Rime-icing of large cylindrical elements in mountainous conditions

Dr. E. Moraliiski and Dimitar Nikolov
National Institute of Meteorology and Hydrology
Tzarigradsko shosse 66, Sofia 1784, Bulgaria, *emil.moraliiski@meteo.bg* dimitar.nikolov@*meteo.bg*

***Abstract*— The regime of rime-icing of plastic and metal cylinders with diameter of 50 cm at Chenry vrah (2286 m) has been experimentally investigated. The meteorological conditions, which determine the process of rime-icing – air temperature, wind speed and wind direction, horizontal visibility in the fog – have been studied and the main parameters of the ice depositions as the shape, the mean thickness and the ice mass, have been obtained. An attempt for modeling of the mean thickness of the ice depositions has been made.**

I. Introduction

In-cloud icing is a phenomenon that can be observed each year in the mountainous regions of Bulgaria and the typical type of the depositions is rime. Due to the geographical location of the country as regards to the ways of the Mediterranean cyclones, the icing here is very intensive and with long duration.

This paper describes the main results form a former special icing measurements on plastic and metal cylinder with diameter 50 cm in the region of peak Cherny vrah (2286 m) in Vitosha Mountain.

II. Descriptions of the measurments

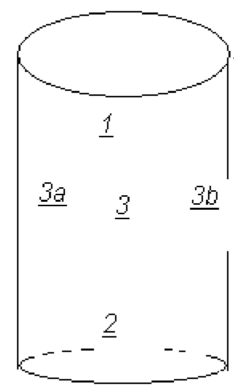
The measurements were carried out in the period from February 1972 until March 1977 on plastic and metal (made of aluminum) cylinder with diameter 50 cm and high 75 cm in the mentioned region. The number of icing measurements and the general number of icing events during the period of the experiment are given at Table 1. The general number of the registered icing events during this period was 194 and 57% from them were measured.

TABLE I
NUMBER OF ICING EVENTS DURING THE MONTHS (1) AND NUMBER OF THE MEASURED FROM THEM (2).

	January	**February**	**March**	**April**	**May**	**October**	**Novembe r**	**December**
1	42	28	26	24	5	9	25	35
2	22	17	13	16	4	2	17	20

The measurements were taken perpendicular of the axis of the cylinders at the end of the icing process and information about the density of the ice depositions was gathered separately with other measuring device. At the beginning the observations started at three points on the cylinders – points 1, 2 and 3 on Fig.1. In order to get better descriptions of the shape of the ice depositions some months latter the measurements continued at five points – 1,2,3 and 3a and 3b on the same figure.

Fig. 1 Scheme of the measurements



III. Main results

A. Meteorological conditions

The typical meteorological conditions during in-cloud icing could give a rough estimation of the expected ice loads. These conditions are presented here. The relative frequency of the duration of the process is given in Table II – from 9 up to more than 96 hours. Most often the duration is between 12 and 48 hours and the maximal one was registered on 02.12.1974 -182 hours. The mean duration is about 36 hours.

The air temperature influences the size of the cloud droplets and the density of the depositions. The temperature in cases of rime icing varies in a wide interval from – 0,5 till – 20,0 ^{o}C but most often it is between –2,0 and –10,0 ^{o}C with mean value of –6,5 ^{o}C.

The wind speed is the main factor which determines the intensity of process. Most often the averaged wind speed is between 9 and 18 m/s. In Table III is presented the distribution of the wind speed and in Fig.2 the wind rose in cases of icing.

TABLE II
RELATIVE FREQUENCY (%) OF THE RIME-ICING DURATION (IN HOURS)

Hour interval	9-12	12.1-24	24.1-36	36.1-48	48.1-60	60.1-72	72.1-84	84.1-96	> 96
n_i/N	10.1	26.3	22.2	15.2	7.1	6.1	5.0	4.0	6

TABLE III
RELATIVE FREQUENCY (%) OF THE WIND SPEED (M/S)

V, m/s	3.1-6.0	6.1-9.0	9.1-12.0	12.1-15.0	15.1-18.0	18.1-21.0	21.1-24.0	24.1-27.0	27.1-30.0
n_i/N	6.0	11.1	28.3	17.2	18.2	8.1	7.1	3.0	1.0

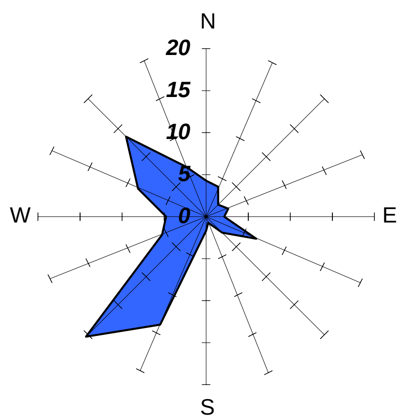


Fig. 2 Wind rose in cases of in-cloud icing at Cherny vrah

Because in the meteorological stations there are not any regular measurements of the liquid water content (LWC) of the cloud, we use in our calculations for estimation of the ice mass one experimental correlation (not presented here) between the visibility in the fog and the LWC [6]. In Table IV is presented the experimental distribution of the mean horizontal visibility (MHV).

TABLE IV
RELATIVE FREQUENCY (%) OF THE MEAN HORIZONTAL VISIBILITY IN CASES OF RIME-ICING

MHV, m	**26-30**	**31-35**	**36-40**	**41-45**	**46-50**	**51-60**	**61-70**	**71-80**
n_i/N	11	24	39	17	6	2	0	1

All these results are confirmed by a former our investigation [1], [6].

B. Parameters of the deposited ice

It turns out that the shape of the depositions is quite complex and the rimed part from the cylinders surface varies in a wide interval. The effective cross section is not big (about 0,375m^2) and almost always the thickness of the deposition is lowest in the middle (p. 3) – the shape resembles saddleback. The estimations show that the vertical profile of the thickness is in the middle point up to 7 times for the plastic and 11 times for the metal cylinder lower than this in the edge points. In Table V are given the averaged vertical and horizontal profiles of the shape. The following formulas have been used

$$Z_V = \frac{\Delta R(1) + \Delta R(2)}{2\Delta \bar{R}(3)} \quad (1),$$

for the vertical profile and

$$Z_H = \frac{\Delta R(3a) + \Delta R(3b)}{2\Delta \bar{R}(3)} \quad (2)$$

for the horizontal profile. Here ΔR(i) is the thickness of the deposition measured in point i.

On Fig. 3 is presented the change of the vertical profile Z_v with the wind speed. As it can be seen this ratio increases rapidly until 7 m/s, then it remains almost the same until 16m/s and by higher wind speeds it drops quickly below unity for wind speed above 26 m/s. This relationship has been used to restore the ice thickness in point 3 when no measurements had been made at this point.

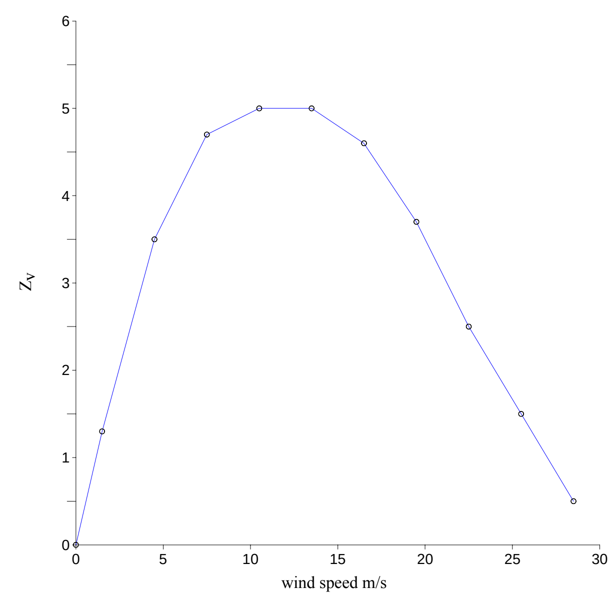


Fig. 3 Change of the ratio Z_v with the wind sped

TABLE V
AVERAGED THICKNESS (CM) OF THE RIME-ICE AT THE POINTS OF MEASUREMENTS IN DIFFERENT MONTHS

cylinder	**PVC**						**Al**						**N**
section / month	**vertical**			**horizontal**			**vertical**			**horizontal**			**Number of measurements**
Points of measurements	(1)	(3)	(2)	(3a)	(3)	(3b)	(1)	(3)	(2)	(3a)	(3)	(3b)	
December, 1973	16	4	12	8	4	8	21	4.5	20	10	4.5	10	8
November, 1974	28	10	28	15	10	15	30	7	32	18	7	18	3
January, 1976	15	4	13	6	4	6	12	2.5	13	5	2.5	5	6

The rimed part from the surface cylinder depends on the change of the wind direction during the process. Most often it is 1/3 from the circumference of the cylinder, which is about 50 cm (Table VI). This is also an indication that the wind direction in 60 % of the cases remains stable. Former investigations [6] have revealed that the processes in this region usually starts from SW and ends form NW. In such cases the rimed part from the surface of the cylinders is 2/3. In 12 cases the cylinders were fully rimed. Such a typical events is the case from 9.12.1976. In the first 21 hours the wind was blowing from SW and for the next 24 hours from NW. As results the cylinders were fully rimed with a basic ice thickness of 3 cm and the main ice cover above this layer was 1/3 from the cylinder's surface with thickness of about 20 cm. Unfortunately not all cases were measured so accurately. The event on 17.12.1973 was similar with 1/3 rimed part and 23 cm thickness of the main deposition but in the archive there were not any information for the thickness of the underlying basic layer.

TABLE VI
RELATIVE FREQUENCY (%) OF THE RIMED PART FROM SURFACE S' OF THE CYLINDERS

	10/10	**9/10**	**4/5**	**2/3**	**1/2**	**1/3**	**1/4**	**1/5**	**1/6**	**1/8**	**1/10**
PVC	9.8	2.9	0.1	10.8	5.9	**56.9**	8.8	0.1	2.0	0.1	0
Al	1.2	0	0	7.0	4.7	**59.3**	19.8	5.8	0	1.2	1.2

The main parameters used for estimation of the ice loads are the shape, the dimensions or volume and the mass of the deposition. In the further calculations the assumption for an equal deposited rime thickness in the rimed part from the cylinder has been adopted. This leads to the parameter averaged ice thickness - $\Delta\overline{R}$ calculated as weighted sum of all measuring points. In such a way the estimation of the real volume of the deposition is reduced to the calculation of the volume of the equivalent segment from the cylinder with equal deposition.

$$V = \pi\left[\left(R + \Delta\overline{R}\right)^2 - R^2\right]Hl \qquad (3)$$

where R is the radius of the cylinder, H is the length of the cylinder and l is the rimed part from the circumference of the cylinder.

It should be mentioned that on 9.12.1974 98 cm were measured in point 2 on the metal cylinder.

In Table VII and VIII are given the distributions of the averaged thickness and the mass of depositions on the cylinders. It can be seen that the mass of the rime ice deposited on the cylinders is most often up to 5 kg. The maximal deposition on the metal cylinder is 200 kg and this on the plastic cylinder is 72 kg.

In Table IX are presented the parameters of some extreme depositions. This includes the averaged ice thickness $\Delta\overline{R}$, the ice masses and the meteorological conditions under which the depositions were formed – air temperature, wind speed, horizontal visibility and duration of the process and the recalculated averaged collision efficiency - α_1.

TABLE VII

RELATIVE FREQUENCY (%) OF THE AVERAGED THICKNESS OF THE EQUIVALENT DEPOSITION ON THE CYLINDERS

Intervals, cm	0.1-2.5	2.6-5.0	5.1-7.5	7.6-10.0	10.1-15.0	15.1-20.0	20.1-25.0	25.1-35.0	35.1-45.0	45.1-55.0	55.1-65.0
PVC cylinder	25.5	24.5	14.9	10.6	9.6	3.2	7.4	3.3	1.1	0	0
Al cylinder	24.3	30.5	18.3	6.1	3.7	4.9	3.7	4.9	2.4	0	1.2

TABLE VIII

Relative frequency (%) of the mass M of the deposition

interval kg	0.1-2.5	2.6-5.0	5.1-7.5	7.6-10.0	10.1-15.0	15.1-20.	20.1-25.0	25.1-30.0	30.1-40.0	40.1-50.0	50.1-60.0	> 60.0
PVC cylinder	19.4	17.9	11.9	9.0	13.4	6.0	4.5	6.0	9.0	1.5	0	1.5
Al. cylinder	25.0	25.0	12.5	5.4	7.1	3.6	0	3.6	7.1	5.4	3.6	1.8
platic pole	81.1	14.9	2.7	1.3	0	0	0	0	0	0	0	0

TABLE IX

EXTREME IN-CLOUD ICING CASES – SOME PARAMETERS AND METEOROLOGICAL CONDITIONS.

Date	ΔR_m		S'		t, °C	V, m/s	MHR, m	L, (hours, min.)	M_{PVC}, kg	$M_{al.}$, kg	α_{PVC}	$\alpha_{Al.}$
	PVC	Al.	PVC	Al.								
22.01.1974	25.4	35.8	1/3	1/2	-9.9	16.3	33	111,45	24.0	29.0	0.014	0.016
08.02.0974	20.9	32.0	1/3	1/3	-5.8	17.7	38	109,15	25.5	45.3	0.015	0.027
04.11.1974	8.8	19.6	1/3	1/2	-7.4	17.4	38	89,40	15.4	40.7	0.012	0.030
27.11.1974	19.1	30.6	1/3	1/2	-3.4	13.1	34	78,00	28.0	52.3	0.029	0.053
09.12.1974	12.2	62.8	2/3	3/3	-7.9	10.7	40	182,05	34.0	211.3	0.021	0.130
04.12.1976	40.7	30.6	1/3	1/3	-4.3	20.8	33	67,15	72.4	48.4	0.054	0.036
09.12.1976	21.4	19.4	1/3	1/3	-4.8	16.4	43	44,40	34.8	31.4	0.058	0.053

C. Model calculations

The basic icing equation [2] has been used in this paper for assessment of the ice loads. This equation is

$$\frac{dM}{dt} = \alpha_1 \alpha_2 \alpha_3 wVA \qquad (4)$$

where α_1 is the collision efficiency, α_2 – sticking efficiency and α_3 – accretion efficiency, w is the LWC, V is the wind speed and A is the cross section of the obstacle. Under typical rime icing conditions at Cherny vrach can be assumed that α and α_3 are unity. On the basis of the data for the final ice depositions the collision efficiency α_1 has been recalculated using the formula

$$\alpha_1 = \frac{\pi\left[\left(R + \overline{\Delta R}\right)^2 - R^2\right]\rho l}{2RwVL} \qquad (5)$$

It should be mentioned that these calculations have been made with the averaged (for the process) values of the variables in the formula and that is way they do not represent the real dynamic of this coefficient, which is time dependent and very sensitive to any changes in the meteorological conditions. This could explain the low values derived for α_1. However, because the available data for the parameter of the depositions had been gathered only at the end of the process this is the only way the make some assessments.

The relative frequency of the averaged collision efficiency is given in Table X and some estimation for some extreme events (as above mentioned) in Table IX.

TABLE X
RELATIVE FREQUENCY (%) OF THE EMPIRICALLY OBTAINED AVERAGED COLLISION EFFICIENCY A_1 FOR THE BOTH CYLINDERS

α_1	0.0010-0.0100	0.0101-0.0200	0.0201-0.0300	0.0301-0.0400	0.0401-0.0500	0.0501-0.0600	0.0601-0.0700	0.0701-0.0800
PVC cylinder	26.3	34.2	18.5	7.9	6.6	3.9	2.6	0
Al. cylinder	38.3	23.3	16.7	10.0	5.0	1.7	3.3	1.7

The averaged wind speed during this experiment was 13,6 m/s and the mean air temperature – 6,5 ^oC. These conditions are very similar to those in the work of Langmuir and Blodgett [3] at Mt. Washington (1900 m). That is way we have used the same value for the dynamic viscosity of the air –

$$\mu = 1{,}658 \times 10^{-4} \text{ gr/cm sec} \qquad (6)$$

Using this value we received that the critical value of the droplet radius (below which no depositions occurs) for the cylinder diameter of 50 cm is 13 μ. Our investigations on the distribution of the droplets radius in cases of icing at Cherny vrah show that only 4-5% from the cloud droplets would collide with the obstacle. This is another confirmation of the low values of the averaged collision efficiency.

Different approaches for the calculation of the collision efficiency α_1 have been used. The first one is based on the formula for suggested by Langmuir and Blodgett [3]

$$\alpha_1 = \frac{K}{K + \frac{\pi}{2}} \qquad (7)$$

$$\alpha_1 = \left(\frac{K}{K + c}\right)^2 \qquad (8)$$

and K is

$$K = \frac{2r^2 V\rho_w}{9\mu R} \qquad (9)$$

Here r is the droplet radius, V is the wind speed, ρ_w is the density of the water droplets, μ dynamic viscosity of the air and R is the radius of the cylinder.

The second one is based on using different constants in formula (8). In Table XI is presented a comparison between the measured and the calculated ice thickness with formula (8) and value of 0,1 for the constant c which has shown the best fit.

Table XI
MEASURED (ΔR_M) AND CALCULATED (ΔRC) THICKNESS OF THE DEPOSITION ON THE CYLINDERS

Date	**ΔR_m, (cm)**	**α_1**	**ΔRc, (cm)**
18.10.1972	4.3	0.017	4.6
20.10.1972	2.0	0.006	1.6
13.11.1972	3.0	0.020	2.2
19.01.1973	7.1	0.013	5.0
08.02.1973	0.4	0.020	0.3
10.02.1973	0.4	0.016	0.5
22.03.1973	0.4	0.006	0.5

And the last one was the approach suggested by Finstad, K., E. Lozowski and E. Gates [4] which actually could not be used because at averaged meteorological conditions K is below its critical value. However we have used this approach for another experiment with plastic pole with diameter 3 cm and the results are presented in Table XII.

TABLE XII

MEASURED AND CALCULATED RADIUS OF THE DEPOSITED RIME ICE ON PLASTIC POLE WITH DIFFERENR FORMULAS FOR α_1

Data	R, cm	$\alpha_{0.5}$	$\alpha_{\pi/2}$	$\alpha_{Finstad}$	$R_{\alpha 0.5}$	$R_{\alpha \pi/2}$	$R_{\alpha FINSTAD}$
09.03.1972	1.8	0.141	0.068	0.062	1.8	1.7	1.6
08.02.1973	2.0	0.126	0.056	0.049	1.7	1.6	1.6
17.02.1973	6.7	0.232	0.153	0.137	5.6	4.2	3.9
05.04.1973	2.3	0.160	0.085	0.077	2.6	2.1	2.0
17.11.1973	4.2	0.201	0.123	0.114	4.1	3.1	3.0
04.12.1973	8.7	0.155	0.081	0.070	8.6	5.2	4.7
22.01.1974	8.9	0.084	0.022	0.012	9.4	3.5	2.7
11.03.1974	2.4	0.099	0.033	0.024	2.6	1.9	1.8
04.11.1974	11.6	0.144	0.071	0.061	10.2	5.8	5.2
22.12.1974	6.4	0.086	0.023	0.014	6.8	2.9	2.4
27.01.1975	2.4	0.093	0.029	0.020	2.2	1.7	1.7
29.03.1975	4.7	0.256	0.177	0.159	4.5	3.6	3.4
12.04.1975	4.0	0.154	0.080	0.068	3.8	2.7	2.5
19.04.1975	2.8	0.114	0.046	0.038	2.7	2.0	1.9
28.01.1977	4.7	0.211	0.132	0.120	4.2	3.2	3.1

The investigation of the dependence of the icing on the wind speed for both the cylinders yield the results

$$I = 3.6\ 10^{-3}V \qquad (10)$$

This formula is close to that one received by Tammelin, B. and Kr. Säntti but more detailed investigation is needed because the correlation coefficient is very poor – about 0,30.

D. Conclusions

This study presents an attempt for assessment of the expected ice loads on large cylindrical bodies on the base of the theoretical knowledge about the icing process. Unfortunately not all from the needed parameters (such as LWC, the median volume diameter or the Macklin, s parameter) are available in the routine meteorological observations either were in this particular data set of experimental measurements. The original available information consisted also only of averaged meteorological values. Despite these limitations the results are relative good. In about 30% of the cases the calculated ice parameters are comparable with the measured data

It should be mentioned again that the values of the collision efficiency α_1 have been determined so low because of the averaged procedure – e.g. these values characterize the process in whole. At the beginning of the process this coefficient is much higher but it decreases rapidly with the increase of the ice diameter. Comparing the estimated values for α_1 with the appropriate table for its theoretical values as function of K and Φ from Langmuir and Blodgett [3] (in the experiment the K is between 0.144 and 0.256 and Φ - between 10 and 1000) a good agreement could be found. In this table the values for the total deposition efficiency are 0,038 and 0,022 and in our calculations the mean value for α_1 for the large cylinders is 0,0281and 0,0387 for the plastic pole with diameter 3cm.

As finally conclusion it could be pointed out that more model verifications are needed. It is planed to make new calculations using meteorological data for each 3 hours. Also data from one automatic ice sensor, mounted on another mountainous peak, will be used.

IV. REFERENCES

[1] D. Nikolov, E. Moraliiski Meteorological Conditions in Cases of Rime Icing in the Mountainous Regions of Bulgaria, *BJMH, vol. 11, 2000, number 3-4*

[2] Makkonen L. Models for the growth of rime, glaze, icicles and wet snow on structures *Philosophical Transaction A, vol. 358, 2000*

[3] Langmuir, I. and K. B. Blodgett (1946): A mathematical investigation of water droplet trajectories. In *Collected works of Irving Langmuir*, vol. 10, *Oxford, Pergamon press*

[4] Finstad, K. J., E. P. Lozowski and E. M. Gates (1988b): A computational investigation of water droplet trajectories. *J. Atmos. Oceanic Tecjnol. 5,*

[5] Tammelin, B. and Kr. Säntti (1996): Estimation of rime accretion at high altitudes – preliminary results., *Proc. of BOREAS III meeting, Finish Meteorological Institute.*

[6] Stanev Sv., E. Moraliiski and Kr. Velchev Rime-icng on power lines in mountainous regions Problems of meteorology and hydrology *1987, vol. 2*