Electrostatic Charge of Fine and Coarse Droplets in LP Steam Turbines

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Separate contributions of the fine and coarse droplets in the wet steam charge density is presented. The tests were performed by means of combined optical extinction and charge probe at the exit of L-0R blades of the nuclear 1000 MW and fossil 210 MW LP steam turbines. Negative charge of the fine droplets was observed together with positive charge of the coarse droplets. Considerably larger charge density was detected in the nuclear LP steam turbine with larger pH value of the steam condensate. Correlation function between the charge and size of fine droplets is presented that can be employed in the analysis of the charging models.

1. Introduction

Diagnostics of fine and coarse droplets forming the liquid phase of wet steam in LP steam turbines has been extended in recent years also in regard to the electrostatic phenomena. Knowledge of the charge of droplets together with the cycle chemistry can bring further progress in understanding of the nucleation and charging processes, blade erosion, and corrosion phenomena occurring within the LP steam turbine flow path. Thus, it is the subject of considerable theoretical interest in two-phase flows of wet steam with direct subsequent contribution to current efforts in improvement of efficiency and reliability of the steam turbines.

The current status of the problem is introduced e.g. in EPRI reports [1, 2] that are part of general electrochemical approach to quantify the processes in the phase transition zone (PTZ) of fossil and nuclear turbines, and to show how these influence the corrosion mechanism (corrosion fatigue and stress corrosion cracking).

The liquid phase of wet steam in LP steam turbines consists primarily of the fine droplets formed during heterogeneous nucleation on chemical steam impurities (ions) in the PTZ, and by homogeneous nucleation during the ongoing steam expansion in case it produces the needed steam supersaturation. It is assumed that the fine droplets carry the negative charge because the negative clusters are statistically more able to develop into the stable water droplets then are the positive clusters [3].

The coarse droplets, formed by break up of shed liquid films from the blade surface, are generally carriers of a positive charge because of a double-layer charging process [1-3].

Reported test results, so far, of the volumetric charge density in a wet steam flow in model and field LP steam turbines have been obtained with spherical (cylindrical) sensors allowing simultaneous impact of the both droplet groups [1, 2]. The charge probe measures, therefore, the resulting charge which consists of contributions from the fine and coarse droplets without possibility to provide separate information on negative or positive charge of each droplet group. These information might be of fundamental importance for nucleation theories accounting for the negative charge of critical nuclei and for confirmation of the positive charge of the coarse droplets. In addition, it can help for better understanding of the charging process of wet steam flow in the LP steam turbines.

The aim of this paper is to present further new results of measurement of the charge of fine and coarse droplets carried out in L-0R exit planes of 1000 MW nuclear and 210 MW fossil LP steam turbines. The tests have been performed with combined optical extinction and charge probe (developed at the CTU in Prague) allowing for separate charge prediction of the both droplet groups [4, 5].

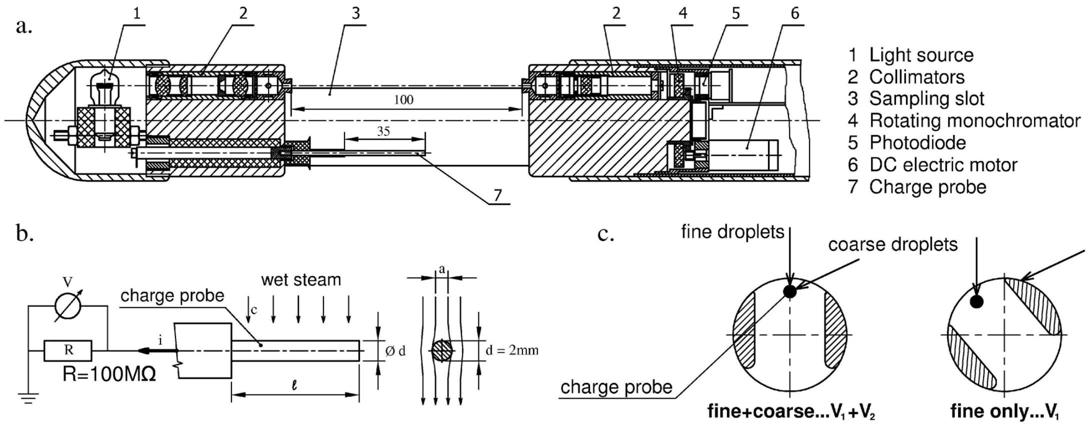

Fig. 1. a. Measuring head of the combined extinction and charge probe.
b. Electrostatic circuit of the passive charge probe.
c. Different yaw angle positions of the probe measuring slot.

2. Combined Extinction and Charge Probe

Current experience with the droplet charge measurements in the LP steam turbines suggest that the tests should be carried out simultaneously with measurement of the droplet size spectra, moisture level and steam velocity. In addition, because of different charging processes of the fine and coarse droplets, there should be possibility to predict separately the charge contributions of the each droplet group.

Therefore, the new combined optical extinction and charge probe was developed at the CTU [4, 5] as it can be seen in Fig. 1a. The charge probe is placed within the measuring slot of the optical extinction probe. Because of different outlet flow angles (yaw angles) of the both considered droplet groups at the exit of L-0R blades, this arrangement makes possible the charge of fine and coarse droplets to be predicted separately by changing the probe yaw angle, as it is seen in Fig. 1c..

During the impact of individual droplets on the cylindrical electrostatic charge probe the charge transfer takes place. The current to earth can then be related to the charge of droplet population in the wet steam. The electric circuit of used passive charge probe is seen in Fig. 1b. The two yaw angle probe positions introduced in Fig. 1c. thus correspond to impact of the both droplet groups with measured voltage $V=V_1+V_2$, and of the fine droplets only with V_1. The contribution of the coarse droplets can then be obtained as $V_2=V-V_1$.

3. Charge of Droplets and Charge Density in Wet Steam

Supposing the liquid phase of wet steam is formed by polydispersed system of droplets then measured reduction in the light intensity I/I_o, caused by the light scattering on droplets and measured electric current to earth $i = V/R$, due to impact of droplets on the charge probe, can be described [4] as:

$$\frac{1}{\ell_E}\ell n\left(\frac{I_o}{I}\right)_i = \frac{\pi}{4}N_v\int_{D\,min}^{D\,max} E\left(\frac{\pi D}{\lambda_i}\right)\varphi(D)D^2 dD \qquad (1)$$

$$i = (d\ell c)N_v\int_{D\,min}^{D\,max}\eta_c(D)q(D)\varphi(D)dD \qquad (2)$$

where ℓ_E length of the measuring slot of extinction probe, N_v number of droplets per m^3, E Mie´s extinction function, D droplet diameter, $\varphi(D)$ probability density function, d diameter of the charge probe, ℓ length of the charge probe, c steam velocity, $\eta_c(D)$ droplet collection efficiency, and $q(D)$ charge of droplet.

Numerical solution of the system of integral eq (1), obtained for different λ_i, gives droplet size spectrum $\varphi(D)$ and steam wetness y (ρ_v, ρ_ℓ - specific density of vapor and liquid)

$$y = \frac{y_v}{\dfrac{\rho_v}{\rho_\ell} + y_v} \qquad (3)$$

where

$$y_v = \frac{\pi}{6} N_v \int_{D\,min}^{D\,max} \varphi(D) D^3 dD \qquad (4)$$

Mean charge of fine droplets (subscript "1") then follows from eq (2) as

$$\overline{q_1} = \frac{i_1}{(d\ell c_1) N_{v1}} \cdot \left[\int_{D\,min}^{D\,max} \eta_c(D) \cdot \varphi_1(D) \cdot dD \right]^{-1} \qquad (5)$$

Finally, the charge density due to the fine droplets in the wet steam will be

$$\sigma_1 = \overline{q_1} \; \frac{N_{v1}}{\rho_v} (1 - y_1) \qquad (6)$$

Different approach had to be used for coarse droplets (subscript "2") because of unknown $\varphi_2(D)$, N_{v2}, c_2. Assuming $\varphi_2(D) = 1$ (for D>5-10 μm) then eq (2) gives mean charge of coarse droplets

$$\overline{q_2} = \frac{i_2}{(d\ell c_2) N_{v2}} \qquad (7)$$

Equation (7) can now be combined with relations for quantity and flow rate of coarse droplets (with droplet mean mass $\overline{m_2}$)

$$y_2 = \frac{N_{v2}}{\rho_v} (1 - y_1) \overline{m_2} \qquad (8)$$

$$y_{2t} = c_2 \; N_{v2} \; \overline{m_2} \qquad (9)$$

to provide contribution of coarse droplets to the wet steam charge density

$$\sigma_2 = \overline{q_2} \frac{N_{v2}}{\rho_v} (1 - y_1) = \frac{i_2}{(d\ell)} \frac{y_2}{y_{2t}} \qquad (10)$$

Approximate information on σ_2 can be then obtained for averaged values [4]:

$$y_2 = 0.045 \; y_1 \qquad \text{[kg/kg]} \qquad (11)$$

$$y_{2t} = 0.033 \qquad \text{[kg/m}^2\text{s]} \qquad (12)$$

Introducing the mean charge-mass ratio ($\overline{q_2} / \overline{m_2}$) of a coarse droplets eq (10) can be rearranged to give another formulation

$$\sigma_2 = \left(\frac{\overline{q_2}}{\overline{m_2}} \cdot y_{2t} \right) \frac{y_2}{y_{2t}} \qquad (13)$$

4. Test Conditions in LP Steam Turbine

Combined extinction and charge probe (Fig. 1) has been used in numerous tests performed at the exit of L-0 rotating blades of the fossil 210 MW and nuclear (PWR) 1000MW LP steam turbines under operation conditions introduced in Table 1.

Analysis of optical test results suggested [4] that different pressure levels p_w within the nucleation region of both considered turbines are responsible for observed considerably different droplet size spectra, as can be seen in Fig. 2.

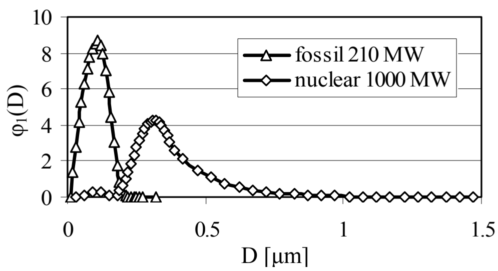

Fig. 2. Droplet size spectra at the blade mid–span.

Corresponding variation of the steam wetness (fine droplets only) along the blade height with radial coordinate z (Fig. 3) is introduced in Fig. 4.

Table 1. Operation conditions of the 210 MW fossil and 1000 MW nuclear LP steam turbines.

			fossil 210 MW	nuclear 1000MW
L-0 rotor blade length	ℓ_B	[mm]	840	1085
LP inlet parameters	p_{IN}	[kPa]	131	690
	t_{IN}	[°C]	181	248.5
LP exhaust pressure	p_{ex}	[kPa]	4.8	6.2
Turbine output	P	[MW]	200	1004
Mean pressure and expansion rate in the Wilson zone	p_w	[kPa]	23.1	142.3
	$(-1/p \cdot dp/dt)_w$	[s^{-1}]	1335	1224
Cycle chemical treatment			AVT, pH=8.8-9	AVT, pH=9.8-9.9

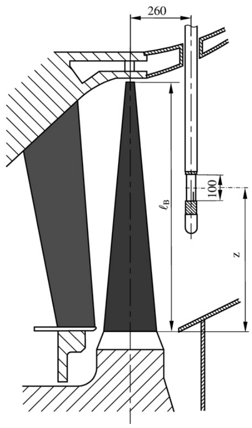

Fig. 3. Combined probe at the exit plane of L-0R blades.

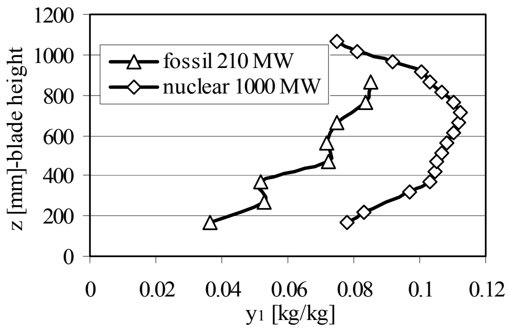

Fig. 4. Variation of steam wetness along the blade height.

The operation conditions and results of the optical extinction measurements of fine droplets ($\varphi_1(D)$, y_1) were used in the following evaluation and discussion of results obtained with the charge probe in considered LP steam turbines.

5. Results and Discussion

Prediction of mean charge of fine droplets $\overline{q_1}$ and charge density of wet steam σ_1 needs the velocity of fine droplets $c_1 = c$ to be known, as it follows from eq (5). In addition collection efficiency $\eta_c(D, c)$ depends on c_1 as well [4]. Therefore, CFD method was employed in evaluating variation of $c_1(\alpha)$ with the probe yaw angle α. It concerns the velocity of fine droplets before impact on cylindrical charge sensor within the probe measuring slot (Fig. 1) and, thus, considerably changing during the probe rotation.

An example of measured variation of voltage V (current $i = V/R$, R = 100 MΩ) with the probe yaw angel α at the blade mid-span is introduced in Fig. 5 together with computed velocity c_1. It is seen that measured voltage follows in principal the velocity variation.

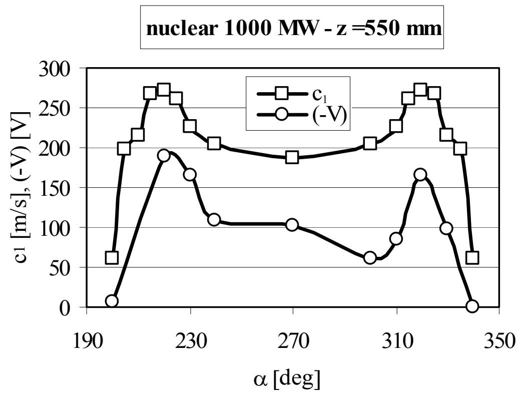

Fig. 5. Variation of measured voltage and computed steam velocity with the probe yaw angle α.

In considered case excluding of the coarse droplets from impact on the charge sensor corresponded to the yaw angel α_1 = 220 [deg]. It thus gives voltage V_1 for prediction of $\overline{q_1}$ and σ_1 according to eqs (5) and (6).

For larger values of α than ~ 240 [deg] the probe detects contributions of the both droplet groups. The second maximum of voltage variation at α = 320 [deg] thus provides needed information for prediction of charge density σ_2 according to eq (10), where $i_2 = i - i_1$.

The method was applied to measurements carried out at several radial positions z (Fig. 3) at the exit plane of L-0R blades with results for nuclear 1000 MW LP steam turbine introduced in Fig. 6.

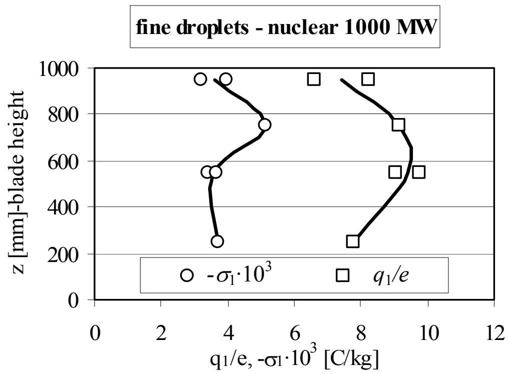

Fig. 6. Variation of mean charge q_1/e ($e = -1.6 \cdot 10^{-19}$ C) of fine droplets and charge density σ_1 of wet steam along the blade height.

It is seen that negative charge of the fine droplets was observed in these tests with no pronounced variation along the blade height.

Predicted variation of the charge flow rate of coarse droplets in Fig. 7 suggests that the coarse droplets were carriers of a positive charge. Observed decrease at the blade – tip region might be result of the water suction slots at the L-0S blades. Specifying the values of y_2, y_{2t} according to eqs (11) and (12) contribution of the coarse droplets to wet steam charge density can be obtained from eq (13).

Similar charge tests have been carried out at the fossil 210 MW LP turbine with reliable measurable charge values only in the blade tip region (z = 850 mm).

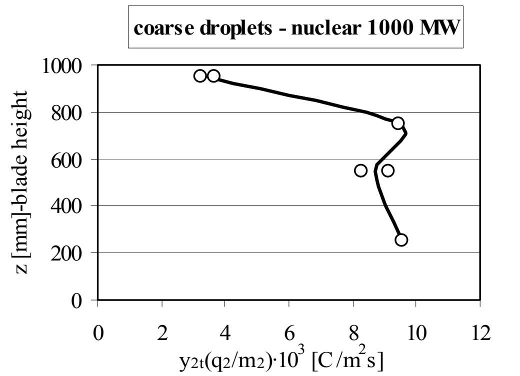

Fig. 7. Distribution of the charge flow rate of coarse droplets along the blade height.

Principal mean results from both considered turbines are summarized in Table 2.

Table 2. Mean results from nuclear 1000 MW and fossil 210 MW LP steam turbines ($e = -1.6\cdot10^{-19}$C).

		nuclear 1000 MW	fossil 210 MW
D_{32}	[μm]	0.499	0.1515
y_1	[kg/kg]	0.1038	0.0812
N_1	[1/kg]	$2.87\cdot10^{15}$	$7.80\cdot10^{16}$
q_1/e		8.44	$3.60\cdot10^{-2}$
σ_1	[C/kg]	$-3.85\cdot10^{-3}$	$-3.70\cdot10^{-4}$
$y_{2t}(q_2/m_2)$	[C/m^{2}s]	$7.22\cdot10^{-3}$	$8.35\cdot10^{-4}$
σ_2	[C/kg]	$1.02\cdot10^{-3}$	$9.25\cdot10^{-5}$
$\sigma = \sigma_1+\sigma_2$	[C/kg]	$-2.83\cdot10^{-3}$	$-2.77\cdot10^{-4}$

These results suggest that of one order larger charge density of wet steam existed in the nuclear than in the fossil LP steam turbine. Observed difference cannot be explained with the different droplet size spectra, moisture levels or steam velocities that are taken into account according to eq (2). Therefore, there have to be other still unknown effects e.q. different pH values (Tab. 1) that might be responsible for observed differences and could be recommended for further research.

6. Correlation between the charge and size of fine droplets

The tests with the combined extinction and charge probe carried out in the nuclear 1000 MW LP steam turbine provided sufficient data for an attempt to predict correlation function between the charge and size of fine droplets.

To account for unknown possible additional charging processes occurring in the expanding wet steam from PTZ to LP turbine exit, the diffusion [6] and bipolar [7] charging processes are considered. This approach, with defined physical background, made possible to start with the corresponding basic form of the correlation function with unknown constants to be predicted from the test data.

Referring for more details to references [6] and [7] the following correlation functions were obtained for considered nuclear 1000 MW LP steam turbine:

(i) Diffusion charging

$$\frac{q_1}{e} = a\,\frac{D}{2}\cdot \ell n\left(1 + b\cdot\frac{D}{2}\right) \qquad (14)$$

$a = 18.5$, $b = 61.7$

Mean quadratic deviation $\vartheta = 15.7$ %

(ii) Bipolar charging

$$\frac{q_1}{e} = -a\cdot\frac{D}{2}\cdot \ell n\,(c) \qquad (15)$$

$c = 7.84\cdot10^{-2}$

Mean quadratic deviation $\vartheta = 14.7$ %

where D diameter of droplets (μm), and ion electronic charge $e = -1.6\cdot10^{-19}$ C. Graphical representation of these correlation functions can be seen in Fig. 8.

A good agreement between measured and computed current with use of eq (2) along the L-0R blade height can be observed for both correlation equations (14) and (15) as seen in Fig. 9.

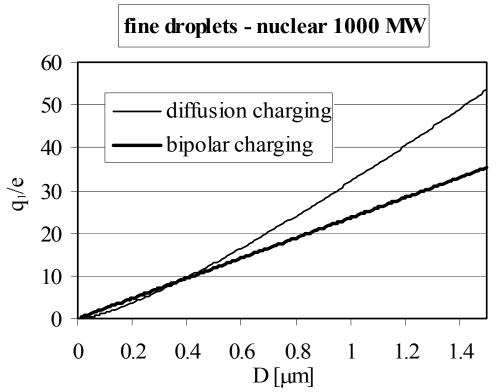

Fig. 8. Correlation between the charge and size of fine droplets (e = -1.6·10^{-19}C).

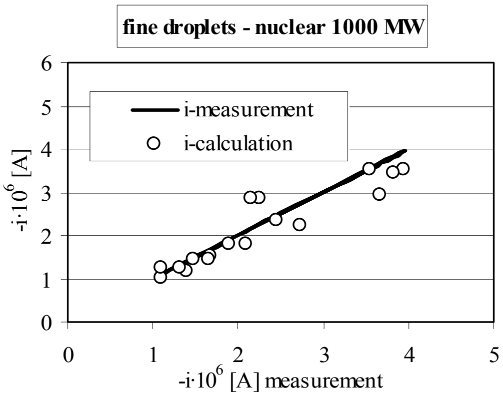

Fig. 9. Comparison of measured and computed current from the charge probe.

It is believed that bipolar charging process is more probable, nevertheless the both considered effects possibly might take part to some extent in the charging process of fine droplets. Introduced correlation equations could thus help for testing of different charging models in the continuing research of the problem.

7. Conclusions

- Combined extinction and charge probe made possible measurement of separate contributions of the fine and coarse droplets in the wet steam charge density.
- The tests carried out at the nuclear 1000 MW and fossil 210 MW LP steam turbines suggest that the charge of fine droplets is negative, while the coarse droplets are carriers of a positive charge.
- Correlation between the charge and size of fine droplets was found for the nuclear 1000 MW LP steam turbine tests. Diffusion and bipolar charging processes were employed for correlation functions with unknown constants predicted from the tests.
- Physical picture of the charging processes of the fine droplets occurring during the wet steam expansion from PTZ towards the turbine exit is still incomplete. The correlation functions could help in testing of different charging models.
- Observed considerably larger charge density in the nuclear LP steam turbine has not been explained yet. It is assumed that it might be the effect of larger pH value of the steam condensate. The problem needs further special attention both theoretical and experimental.

Acknowledgements

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