Faculty of Mechanical Engineering
University of Belgrade

The occurrence of icing rain drops on powerlines

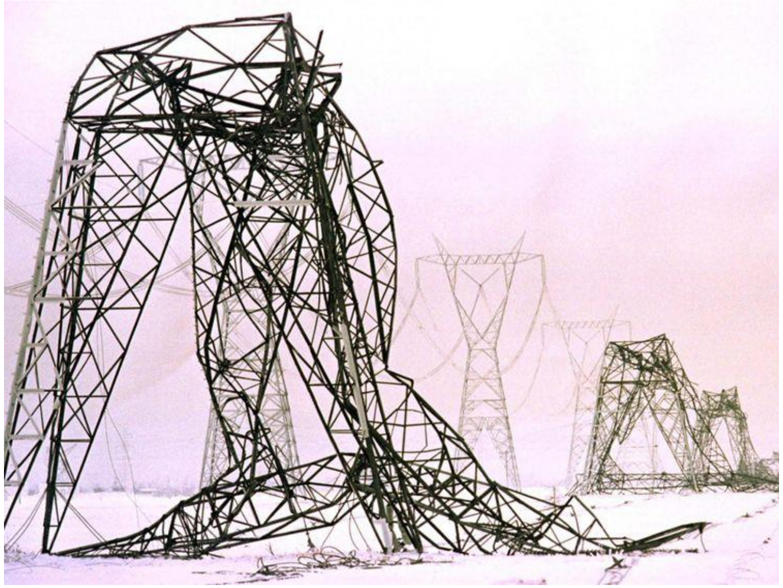
-National Student Competition within the 49th International HVAC&R Congress and Exhibition-

Student: Marija Orlovic
Mentor: Professor Milos Banjac, Ph. D. Mech. Eng.

Belgrade 2018

INTRODUCTION

- Freezing rain and hail are the most dangerous precipitation
- Ice load on power lines increases its weight which can lead to disasters, collapse of load-bearing structures, transmission lines and poles



INTRODUCTION

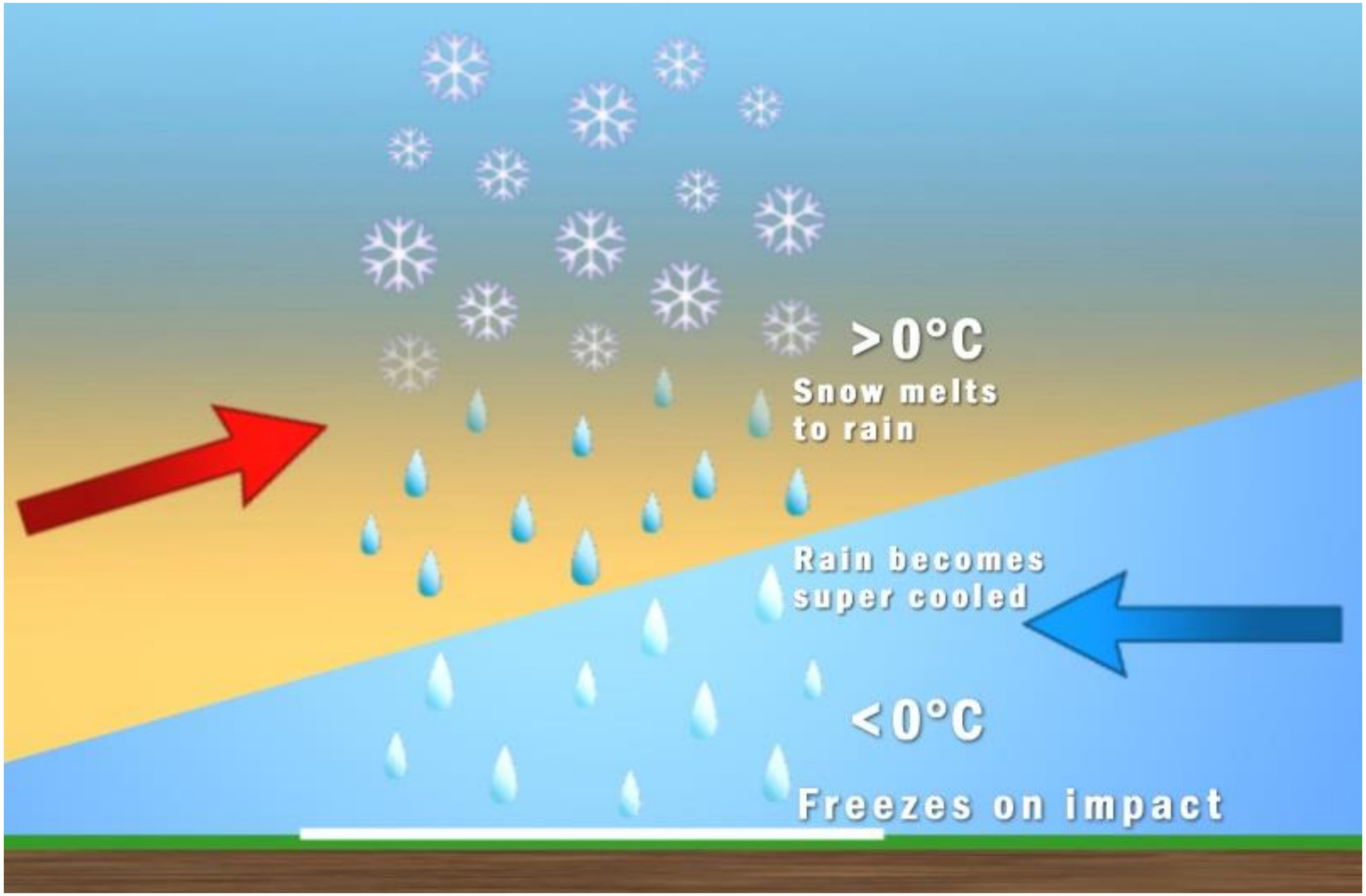
- There are two ways of forming ice load on hanging power lines of the electric power network:

  - Due to the freezing rain

  - If the temperature of rain droplets is above freezing point and they contact solid surface which temperature is below freezing point

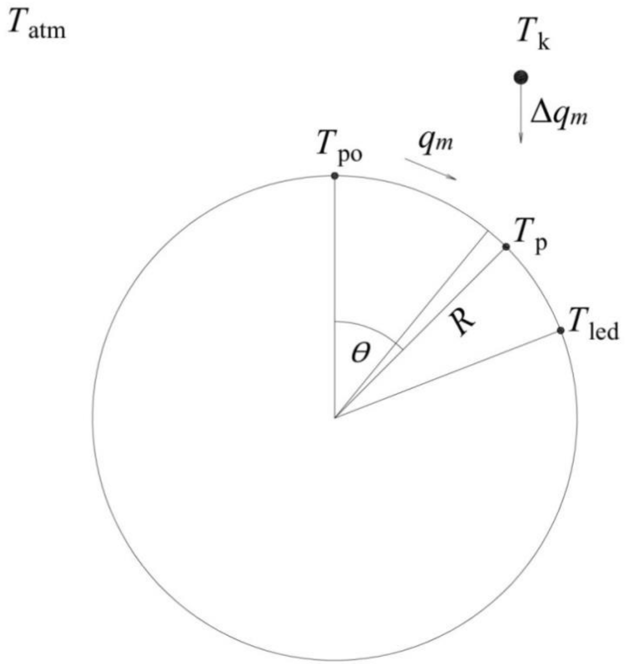
INTRODUCTION

- Freezing rain – droplets of supercooled water



DESCRIPTION OF THE MODEL

- Assumptions:
  - Temperature of rain droplets is above freezing point
  - The air temperature is below freezing point
  - Rain droplets contact solid surface which is presented as horizontal cylinder that has zero heat capacity and thermal conductivity. The cylinder is exposed to vertically falling rain droplets.



DESCRIPTION OF THE MODEL

- The mass balance equation for the upper half of the cylinder is determined as:

$$\frac{\mathrm{d}q_m}{\mathrm{d}s} = \Delta q_m \cos\theta \qquad (1)$$

- By the integration of equation (1) it is obtained:

$$q_m = \Delta q_m R \sin\theta \qquad (2)$$

- Where:
  - q_m (kg/ms) – mass flux of water flowing along the cylinder
  - Δq_m (kg/m^{2}s) – rainfall rate
  - θ (rad) – angle measured from the top of the cylinder
  - s (m) – distance along the surface ($\mathrm{d}s=R\mathrm{d}\theta$)
  - R (m) – cylinder radius

RESULTS

- It is assumed that there is no radial temperature gradient inside the water film
- Kinetic energy of air and water, heat released by evaporation and heat released by runback water are neglected
- Therefore, rate of change of water’s internal energy depends on the sensible heat of warm droplets which vertically fall on the surface of the cylinder and the convective heat loss to the air of the temperature below the freezing (heat balance equation):

$$c_w q_m \mathrm{d}T_\mathrm{p} = c_w \Delta q_m \left(T_\mathrm{k} - T_\mathrm{p}\right) R \cos\theta \mathrm{d}\theta + h\left(T_\mathrm{atm} - T_\mathrm{p}\right) R \mathrm{d}\theta \qquad (3)$$

- In order to non-dimensionalize the model, the heat balance is written for the upper half of the cylinder as:

$$0 = c_w \Delta q_m \left(T_\mathrm{k} - T_\mathrm{po}\right) + h\left(T_\mathrm{atm} - T_\mathrm{po}\right) \qquad (4)$$

RESULTS

- Also, dimensionless surface temperature is written as:

$$\Theta = \frac{T_{\mathrm{p}} - T_{\mathrm{atm}}}{T_{\mathrm{po}} - T_{\mathrm{atm}}} \qquad \mathrm{d}\Theta = \frac{\mathrm{d}T_{\mathrm{p}}}{T_{\mathrm{po}} - T_{\mathrm{atm}}} \tag{5}$$

- Dimensionless form of the equation (3) is obtained:

$$\sin\theta \frac{\mathrm{d}\Theta}{\mathrm{d}\theta} + \left(A + \cos\theta\right)\Theta = \left(A + 1\right)\cos\theta \tag{6}$$

- Where $A = \frac{h}{c_w \Delta q_m}$ and $0 \le \theta \le$ π/2

- Equation (6) is first ordered linear differential equation which can be solved by Fourier’s method of separation and has an analytical solution for A=1:

$$\Theta\left(\theta\right) = u\left(\theta\right)\cdot v\left(\theta\right) = \frac{\ln\left(1+\cos\theta\right) - \cos\theta + 1 - \ln 2}{0,5\left(1-\cos\theta\right)} \tag{7}$$

RESULTS

- The heat balance equation of the lower half of the cylinder can be shown by equation (8) (sensible heat of the warm falling droplets):

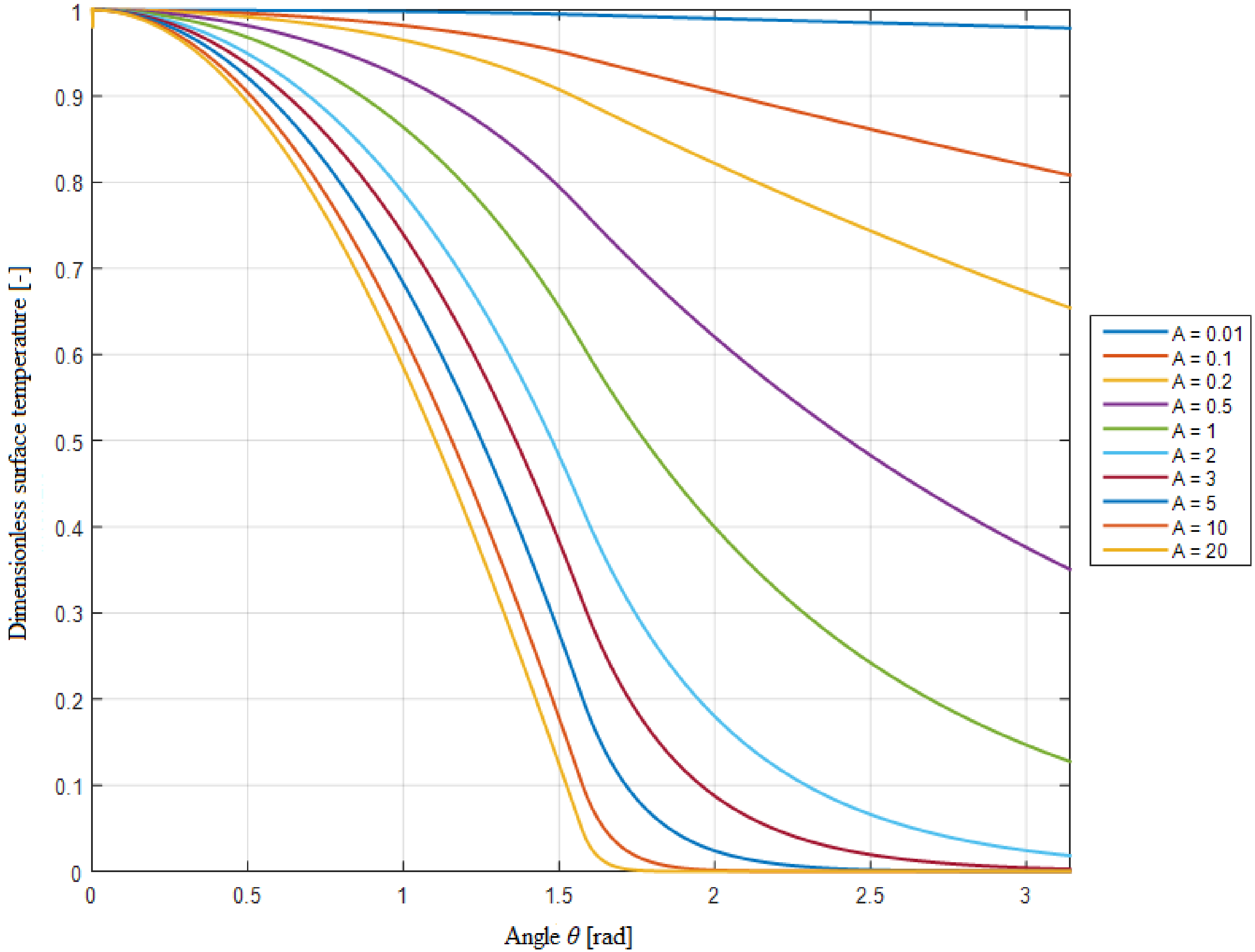
$$c_w \Delta q_m R \mathrm{d} T_{\mathrm{p}} = h\left(T_{\mathrm{atm}} - T_{\mathrm{p}}\right) R \mathrm{d}\theta \qquad (8)$$

- The distribution of dimensionless surface temperature for lower half of the cylinder is obtained by the integration of the equation (8):

$$\frac{\Theta(\theta)}{\Theta\left(\pi/2\right)} = e^{-A\left(\theta - \frac{\pi}{2}\right)} \qquad (9)$$

- Where π/2 ≤ θ ≤ π

- Dimensionless surface film temperature around the cylinder (equations (7) and (9)):



RESULTS

- Freezing begins when heat loss to the air is in balance with sensible heat secured by impinging warm droplets:

$$h\left(T_{\mathrm{led}} - T_{\mathrm{atm}}\right) = c_w \Delta q_m \left(T_{\mathrm{k}} - T_{\mathrm{led}}\right) \cos\theta_{\mathrm{C}} \qquad (10)$$

- Location where freezing begins is given by critical freezing angle:

$$\theta_{\mathrm{C}} = \arccos\alpha \qquad (11)$$

- Where α is heat-ratio parameter:

$$\alpha = \frac{h\left(T_{\mathrm{led}} - T_{\mathrm{atm}}\right)}{c_w \Delta q_m \left(T_{\mathrm{k}} - T_{\mathrm{led}}\right)} \qquad (12)$$

RESULTS

- The mass of ice ρ_{led}^{*} (kg/m) which is formed during a time interval *t* (s) is proportional to the difference between the convective heat flux from the cylinder and the sensible heat flux of the warm droplets:

$$\rho_{\text{led}}^{*} = \left[2R\pi h\left(T_{\text{led}} - T_{\text{atm}}\right) - 2c_w R\Delta q_m\left(T_{\text{k}} - T_{\text{led}}\right)\right]\frac{t}{r_{\text{led}}} \qquad (13)$$

- The volume of ice per length meter is equal to the surface of the ice accretion which is perpendicular to the cylinder axis, ie surface of the cross section of cylinder area. Therefore, the thickness of the ice layer is:

$$\Delta R = \left(R^2 + \frac{\rho_{led}^{*}}{\pi\rho_l}\right)^{0,5} - R \qquad (14)$$

- Where:
  - T_{led} (K) – freezing temperature
  - r_{led} (J/kg) – heat gained for phase changes
  - ρ_l (kg/m^3) – ice density

CONCLUSION

- The icing of overhead electrical transmission lines may cause many problems such as overloading, non-uniform icing, damaged power cables and towers

- These processes are more often appeared in Serbia

- Mass of ice formed on hanging lines has no influence on the distribution of electricity, just on increasing cable weight

THANK YOU FOR ATTENTION!