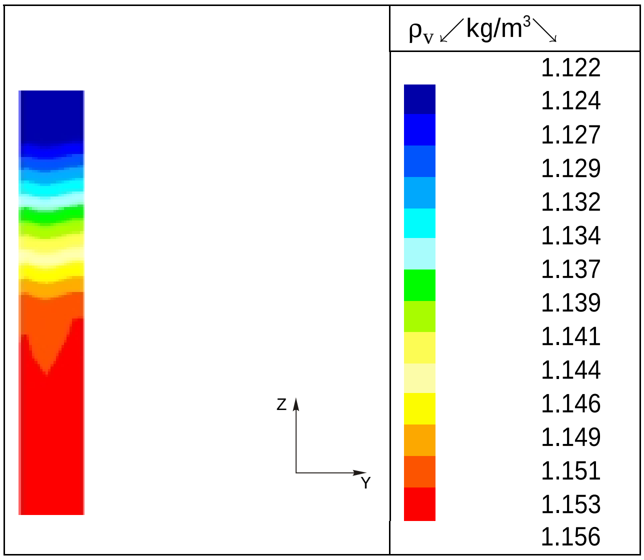

Fig. 8. Air density variation - vertical cross section

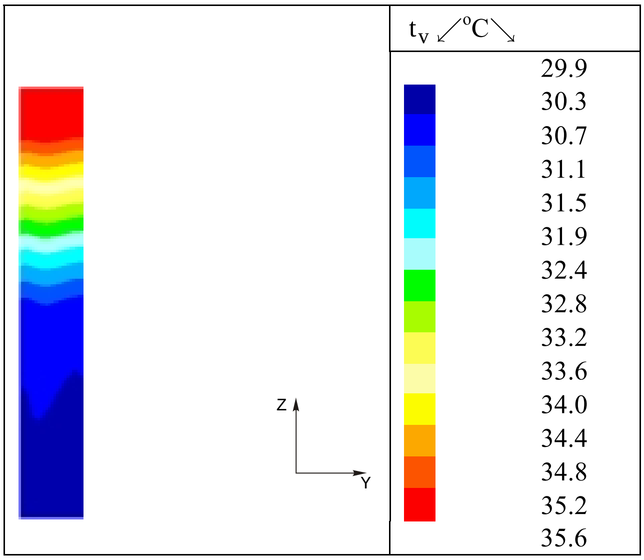

Fig. 9. Air temperature variation - vertical cross section

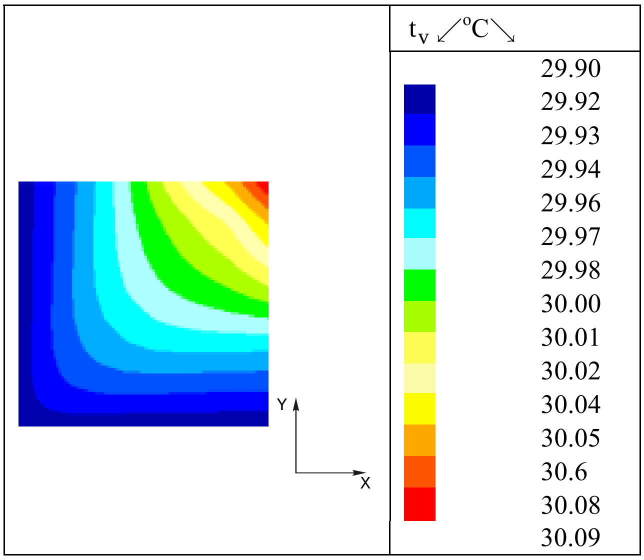

Fig. 10. Air temperature variation - horizontal cross section at packing inlet

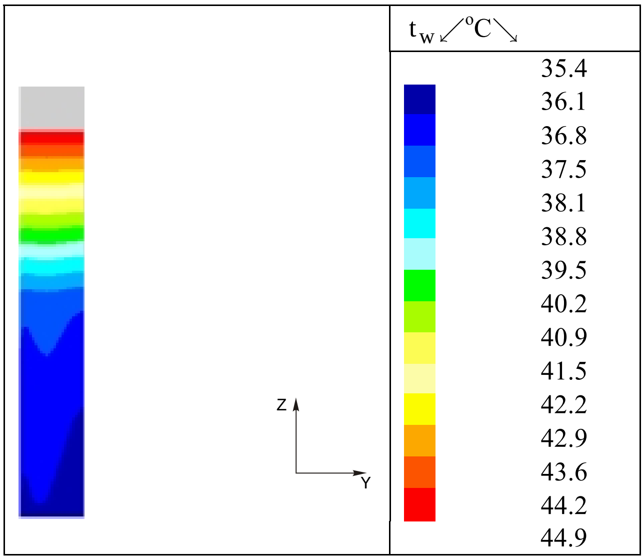

Fig. 11. Water temperature variation - vertical cross section

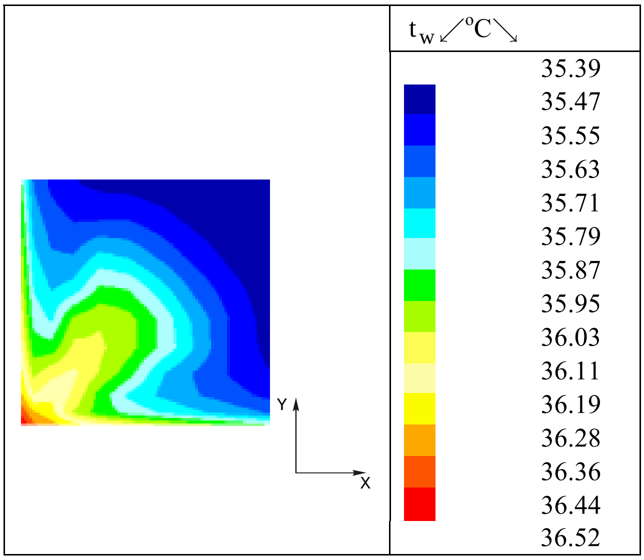

Fig. 12. Water temperature variation - horizontal cross section at packing outlet

6. Conclusion

In this paper the results of the experimental investigation on local intensities of heat and mass transfer in fill of wet cooling tower, have been presented.

The experimental cooling tower has been constructed and installed in Thermal Engineering Laboratory at Mechanical Engineering Faculty Niš.

The experimental results have confirmed the assumption of the authors that due to unsteady flows of water and air, and depending on air number the rain droplets have been lifted from the lower edge of packing up to 1/2 of fill height. This phenomenon justifies the assumption of changeable phase contact surface across the whole volume especially along the height of fill. The determination of the phase contact surface area is almost impossible so the majority of the authors in this field are defining the volume averaged heat and mass transfer coefficients in tower fill.

On the basis of analysis of many papers, the authors have concluded that the influence of the phase contact surface variation in the fill is no important, and that contribution by phase contact changing is negligible in comparison to the totally transferred heat and mass, so the averaged values of heat and mass transfer coefficients have been accepted across the fill volume.

The heat and mass transfer coefficients are changeable not only along the fill height but also across the cross section, so the assumption of its invariance leads to error which has the order of magnitude of about 6%, according to our analysis. The final consequence is the increasing of the fill volume.

In 1-D numerical model the influence of the magnitude of the phase contact surface variation, is assumed to be the function of the z-coordinate, and so the good agreement between experiment and prediction has been achieved.

The application of a very sophisticated 3-D numerical model has contributed to the better understanding of such a complex phenomenon as the heat and mass transfer in two phase flow is.

Nomenclature

t_w - water temperature
t_v - air temperature
h_k - rain zone height below packing
h_i - height of packing
Δt - water or air temperature difference
exp - experimental results
fit - fitted results
num - 1-D and 3-D numerical model results

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EKSPERIMENTALNA STUDIJA PROSTIRANJA TOPLOTE I MASE U RASHLADNIM TORNJEVIMA

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U ovom radu su prikazani rezultati eksperimentalnog određivanja koeficijenata prenosa toplote i mase u ispuni vlažnih rashladnih tornjeva. Istraživanja su obavljena na eksperimentalnoj aparaturi konstruisanoj u Laboratoriji za termoenergetiku i termotehniku na Mašinskom fakultetu u Nišu. Prikazana je eksperimentalna instalacija i instrumentacija.

U eksperimentalnom istraživanju korišćena je ispuna napravljena od pleksiglas ploča debljine 5 mm i visine 1200 mm, koje su postavljene na međusobnom rastojanju od 40 mm. Ispuna je smeštena u vertikalnom kanalu kvadratnog poprečnog preseka 470×470 mm. U toku eksperimentalnog istraživanja varirana je brzina vazduha u opsegu 1,5-5 m/s i protok vode u opsegu 2-3 m^3/h. Promena temperature po visini ispune merena je pomoću 26 pogodno postavljenih termoparova. Dobijeni rezultati su prikazani u formi dijagrama.

Ključne reči: *rashladni toranj, eksperiment, numerika*