New measurement method for in-field measurements of liquid phase drift from cooling towers

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Abstract. This contribution introduces a newly proposed thermal based method for measurements of drift for in-field applications on real cooling towers up to an eliminator efficiency of approximately 0.0001% of circulating water flow. This method should thus become the main alternative to the methods used nowadays. The main advantage of this newly proposed measurement procedure should be its easy preparation and implementation and quick analysis of measurement results. The article summarizes the development of an innovative probe, and why this new probe and the entire method is needed for the industry. The design of this new probe consists of two main directions of development pathways: the electronic part and the aerodynamic part. The first one lies in the development of a sensor (and the accompanying electronics) and sums up the theoretical principle of the method (the calculation of droplet sizes scatter based on statistics, and the calculation of power needed for the sensor). The aerodynamics part derives from the desired efficiency and accuracy of the measurement and is based on precedent modelling and calculations of flow, containing droplets of various sizes through various uniquely shaped channels. The contribution also demonstrates an experiment made thus far, showing quantity measured and the drift evaluation process.

1 Introduction

Drift is a cluster of water droplets released from cooling tower to surroundings. The drift poses a problem for infrastructure in vicinity of its source and tower structure itself, as it could be damaged, but it also represents important problem for environment. Water droplets released from cooling tower contain the same chemicals and the same biology as the circulating water. This is a potential risk for environment and also health.

The drift also causes considerable water loses; at least, the water loss can be 0.0007-0.0014 15 $m^3/h/m^2$, which, in the case of cooling towers in Temelín, represents a lower hundreds of cubic meters per one cooling tower per day.

Determining a drift rate from a real cooling towers in operation becomes very important part of the overall cooling tower operation. In line with these facts multiple states worldwide work or already accepted legislation, which sets up required minimal drift eliminator performance rate – e.g. for France 0.01 %, Spain 0.001 %.

The drift eliminator efficiency is one of the two crucial characteristic parameters. The drift emission from a cooling tower is usually expressed as a percentage of the total circulating water flow rate. It can also be expressed as a mass per unit time related to water or air flow (as defined in [1]).

There are several methods used for eliminators drift measurement. The bellow diagram (Fig. 1) shows their overall classification. More of these methods could be find in [2],[3] and [4].

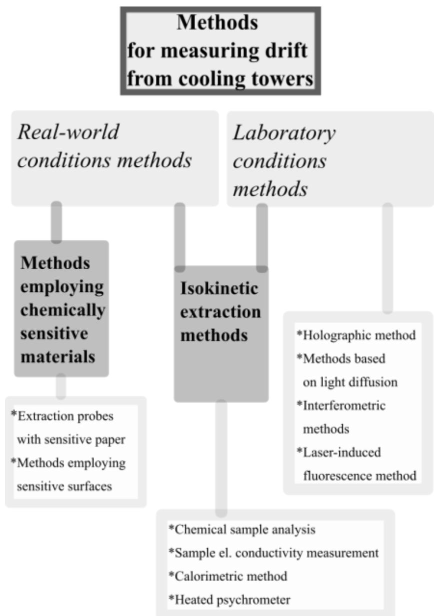

Fig. 1. The state of the art methods for measuring drift from cooling towers.

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All these methods, recently used, for determining drift from cooling tower or drift eliminators certification are long used but, slow, quite complex and costly. The entire industry would accept any new method, which could be used in both lab and field environment at lower cost, if it provides reliable results.

1.1 Calorimetric based principle for the new method

The method is to be based on calorimetric principle. The calculations for this principle are as follows:

First, the total amount of water captured in the new probe in the dependency on sampling time must be determined.

$$m_{DRIFT} = \dot{m}_{DRIFT} \cdot t_{SAMP} = \mu \cdot \dot{V}_{CIRC} \cdot \rho_{WATER} \cdot \frac{A_{PROBE}}{A_{UNIT}} \cdot t_{SAMP} \quad (1)$$

Assumed and intended values are: cross-section area A_{PROBE} = 10 x 10 mm, typical value of water flow rate V_{CIRC} = 15 $m^3/h/m^2$, density of water ρ_{WATER} = 997 kg/m^3, drift eliminator efficiency μ = 0,001% and a sampling time of 20 minutes (t_{SAMP} = 1200s). The total heat needed for evaporation simply comes out from this value and specific heat of water on boiling:

$$Q_{DRIFT}=m_{DRIFT}.L_{water} \quad (2)$$

2 Theoretical analysis of the drift

The above reasons led to an idea of new measurement methodology to be developed to determine the amount of the drift via the net of simple sampling probes working on the calorimetric principle. The method will be able to determine the drift with sensitivity at least of 0.001 % of the circulating water and will require max 8 hours in a common cooling tower/cell. This sensitivity was chosen because it is a threshold required by some of the legislations in Europe and also worldwide (Green Building CTI Japan, LEED – 0.002 % drift rate for counterflow towers and 0.005 % for cross-flow towers). This new proposed method started with exact theoretical analysis of the drift.

2.1 The efficiency of the new designed probe

The efficiency of eliminators used in the cooling towers to capture the cooling liquid is one of their two main characteristic parameters. It is defined as the ratio of the drift (i.e the volume of water that passes through the eliminator unit area per unit time and eventually leaves the cooling tower in the form of droplets) to the total water flow through the cooling tower unit area.

Although this parameter is illustrative and very well understood by the general public, it is not a correct parameter. The total volume of water that is not captured by the eliminator, in addition to its geometry and the magnitude of the velocity in the eliminator space, also depends on the size of the droplets that the eliminator is to separate from the flowing air. This fact follows from the principle on which the eliminator separates droplets from the flowing air. It is basically only a curved channel, when due to centrifugal accelerations in each individual bend of the eliminator the droplets cease to be able to follow the flowing air and hit the walls of the duct, where they gradually merge up to drops which, by their weight, exceed the tangential stress and more or less in the form of a water film flow back into the cooling circuit. Correctly defined efficiency should therefore be based on the spectrum of droplets that the eliminator is unable to capture at a given speed.

Although the above-mentioned approach to the definition of eliminator efficiency is inaccurate, it is not possible to use another principle for the initial design, mainly because it is not possible to obtain the necessary experimental data for commonly available eliminators.

Therefore, the efficiency defined by the world's renowned manufacturers was used in the design of the thermal probe. The second mentioned approach (based on the distribution of the spectrum of drops below and above the eliminator) was then used to get at least a basic idea of how many and which droplets stick to the walls of the eliminator.

According to the valid certification standards used in Europe, currently manufactured eliminators must meet the condition that their efficiency, at the air velocity of 3.5 $m.s^{-1}$, reaches at least 0.007% of the total water flow through the cooling tower; the value 0.007% is the limit value for which the eliminator is still declared compliant. The new designed probes for measuring its efficiency have to be designed for lower value of this. The value 0.001% was chosen as the limit value that the method should still be able to detect.

2.3 Considerations of a measurement success rate with respect to droplet size

With regard to the above information and the calculations, which will be carried out later in the chapter 3 describing the probe design, the power for the heated element was set at 100 mW to start with; this information, even maybe posted here in this chapter is a bit premature, is needed for another theoretical consideration of great importance: *measurement success rate with respect to droplet size.*

With water captured in the probe at 0.001% of drift and cooling tower water load of 15 $m^3/h/m^2$ the evaporation of a 1200 second sample collection will occur in approximately 113 s.

The water content is delivered to the probe in the form of droplets of various sizes of the order of about 5 μm to 100 μm. A droplet with a diameter of 100 μm has a total volume three orders of magnitude higher than a droplet with a size of 5 μm, but the probability of its occurrence is on the other hand several orders of magnitude lower than with droplets of the order of 5 - 20 μm. By right, there was a concern that the random presence of large droplet could significantly affect the measurement, respectively, debase it. It is obvious, that although the big droplets which will pass through the eliminator are not statistically relevant by their number, they might have significant impact on the total water volume of the captured water.

So, an estimation (with use of some measured data from drift eliminators, calculations of water collected in a probe of considered effectiveness and with help of Rosin-Rammler particle-size distribution statistics [5]) was processed.

First of all, for some idea, a model with one large droplet with considered diameter 100 μm brought into a group of small droplets was tested. The result was surprising, even this one single droplet represents 11 % of the total water volume. This phenomenon might have significant impact on the method preciseness, especially when total droplet count is low.

After that, a calculation of droplets quantity, which will be captured by the probes in 1200 s time period, was then processed. It was based on data measured in the drift eliminator by IPI method.

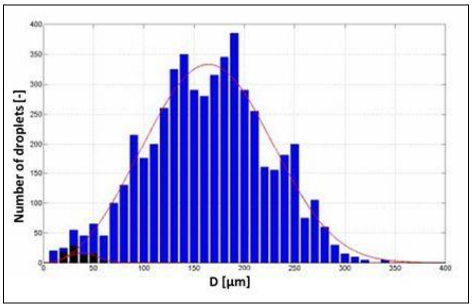

Fig. 2. Example of measured droplets histogram, below (blue) and above (black) eliminator.

The histogram shown above (Fig. 2) is based on data obtained by IPI (Interferometric Particle Imaging) optical measurements. It is clear from it that the number of recorded droplets in the space above the eliminator in the area of the order of 0.1x0.1x0.005 m in the total sum reaches the value of 250.

Normalized distribution of the spectrum of drops above the eliminator based on the IPI measurement is shown in Fig. 3.

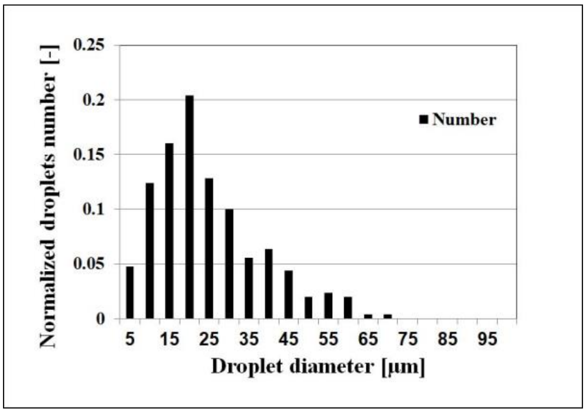

Fig. 3. Normalized number of droplets.

Then, when considering one probe and the calculated volume of water collected in probe for specified time plus Rosin-Rammler distribution, the time, for which a drop will definitely appear in the probe, was determined (Fig. 4).

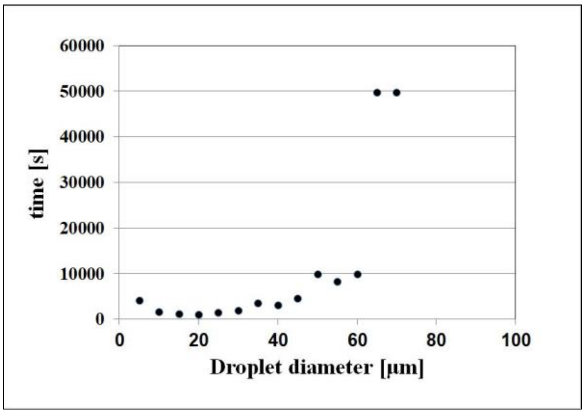

Fig. 4. The time, for which a drop of appropriate diameter, will definitely appear in the probe.

It showed that the impact of big droplets on the method preciseness will be negligible, because their appearance in the probe is very unlikely in comparison to smaller ones (the most common occurrence is recorded in droplets with the diameter of 20 μm).

3 Probe design

3.1 The design of microelectronics part of the new probe

The probe itself consists of two parts, which have to be designed: microelectronics component and aerodynamics proposal of the channel. Schematic illustration of such probe see in Fig. 5. From the microelectronics point of view, an active element together with whole control unit was designed. The main parameter for the active element, which has to be prepared from the theoretical analysis, was required power.

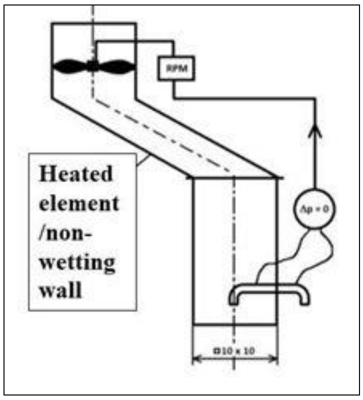

Fig. 5. Probe scheme.

There were several preconditions laid down for sample collection. On one hand the element can evaporate water in a suitable time (short enough so that the value is not affected by other droplets introduced into the probe space) and on the other hand that its temperature does not exceed a reasonable limit.

The cross section of the probe was chosen to be the size 10 x 10 mm, the flow of uncaptured water through the probe therefore corresponds to a value of 0.01 - 0.02 g/hour, resp. 0.17 - 0.33 mg/min.

For the design value of probe cross-section area (A_{PROBE} = 10 x 10 mm), typical value of water load (V_{CIRC} = 15 $m^3/m^2/h$), density of water (ρ_{WATER} = 997 kg/m^3) the drift eliminator efficiency (μ = 0.001%) and a sampling time of for instance 20 minutes is the total amount of water in the probe m_{drift} = 5mg. The total heat needed for evaporation is then Q_{drift} = 11.32 J.

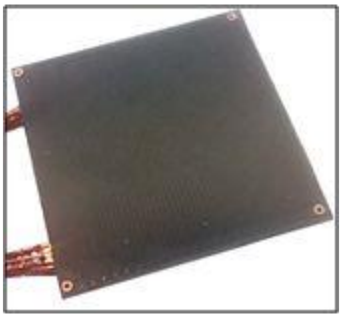

Fig. 6. Custom made heated element.

This heated element (see Fig. 6) is driven by control unit. PCB of this control unit is shown below (Fig. 7).

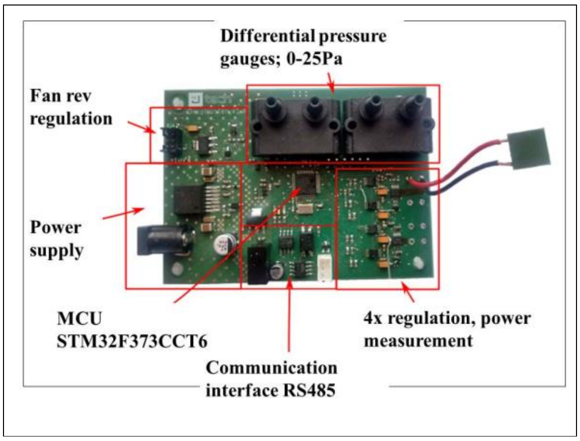

Fig. 7. PCB of the probe control unit. Apart from the heated element, it also controls the pressure gauges and the fan. The latter two components are required to comply with certain measurement conditions.

3.2 Probe shape design

The design of the hardware part of the probe started with the simple scheme (see Fig. 2). In principle, it should be a curved channel, the shape of which is based on the shapes of highly efficient eliminators with known efficiency values. On the other hand, there is another aspect that must be taken into account: at the same time, the probe must be an easily manufacturable channel, not only for the purposes of a prototype of the probe, but also for an experiment using optical methods. So far, the last design deviated from the originally proposed scheme and settled on a probe of uncomplicated shape with incandescent elements located on the side opposite the inlet opening. One of the tested designs see in Fig. 8.

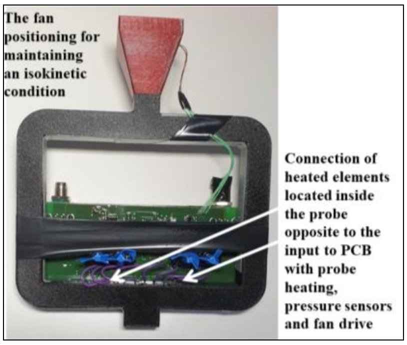

Fig. 8. The probe.

3.3 Verification tools

Given that this is an innovative approach to measuring the drift, it was also necessary to design or possibly expand existing experimental or theoretical methods that will serve as tools to verify the theoretically designed principle of the probe. Chapter 3.3 Verification tools deals with their design, development and testing.

Two options were chosen from the available tools for verifying the probe principle. The first of these was the Interferometric Particle Imaging (IPI) method, the second was another optical method using similar experimental equipment Particle Image Velocimetry (PIV).

In the case of IPI, it is a non-invasive optical method providing mainly information on the size of individual droplets below and above the probe channel. The results obtained may generally include the integral value of the cooling tower drift as well as the efficiency of the eliminator (or in our case the probe channel) according to particle size, correlation between particle size and even speed, etc. The great advantage of this method is that the minimum measurable droplet sizes are almost order of magnitude smaller compared to other methods.

Similarly, the other optical PIV method is a non-invasive method using the same laboratory laser and the same high-speed camera. In principle, this is nothing more than taking two images of the same space with a very short time interval (in the order of hundreds of microseconds depending on the expected velocity), the setting of which is the basic input parameter for obtaining relevant data. From these duplicates, the flow rate in the probe can then be determined using complex algorithms used to process the image. The probe efficiency can be obtained from the subsequent purely mathematical processing after calculating the behavior of the two-phase flow.

3.3.1 Measuring stand for IPI and PIV measurement

It is an open wind tunnel - a discharge line with a drive. The fan is driven by a motor with speed control. The output cross section is 250mm x 250mm, the speed of the air flow is continuously adjustable in the range of 4-25m/s. Two-phase flow is provided by a droplet generator. The track was designed as variable for easy exchange of the measured channel so that it is possible to test different variants of the channel. Experimental setup see in Fig. 9.

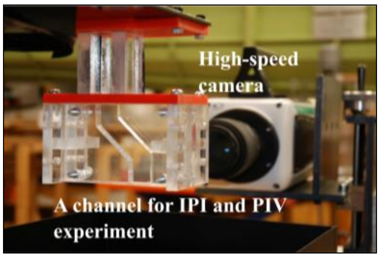

Fig. 9. The detail of an experiment setup for IPI and PIV veryfication measurements.

3.3.1.1 Experiment results from IPI and consequent evaluation method development

Measured data from IPI first served as a underlying material for a program, which is being developed for later droplets interferograms automatic detection. This program is called *IPIDET*. Its development will be described later in this subchapter. Thus, the data from IPI experiment have not yet been acquired primarily for the purpose of evaluating the drift, but rather setting the image detector. This means that the images do not contain interferograms of droplets taken before entering the canal and after leaving it, which would be the right approach to measure the number of droplets before and after the probe (from which the capture rate is evaluated), but directly in it.

The settings of the measuring apparatus were as follows: the lens has a focus of 105mm, the aperture value is set to F2.8 and the distance laser plane - front lens is approximately 200 - 210mm (depending on the configuration) and this distance is measured with an accuracy of about 5 percent. The picture (Fig. 10) shows interferograms in channel No. 1., manually labeled.

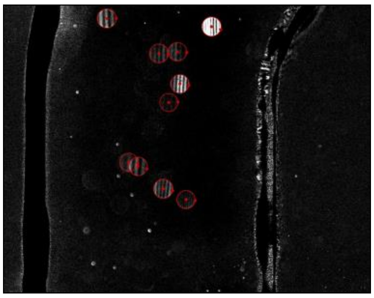

Fig. 10. Interferograms of the droplets in the channel No. 1.

The goal of the developed software called IPIDET (acronym composed of IPI Detection), which is created in the python programming language, is to automatically detect droplets interference images from measurements obtained by the IPI method and then calculate the number of their minimum / maximum.

The whole image processing algorithm consists of two main parts:

1. Detection of interference images (droplets).
2. Edge counting.

For example, an image obtained using IPI might look like this (Fig. 11):

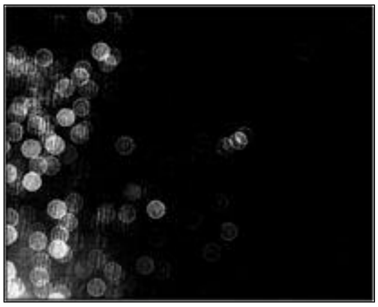

Fig. 11. Interferogram obtained by experimental IPI method.

It can be seen that there is a large overlap of images, some of which are overexposed, others underexposed. Of course, it depends on the skills and especially the experience of the experimenter to be able to prevent similar-looking images by precisely setting the measurement technique, however, this could not be expected from the first data sets available for programming and it was necessary to obtain data for program creation. The advantage may have been that it was necessary to deal with worse input data at the outset and tune the detector to various picture difficulties. Therefore, when most images have one overexposed area containing a lot of droplets, while the rest is underexposed, the detector has been programmed from the beginning, for example, in the way that it does not ignore these dark areas that also contain droplets. Therefore, before the detection itself, the program performs image preprocessing. Pretreatment is performed using CLAHE (Contrast Limited Adaptive Histogram Equalization).

Further, in order to detect the droplet image, the images must first be resampled to reduce the computation time. The image is then correlated with a circular image of approximately the same size as the droplets. The result of this correlation looks like this: the image is still quite noisy and the so-called peaks, which then need to be searched, are not so well defined (Fig. 12 - left). Therefore, the second correlation is performed using the Gaussian kernel (Fig. 12 - right).

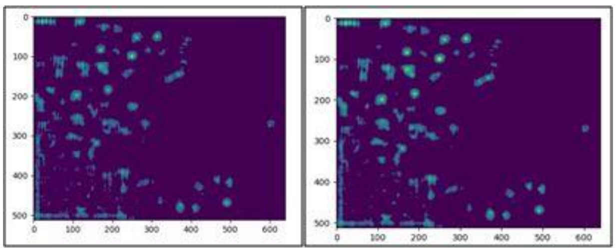

Fig. 12: Resampled data.

In such image, it is finally possible to detect individual peaks for further processing.

Droplet slices are extracted from the image using the coordinates obtained in the previous section. To calculate the number of droplet interference image fringes, the following procedure is done with the image:

1. | 2D FFT |.
2. Standardization.
3. Finding adjacent peaks (except for the DC component in the middle).
4. Calculation.
5. The droplet size calculation follows.

3.3.1.2 Experiment results from PIV and consequent evaluation method development

The velocity field was measured using the time-resolved PIV method. The experiment was carried out for the first proposed channel geometries, which were still based on the original idea (as was shown in Fig. 5). The figures below show the channels that were prepared for optical measurements using plexiglass (models of the channels see in Fig. 13).

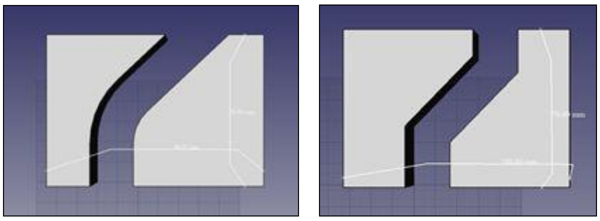

Fig. 13. 3D Models of plexiglass channels: the channel No. 1 (left) and the channel No. 2 (right).

The experiment was performed with the following equipment in the configuration described below.

The measuring device consists of a New Wave Pegasus laser and a CMOS camera. The Phantom V611 camera with a resolution 1,280 x 800 pixels is capable of capturing double images with a frequency of up to 3 kHz (full resolution) and uses an internal memory of 8 GB. The data were obtained and subsequently processed in Dynamic Studio software. The evaluated velocity field consisting of 77 x 47 vectors was taken at a frequency of 100 Hz, one record contained 1,000 double frames representing 10 s in real time. The time between pulses was set at 50 μs. SAFEX tracer particles, oil droplets with a diameter of 1 mm, were used.

The experiment results prepared for the later numerical evaluation of the particle trajectory are shown in the following figures (Fig. 14 and 15). Q 45% (or 70%) means 45% (or 70%) of the maximum fan speed.

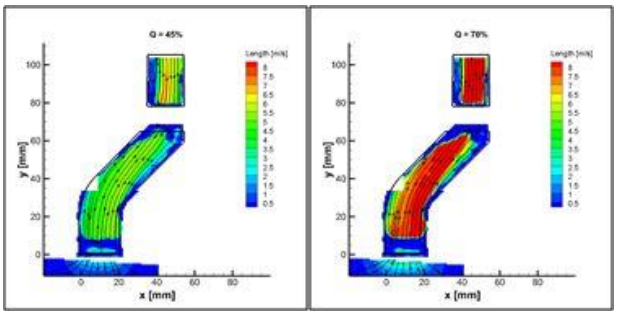

Fig. 14. Velocity field evaluated for channel No. 1 and two flow values.

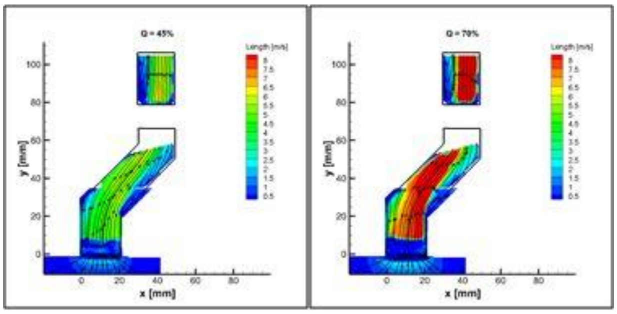

Fig. 15. Velocity field evaluated for channel No. 2 and two flow values.

Such results are useful for the real probe design itself (as they help with the aerodynamics), but as they are, they need another theoretical calculation for the probe efficiency determination.

The search for this problem was performed with the help of L. Novakova dissertation thesis [6]. The efficiency of capturing the liquid phase by the probe can be determined by calculating the trajectories of the droplets carried by the air stream. The trajectory calculation is being performed under certain necessary assumptions, for example: the velocity field is not affected by the presence and movement of droplets, mutual interactions of droplets are not considered, the probability of droplets with a given radius is constant along the entire entrance or the effect of water film on walls is not considered. The trajectory of the particle motion was calculated based on the solution of the equation of motion. As the input data, detailed information of the flow in the channel, using the velocity field measured by the PIV method are used. The algorithm is still in progress.

4 First experiments and experimental verification method

4.1 First experiments

First tests with heated elements were performed in a lab. Three configurations were measured in simple configuration to prove the principle of the designed probe: a) dry heated element, b) heated element with water droplet attached and c) heated element covered by water film. Also different power values for evaporation were set – 50 mW, 100 mW and 150 mW. Results are shown in the charts bellow (Fig. 16).

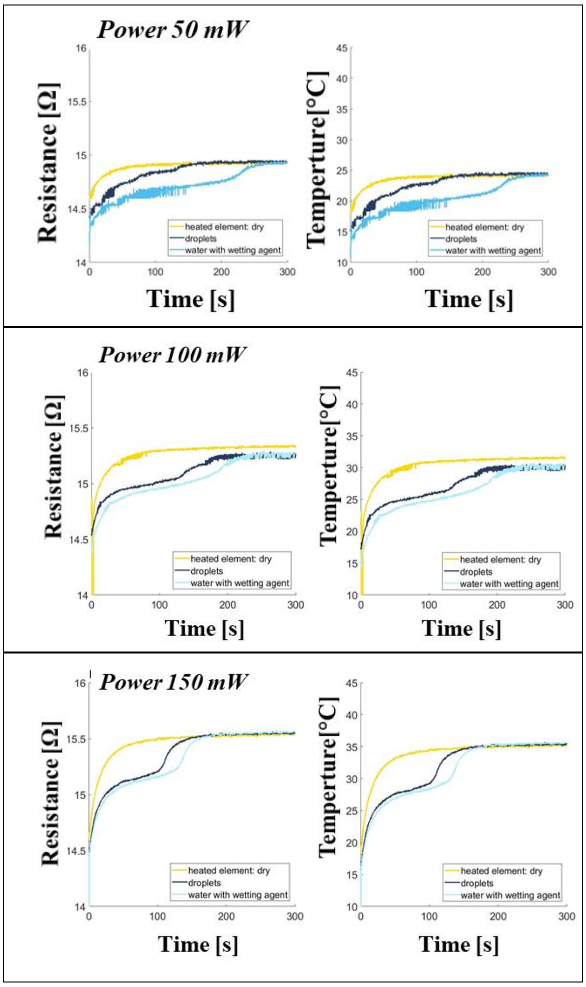

Fig. 16. Resulting resistance and temperature for three sets of power on heated element in configuration: dry, with droplet attached to the surface and with the water film covering the element.

The repeatability experiments are planned in the spring of 2022. So far, measurements have been made in a small laboratory tower equipped with an ultrasonic fog generator (Fig. 17).

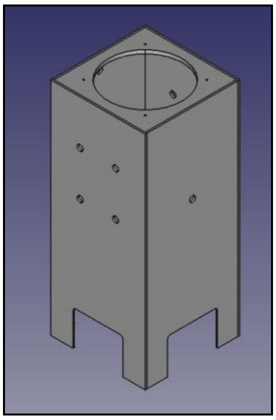

Fig. 17. 3D model of small laboratory cooling tower (height 700 mm).

The testing was performed for a flow velocity in the tower of 2 m.s^{-1}, which was measured at the point of probe entrance with a Testo 425 anemometer. The probe was equipped with a fan necessary to maintain the isokinetic conditions at the outlet and four heated elements located opposite the entrance to the probe; it is possible that in the ongoing tests this configuration will be extended by other positions of the heated elements. The output of the measurement monitored so far was the change in resistance of the heated element over time. A large number of experiments have been performed, where the droplets collection takes place for different times and each of these collections is completed by evaporation of one set value of glow power and one set value of evaporation time. Data processing is in progress at the time of submission and further experiments are planned, so no specific results will be given here.

The probe was further tested for mechanical endurance under cooling tower conditions. The real conditions in which the probe will operate represent a burden for the control and power electronics. The most important were the water resistance tests, both for the microelectronics itself and for the fan providing the isokinetic condition. For real operation, the electronics must withstand at least two days of such a load, which has been proven by above described testing.

4.2 HGBIK probe

The effectiveness of the probe in the experiment will be compared with the method that is certified by the highest authorities in the discipline for the measuring of the drift - the HGBIK method (Heated Glass Beads Isokinetic). Its production in accordance with the CTI-140 standard [7] also belongs to the range of activities that needed to be carried out during the development of the probe.

Method is based on the calorimetric principle with subsequent chemical analysis of the captured sample. It is characterized by isokinetic extraction of air samples containing water droplets with so-called tracers. The measured quantity is the total mass flow. The HGBIK method is tested and introduced in the certification practice of measuring the efficiency of the drift eliminators, therefore this was chosen for the verification measurement of the new developed probe. It is one of the most widely used methods in the industry. Schematic illustration see in Fig. 18, finished probe in Fig. 19.

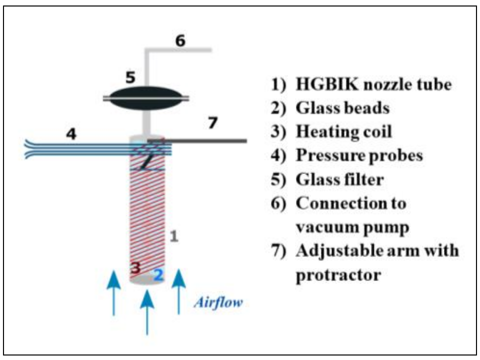

Fig. 18. Schema of the HBIK probe.

Fig. 19. The HGBIK probe.

5 Conclusion

The purpose of this paper was to present the development of a new probe for measuring drift in real and laboratory conditions. This is a development from the initial theoretical analysis of the drift (its probable capture in the probe of the selected cross-section, size and frequency of droplets) through practical tasks both in terms of microelectronics and selection of a suitable aerodynamic channel shape for sampling air flow, to the development of the methods, which will verify the effectiveness of the meter.

These are advanced experimental methods of PIV and IPI and subsequent processing of the achieved results. In the case of the PIV method, it is a calculation of the efficiency of the probe based on PIV experimental data. On the basis of PIV measured data, the geometry of the channels was modified, which was a bonus output of this experimental part. In the case of the IPI method the programming of a droplets detector and the calculation of their size isbeing developer. The IPI method uses the same measuring device as the PIV method, but its output is a little bit different and the results will have to wait a while until the program for detecting droplets and calculating their size IPIDET is finalized. This is an integral part of the whole development, because the entire development is more or less focused on the size of the drift droplets.

By completing the calculation of droplet trajectories from the PIV data and finalizing the IPIDET program, two methods for determining the efficiency of the probe will be obtained. After its full deployment in a real experiment in the cooling tower, another method will be added, which will verify the probe. It is the method of certified isokinetic sampling by the HGBIK probe.

All three methods are either so important or so interesting from the point of view of scientific contribution that they are all gradually used for verification and experimentation. By measuring using the IPI method it is possible to obtain an accurate distribution of drift droplet size and thus reduce the measurement uncertainty of this quantity. Using of PIV, an overview of the velocities of the droplets and especially the direction of their movement within the two-phase flow, which clearly determines the ideal place of capture and thus the location of the heated elements , will be obtined. And using the HGBIK certified isokinetic sampling method, the new probe, compared to the results from the measurement with HGBIK prope, will gain maximum confidence.

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