# An experimental analysis of droplet charging in a wind tunnel

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**Abstract.** The aim of this paper is to introduce an experimental analysis of droplet charging that occurs due to liquid film atomization on two different surfaces. The atomization of the droplets from the liquid film at high speed is still not satisfactory understood. The phenomena can be found in steam turbines, wind turbines, aeroplanes and other technical applications. The liquid film atomization is associated with the electrostatic charge of the formed droplets. The paper describes the experiment when the coated and non-coated surfaces were tested for an estimation of the droplet size distribution function and the droplet charge. A new wind tunnel was developed for the study of liquid film atomization in similar conditions in steam turbines. The coarse droplets are formed in the steam turbine from the liquid films on the blades and inner casings. The coarse droplets formed on the non-moving blades don´t exactly follow the bulk flow and they collide with the moving blades. These collisions cause erosion and corrosion processes which have an unfavourable effect on the reliability and the efficiency of steam turbines. The tunnel is equipped with the standard instrumentation for the measurement of the flow properties and for the analysis of the size distribution function of the droplets. Two measurements methods were used to attain the size of the droplets, along with their photogrammetry and light scattering. The first tested surface is polished stainless steel and the second is the electrical isolating and hydrophobic coating. The results from the measurement suggest the possibility of the better understanding the erosion processes in steam turbines.

## 1 Introduction

The presence of the liquid phase in the flowing wet steam has a very unfavourable effect on the operating characteristics and reliability of steam turbines [1]. Electrostatic charge could be involved in the formation of a liquid phase in the flow section of steam turbines on one side, and on the other side, of the erosion process. Knowledge of the electrostatic charge phenomena in steam turbines is therefore essential, especially these days when such understanding has the potential to enhance steam turbine performance. The presence of an electrostatic charge in the flowing steam has been proven by the measurement of steam turbines [2,4], which showed that the charge distribution in the flow was not homogeneous and was probably influenced by the operation and chemical mode of the thermal cycle.

The wind tunnel, located at the Institute of Energy Engineering, Faculty of Mechanical Engineering of the Czech Technical University in Prague, was developed to study liquid film disruption and to research the electrostatic charge in the flowing air or steam.

The paper describes the measurement of the electrical current on two surface properties. The experiment simulates a situation when manufacturers of steam turbines use the coating to modify the coarse droplet distribution that allows for an extended blade life. The existence of the electrical charge in the steam turbines is well documented since steam turbines expand to the wet stem. A similar situation occurs during aeroplane charging in the flow through rain.

## 2 Droplet charge

Several known methods of droplet charging have been investigated (diffuse bipolar and unipolar, electrostatic field charging, water droplet charge dropping on the probe surface). The measured reality best described the model based on the disintegration of the water film that forms on the surface of the blade and the probe. This proposal is based on work on an electric double-layer [3,4]. The water that collects on the electrostatic probe is in turbines created directly during spontaneous condensation and therefore we can assume higher concentrations of chemical impurities [4] than in the bulk condensate and in the wind tunnel the liquid used is mostly standard fresh water. According to the derivation at work [2], the charge magnitude of the resulting drop is more dependent on geometric characteristics than on electrochemical properties and can be estimated at approximately $\mathbf{q} = 3{,}3\cdot 10^{-15}$C. Since it is obvious that the radius of entrained droplets is crucial, it was determined according to the Weber number [5]. Geometric characteristics are further responsible for the erosion processes in the turbines. Erosion of the steam turbine blades can be defined as a progressive loss of material from the solid surface bodies caused by collisions with the water droplets which possess high kinetic energy.

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The blades are most often subject to this type of erosion due to the high relative velocity between the coarse droplets and themselves. The swept droplets don't follow the bulk flow and they are insufficiently accelerated before colliding with the blades. Erosion reduces efficiency, turbine power and decreases time between overhauls. The problem of the formation of water droplets due to condensation of water vapour in the last stages of the turbine is the subject research for several decades, but nowadays is even more urgent due to the rise of the use of the renewable energy sources. The serious impact on reducing the life of turbines is the reason for the constant interest and efforts to develop new measures to reduce blade wear.

## 3 Measurement

The experiment was carried out in the wind tunnel with the two blades placed in the air flow. The first blade was coated with electrical insulating and hydrophobic paint and second was polished stainless steel. The overall view of the tunnel is in Fig. 1.

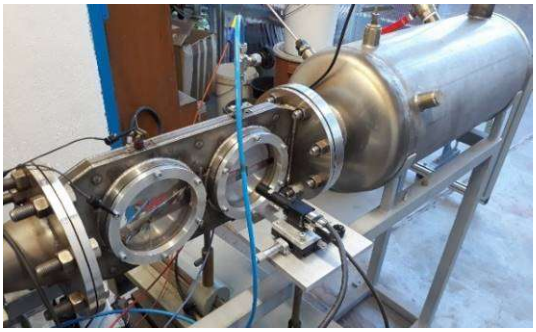

**Fig. 1.** The wind tunnel.

### 3.1. The wind tunnel

The motivation for the wind tunnel assembly arose from a previous measurement [5] of the coarse droplets in the steam turbine under operational conditions. The measurement was performed in three steam turbines in the Czech Republic. The amount of the acquired coarse droplets was very low due to their low number density level. Due to difficulties connected with measurements in an operating steam turbine, a wind tunnel was designed and manufactured for the analysis of the coarse droplet formation from the liquid films. The aim of the design was to create, as closely as possible, the conditions in a steam turbine while utilising the advantages of working in the laboratory.

The wind tunnel is designed as a classical CD nozzle, but the planned operational regime is mainly subsonic or transonic. An aerofoil NACA0008 is placed 50 mm behind the nozzle throat. The aerofoil simulates the blade in the turbine and it is possible to remove or replace it. There is a groove on the aerofoil which supplies liquid to the surface. The liquid is pumped to the aerofoil through the dosing pump with a flow from 1 ml/min to 500 ml/min. The tunnel is equipped with four large optical windows that provide good optical access for the measurements. It is possible to operate the tunnel with steam in continuous mode or with compressed air in periodic mode.

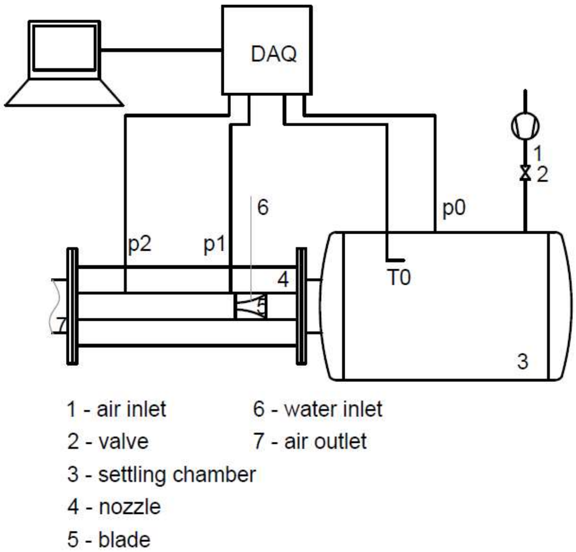


**Fig. 2.** The wind tunnel measurement schema.

### 3.2 The size distribution measurement

The droplet distribution function measurement was performed on a Spraytec instrument (Malvern, Inc.). Both blades were tested under the same conditions in the wind tunnel. The measuring position of the laser beam was about 20 cm behind the trailing edge of the blade. Due to the principle of measurement (scattering of light on the droplets), the conditions for evaluation were not always met, therefore the results are calculated only for the states when the conditions for evaluation were acceptable. In Fig. 3, the volumetric or mass fraction distribution is shown. It is possible to see the bi-modal distribution.

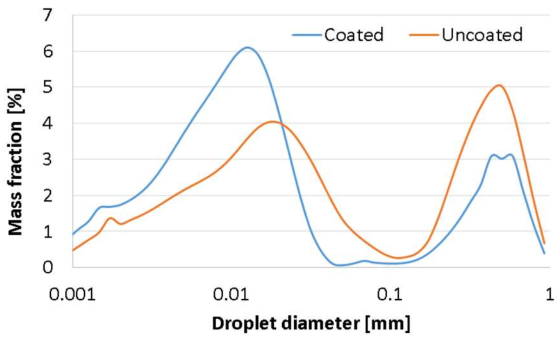


**Fig. 3.** The droplet size distribution.

Fig. 4 shows the image of the trailing edge of the blade in the tunnel. It is a typical example of liquid film break up. The image was taken by the developed photogrammetric probe [6]. The situation on the image indicates the formation of small particles and randomly formed large droplets.

**Fig. 4.** An example of liquid break-up on the trailing edge of the blade.

### 3.3 Charge measurement

The electrostatic probe is schematically shown in Fig. 5. The impacting droplets carrying the el. charge produce the el. current. The recorded electric current is the result of the interaction between the droplets and the active part of the probe. A similar process also occurs as the droplets leave the probe. The projection area of the active part of the probe is 20 x 2 mm. This probe can measure across the nozzle channel. The flow field influence for different positions of the active part can be considered constant for all positions of the active surface of the probe.

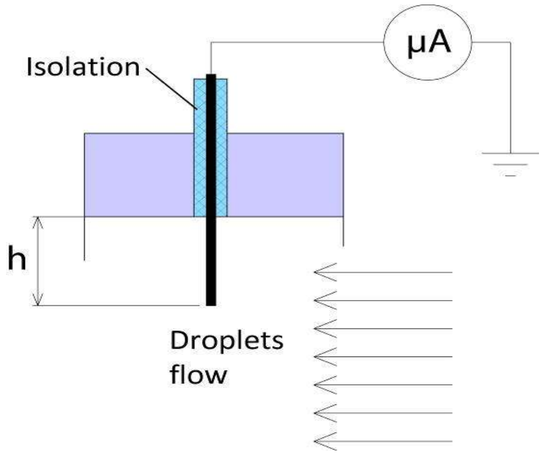


**Fig. 5.** Electrostatic probe measurement schema.

### 3.4 Measurement accuracy

The experiments presented in this paper are more qualitative analyses of the phenomena, whereas classical error analysis is not possible to suggest. The coefficient of variation for the droplet optical measurement is smaller than 1% for a monodisperse sample. The error of the micro-amperemeter is smaller than 1% of the span.

## 4 Data processing

The electric current *I* generated by the water droplets carried in the steam flow upon impact on the probe can be expressed by the following formula (1)

$$I = AcN_v \int_{rk,min}^{rk,max} \eta_z (r_k)\alpha(r_k)q(r_k)\varphi(r_k)dr_k \quad (1)$$

Where $\mathbf{r_k}$ is the radius of the droplet, **A** is the projection of the probe surface perpendicular to the flow axis, **c** is the steam velocity, $\mathbf{N_V}$ is the number density of droplets in $1m^3$, $\boldsymbol{\eta_z}$ ($r_k$) is the drop impact efficiency on the probe, $\boldsymbol{\alpha}$ ($r_k$) is the probability of the charge transfer from the droplet to the probe, $\boldsymbol{\varphi}$($r_k$) distributing the droplets in the stream by the radius.

Due to existence bi-modal distribution, the data of the size distribution function of the droplets were divided into two groups and the Sauter mean diameter was computed for both groups. The edge diameter between small and large droplets was estimated at 60 µm (approximate saddle between modes).

$$D_{32} = \frac{\sum d^3}{\sum d^2} \quad (2)$$

For the simplified analysis of the measured el. current the eq. 1 may be applied. The dependence on the diameter can be reduced by two Sauter diameters of the two groups from the droplets' distribution measurement. The charge transfer efficiency and impacting efficiency could be in this simplified situation expected to be a unity. The density level of the droplets was determined according to the volumetric concentration and the measured mass flow of the liquid on the blade surface. In all cases 1ml/min. The cross-section of the electrostatic probe is 6% of the nozzle channel. The final simplified equation can be written as,

$$I \approx e(\dot{R}_s q_s + \dot{R}_b q_b) \quad (3)$$

where **e** is the elementary charge $-1{,}602e10^{-19}$ C, **R** is the collection rate [$s^{-1}$] of the el. stat. probe of small and large droplets. **q** is the mean droplet charge expressed in the elementary charge. The ratio between mean charge of the small and large droplets $\mathbf{q_b}$ /$\mathbf{q_s}$ is an important parameter which can be useful for practical application. Large droplets are mostly responsible for the erosion of the turbine blades.

## 5 Results

Three measurements of the coated and uncoated blade were chosen for the data processing. In Table 1, the result of the Sauter mean diameters for both droplets group are presented alongside as their ratio. In Fig. 6, the time dependent profiles of the current measurement are presented. The el. current seems similar for all measurements with a change of polarity. Direct data processing is not possible because the el. probe proves

**Table 1.** Droplet size distribution results.

| | Diameter $D_{32}$ [µm] | | Mass Ratio [%] | |
|---|---|---|---|---|
| Group | Small | Large | Small | Large |
| Coated 1 | 5.3 | 386.2 | 72.4 | 27.6 |
| Coated 2 | 5.0 | 458.8 | 88.3 | 11.7 |
| Coated 3 | 4.8 | 353.3 | 75.6 | 24.4 |
| Uncoated 1 | 7.9 | 332.2 | 59.8 | 40.2 |
| Uncoated 2 | 5.8 | 136.8 | 75.9 | 24.1 |
| Uncoated 3 | 5.2 | 209.4 | 84.2 | 15.8 |

impossible to distinguish a charge which is coming with the droplets from the blade and one which is leaving the probe with the droplets. From this reason, we are only able to make similarity comparisons. The best fit between eq. 3 and measured data was determined for the ratio ($\mathbf{q_b}$ /$\mathbf{q_s}$) ≈ $10^5$.

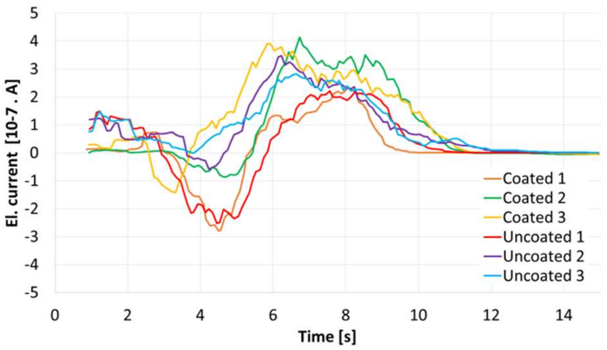


**Fig. 6.** Electrostatic probe measurement.

## 6 Discussion

The explanation of the result is not direct and it is necessary to realise the source of the charging which is the expected double layer disruption of the liquid film. The presence of the el. charge on the droplets is already proven. But the polarity and charge distribution in respect to droplet diameter is still not clear. In Fig. 7, the mean droplet charge profile for a coated and uncoated blade is presented. Both dependencies have similar profiles, but we expect the charge ratio is ($\mathbf{q_b}$ /$\mathbf{q_s}$) ≈ $10^5$, but the mass ratio of both droplets groups $\mathbf{m_b}/\mathbf{m_s}$ ($D_{32}$) is $3.10^5$. From this perspective, the coated surface produces more charged particles and the larger particles have a lower charge mass ratio. Moreover, the large droplets mean charge $\mathbf{q_b}=10^{10}$ of elementary charge is very close to the Rayleigh limit of the droplet charge which is, in our case for large droplets, in order $10^{12}$ units of elementary charge. In Fig. 4, it is possible to see the excess of the charge at the end of the liquid columns and the explosive production of the small particles at their tips.

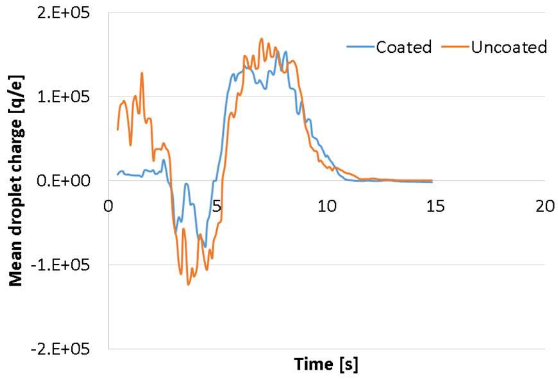


**Fig. 7.** Small droplet mean elementary charge.

## 7 Summary

The results presented in this paper are selected examples and they are presented as temporarily results. The complexity of the phenomena is extremely extensive. The formation of the droplet charge involves aerodynamic, chemical, surface and electrostatic forces. For this reason, this paper only presents the current progress in the data processing and the example of the possible result.

We gratefully acknowledge the support of the Grant Agency of the Czech Technical University in Prague, Grant No. SGS 21/154 and National Centre for Energy TN01000007.

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